Thermography and Thermal Sensors as a Breast Cancer Early Diagnosis Technique: A Review

MKPSSA Perera[1#], MPA Karunaratne[2], WPLK Wijesinghe[3] and NMA Perera[4]

[1,3]Department of Electrical, Electronic, Telecommunication & Biomedical Engineering, Faculty of Engineering, General Sir John Kotelawala Defence University, Ratmalana, Sri Lanka
[2]Department of Mechanical Engineering, Faculty of Engineering, University of Moratuwa, Moratuwa, Sri Lanka
[4]Kings Hospital, Colombo 05, Sri Lanka

[#] <angeloperera@ieee.org>

Abstract— *Breast cancer is a widespread and devastating disease with significant global morbidity and mortality. Early detection plays a crucial role in improving outcomes and survival rates. However, current breast cancer screening methods, such as mammography, ultrasound, and magnetic resonance imaging, have limitations, including false-positive and false-negative results, high costs, and radiation exposure. This literature review examines the potential of thermography and thermal sensors as a non-invasive and radiation-free screening technique for breast cancer detection. Increased metabolic activity around tumor cells leads to temperature asymmetry and alterations in blood flow, which can be detected through thermographic techniques. Nevertheless, research studies have shown promising results, demonstrating high sensitivity and specificity in detecting breast cancer using thermography. Recent developments in breast cancer screening involve using surface thermal sensors, such as integrating flexible antennas into wearable bras and utilizing thermal sensor arrays. While these advancements show potential, they require further validation and improvements. Thermography and thermal sensors hold promise as a non-invasive, radiation-free, and potentially cost-effective screening method for breast cancer detection, and technological advancements are necessary to overcome current limitations to establish its efficacy as a standalone or complementary screening tool.*

Keywords— **Breast Cancer, Thermal Sensors, Early Diagnosis, Thermography**

I. INTRODUCTION

Breast cancer has emerged as the most prevalent cancer worldwide, surpassing lung cancer and accounting for approximately 11.7% of all cancer cases (Sung *et al.*,). Shockingly, breast cancer comprises one out of every eight diagnosed cancers, resulting in about 2.3 million new cases in 2020 alone (Arnold *et al.*, 2022). The devastating impact of breast cancer is further highlighted by the staggering number of deaths it causes, with an estimated 685,000 women succumbing to the disease globally in 2020 (Arnold *et al.*, 2022). Distressingly, developing countries face a survival rate of only 50-60%, primarily due to late-stage diagnosis (da Costa Vieira *et al.*, 2017; Rakhunde, Gotarkar and Choudhari, 2022). Even in countries with advanced treatment techniques, the survivability drastically decreases to 24% when breast cancer is diagnosed at or after the second stage, underscoring the critical importance of early detection, where the survival rate reaches 85% at the first stage (*Breast cancer statistics | World Cancer Research Fund International*, 2022).

The mortality rate of breast cancer remains alarmingly high, as evidenced by the less than 30% five-year survival rate in patients receiving chemotherapy for metastatic breast cancer (Kashyap *et al.*, 2022). These grim statistics shed light on the urgency of implementing effective screening strategies. Unfortunately, studies have shown that a significant proportion of women fail to engage in regular breast self-examinations (17.4%) and clinical examinations (13.5%) (Kayan and Cinar, 2022). This lack of proactive screening contributes to delays in diagnosis and treatment, responsible for 60% of recorded breast cancer deaths (Hakim and Awale, 2020). Numerous studies and expert opinions emphasize that early screening is the cornerstone for breast cancer control, resulting in improved outcomes and greater life expectancy (*Breast cancer*, no date; Ginsburg *et al.*, 2020; The American Cancer Society medical and editorial content team, 2022).

Early detection involves three crucial steps: breast education and public awareness, yearly screenings, and clinical breast examinations (Geetha and Umamaheswari, 2022). Timely diagnosis holds immense potential for a complete breast cancer cure, as stated by Dr. Hasarali Fernando, a physician from Sri Lanka, who believes that early detection and treatment can restore everyday life for breast cancer patients (Ginsburg *et al.*, 2020; Aloysius, 2022). Age is a significant risk factor, with women over 50 exhibiting a higher tendency to develop breast cancer, as highlighted by the latest statistics (Moreno and Herrera, 2019).

A non-invasive device or a technology that is free from radiation and is comfortable for patients to diagnose breast cancer is still not developed (Geetha and Umamaheswari, 2022). Despite advancements in technology, such as the emergence of digital mammography and computer-aided detection systems, the drawbacks associated with these techniques persist. The lack of a device that addresses the limitations of existing screening methods poses a substantial barrier to achieving optimal early detection rates.

II. METHODOLOGY

The methodology employed for this literature review involved a comprehensive search of relevant scientific databases, including PubMed, IEEE Xplore, and Google Scholar, using a combination of keywords such as "thermal sensors", "breast cancer", "thermography" and "early detection." The main aim of the research paper is to identify the current availability of an FDA-approved methodology that can reliably detect breast cancer with minimal patient complications. The search was limited to studies published between 2010 and 2023 to ensure the inclusion of recent advancements in the field. The initial search yielded a substantial number of articles, which were screened based on their titles and abstracts for relevance to the topic. Selected articles were then thoroughly read, and their reference lists were examined to identify additional relevant studies. Data from the included studies were extracted and organized according to various themes, including the thermal imaging techniques, the study population, and the performance metrics employed for breast cancer detection. The findings were synthesized, and critical insights were summarised to provide a comprehensive overview of thermal breast cancer detection techniques' current state and efficacy.

III. CONVENTIONAL BREAST CANCER SCREENING TECHNIQUES

A breast cancer diagnosis enables timely interventions and improves patient outcomes. However, the currently available screening methods for breast cancer exhibit limitations in their sensitivity, particularly in detecting cancer at early stages. These methods often fail to diagnose breast cancer until it has progressed to stages 2 to 4 when the tumor has grown into a noticeable lump (Geetha and Umamaheswari, 2022). Alarmingly, approximately 70% of diagnosed breast cancer cases involve lumps larger than 30mm, further underscoring the limited sensitivity of existing screening systems (Saadatmand *et al.*, 2015). Different methods that are currently used for breast cancer screening are reviewed below.

Table 1 - Comparison Between Conventional Breast cancer screening methods and Thermography (Omranipour et al., 2016b; Wang, 2017; Thermography: Procedure, Risks, Cost, and More, 2018; Limitations of Mammograms | How Accurate Are Mammograms?, 2022)

	Mammogram	**Ultrasound**	**MRI**	**Thermogram**
Checks for	Anatomical Behavior	Anatomical & Physiological Behavior	Anatomical Behavior	Physiological Behavior
Area of detection	Neck, Breast, Under Arms	Neck, Breast, Under Arms	Neck, Breast, Under Arms	Only Breasts
Sensitivity	67.8%	83.0%	94.4%	-
Specificity	75.0%	34.0%	26.4%	-
Cost	High	Average	Very High	Cheap
Age	50+	No age restriction	No age restriction	No age restriction
If undergone Mastectomy	Not effective	Not effective	Not effective	Irrelavant
Implants	Not very effective	Not very effective	Not very effective	Effective
Breast Density	Dense Breasts have low sensitivity	Low Dense Breasts have high sensitivity	Density is irrelevant	Density is irrelevant
Pain and Fear	Painful	Not Painful	Not Painful	Not Painful
Rupture Risk	Very High	Very Low Risk	No Risk	No Risk
Radiation	The patient will be exposed to radiation	No Radiation	No Radiation	No Radiation
FDA approval	Approved	Approved	Approved	Approved as an adjunct to mammogram
Accessibility	Less	Less	Less	Easy
Social Privacy	Less Privacy	Less Privacy	Less Privacy	Less Privacy
Time Taken	few seconds	10-20 minutes	40-60 minutes	few seconds

A. *Mammogram*

Mammography is currently considered the gold standard for breast cancer screening, widely adopted as the standard screening method (Geetha and Umamaheswari, 2022; Rakhunde, Gotarkar, and Choudhari, 2022). It has demonstrated the potential to reduce mortality rates by 23-49% and achieve an early diagnosis success rate of 80-90% *(Coldman* et al.*, 2014)*. However, despite being regarded as the best available screening method, the effectiveness of mammograms remains a subject of debate due to inherent limitations (Geetha and Umamaheswari, 2022; Rakhunde, Gotarkar and Choudhari, 2022). False-positive diagnoses are a notable concern, with a higher volume of such cases reported from mammograms since their introduction in the 1960s (Geetha and Umamaheswari, 2022). Moreover, false-negative results occur in one of every eight breast cancer diagnoses made through mammography, and dense breast tissue can contribute to false-positive findings (Rakhunde, Gotarkar and Choudhari, 2022). Mammograms are recommended for women above 50, as younger women often have denser breasts, resulting in less radiation penetration *(*Dense Breast Tissue | Breast Density and Mammogram Reports*, no date; Berrington De González and Reeves, 2005; Geetha and Umamaheswari, 2022)*. There is also a potential risk of mutations in the BRCA1 and BRCA2 genes due to radiation exposure during mammograms, directly impacting the development of breast cancer and other complications *(Arevalo* et al.*, 2016; Geetha and Umamaheswari, 2022)*. The high compressions during the mammogram procedure also risk damaging cancerous tissue cell walls, potentially leading to further complications *(Grimm* et al.*, 2022)*.

B. *Breast Ultrasound*

Breast ultrasonography has emerged as a valuable technique for breast cancer screening, particularly in cases where mammography struggles to detect cancer in dense breast tissue *(Geetha and Umamaheswari, 2022; Jabeen* et al.*, 2022)*. This non-invasive and radiation-free method has gained widespread use in the screening of breast cancers *(Jabeen* et al.*, 2022)*. However, the sensitivity of ultrasound diminishes in detecting non-palpable malignant cells, which highlights the importance of not relying solely on ultrasound for breast cancer screening (Geetha and Umamaheswari, 2022). Furthermore, ultrasound faces challenges in identifying tumors located deep within the breast and exhibits reduced sensitivity in detecting microcalcifications, which are significant indicators of early-stage breast cancer (Hakim and Awale, 2020).

C. *Breast Magnetic Resonance Imaging*

The American Cancer Society has recognized breast magnetic resonance imaging (MRI) as the most accurate screening method for breast cancer, offering the advantage of no radiation exposure *(*What Is a Breast MRI? | Breast Cancer Screening*, no date)*. The exceptional clarity of MRI images enables the clear visualization of very tiny lesions, which is crucial for early detection and diagnosis (Hakim and Awale, 2020). However, despite its advantages, breast MRI does have limitations. The high cost associated with MRI scanning poses a significant barrier to its widespread use as a screening tool. Additionally, the high number of false-positive results obtained from MRI scans reduces sensitivity in accurately diagnosing breast cancer (Geetha and Umamaheswari, 2022). Furthermore, breast MRI exhibits reduced sensitivity in identifying microcalcifications, essential indicators of early-stage breast cancer (Hakim and Awale, 2020).

IV. THERMOGRAPHY AS A BREAST CANCER SCREENING TECHNIQUE

Thermography has emerged as a potential method for breast cancer detection, focusing on capturing the thermal

Table 2 - Summary of the literature on surface thermal sensors as a breast cancer screening technique

Reference	Methodology	Results
(Elsheakh *et al.*, 2023)	Smart Bra prototype using magnitude, reflection phase, and transmission coefficients tested on a phantom.	It was validated only on simulation models with 83% and 100% accuracy for 10mm and 20 mm tumors. Not clinically validated.
(S *et al.*, 2020)	iTBra (CBM) used 16 thermal sensors to develop a predictive model.	The model achieved 78% accuracy, 83.6% sensitivity, and 71.5% specificity. Not clinically validated.
(Elouerghi *et al.*, 2022)	An IOT prototype device made with 28 bioheat microsensors tested on a phantom.	Measured breast temperatures to a precision of 0.1°C. Not clinically validated.
(Moreno and Herrera, 2019)	SBra prototype using thermal and electrical impedance sensors	No Validations were available.
(Al Masry *et al.*, 2021)	EVA Bra prototype made using 200 thermal sensors.	No Literature available
(Prasad *et al.*, 2021)	Fibre Bragg Grafting, thermal sensor array, tested on a phantom.	Sensitivity of approximately 1~pm. Not clinically validated.
(Porter *et al.*, 2016)	A prototype made with 16 microwave antennas and tested on a volunteer over 28 days.	Discernible variations in permittivity were observed.

emission from high vascular abnormal cells, which serves as a cornerstone for its application (Lubkowska and Chudecka, 2021; Geetha and Umamaheswari, 2022). The underlying principle of thermography is that rapidly dividing tumor cells require an increased oxygen-rich blood supply, leading to enhanced vascularity and angiogenesis (Rakhunde, Gotarkar and Choudhari, 2022).

Notably, thermographic techniques can detect changes in the human body's thermal characteristics even before visible symptoms manifest, making it a promising approach for early screening (Lubkowska and Chudecka, 2021). The human body exhibits surface temperature symmetry, which becomes disrupted due to the presence of a tumor (Lubkowska and Chudecka, 2021). This asymmetry is attributed to the increased metabolic activity around tumor cells, resulting in temperature increments and the secretion of nitric oxide, leading to microcirculation and vascularity (Gautherie, 1980; Rakhunde, Gotarkar and Choudhari, 2022). Heat dissipation from the body is considered an accurate measure for diagnosing breast cancer in its earliest stages (Rakhunde, Gotarkar and Choudhari, 2022). Despite the Food and Drug Administration approving thermography as a screening technique for breast cancer in 1982, it has not surpassed the popularity of mammography (*Breast Thermography: History, Theory, and Use | Natural Medicine Journal*, no date; Rakhunde, Gotarkar and Choudhari, 2022). One of the challenges in implementing thermography is the lack of a standardized range of values for women's breasts, necessitating a progressive adaptation from person to person (Lubkowska and Chudecka, 2021).

Nevertheless, research studies have demonstrated promising results. For instance, screening tests involving 470 women showed a sensitivity of 91.02% and a specificity of about 82.39% (Kakileti *et al.*, 2020), while a study comparing mammograms and thermography in 132 women reported sensitivities of 80.5% and 81.6%, respectively (Omranipour *et al.*, 2016a). Thermography can capture tumor lumps and early indicators such as vasodilation, angiogenesis, and alterations in blood cell flexion (Kakileti *et al.*, 2017). However, it is essential to note that thermal imaging alone cannot differentiate between elevated breast temperatures caused by breast cancer and other conditions, such as mastitis, which can limit its efficiency (Rakhunde, Gotarkar and Choudhari, 2022). Animal studies have also supported the potential of thermography, with experiments on Wistar rats showing average temperatures of 36.66°C, 37.77°C, and 38.87°C in average, growing, and cancerous breasts, respectively (Poerbaningtyas *et al.*, 2021). Additionally, by employing machine learning techniques such as support vector machines (SVM), researchers have achieved high accuracies of 98.11% on mammograms and 96.57% on thermograms, further highlighting the diagnostic potential of thermography (Khan and Arora, 2021). According to Table 1, thermography's painless, cost-effective, portable nature and its radiation-free approach position it as a promising method for identifying breast cancers.

V. BREAST CANCER SCREENING USING SURFACE THERMAL SENSORS

The proposed "Smart BRA" has gained attention as a potential advancement in breast cancer detection. It involves the integration of fully flexible antennas into a wearable bra, employing flexible Roger substrate and conductive fabric on cotton substrates. These antennas function as sensors, utilizing the magnitude and phase of reflection and transmission coefficients within the microwave bandwidth to detect tumors (Elsheakh *et al.*, 2023). However, it is essential to note that the Smart BRA has only been tested on a model breast and has not yet been validated on human breasts. The simulations showed 83% and 100% accuracy for 10mm and 20 mm tumors respectively. Another such development involves a prototype equipped with 16 microwave antennas, tested on a volunteer over 28 days, revealing discernible variations in permittivity. Although this prototype shows promise, further improvements are necessary to diagnose breast cancer accurately (Porter *et al.*, 2016). Another noteworthy advancement is the Fibre Bragg Grafting thermal sensor array, specifically designed to diagnose breast cancer in its earliest stages. This sensor array was subjected to experimentation on a phantom and simulated using COMSOL, resulting in an impressive sensitivity of approximately 1 pm. This breakthrough underscores the potential of thermal sensing technology in the early detection of breast cancer (Prasad *et al.*, 2021). Similarly, Elouergh et al. developed an IOT-based prototype using 28 bioheat micro sensors, which were experimented on a phantom and simulated in COMSOL. The prototype measured breast temperature with a precision of 0.1℃ at any depth but has not yet been validated to diagnose breast cancer. Also, the patient should be stabilized for about 20 minutes to accurately measure the breast temperature, a major disadvantage of this prototype (Elouerghi *et al.*, 2022). Other prototypes, such as the EVA Bra and SBra, have utilized thermal and electrical impedance sensors on breast surfaces, but proper validation and research publications are limited (Moreno and Herrera, 2019; Al Masry *et al.*, 2021). It was mentioned that there were 200 thermal sensors attached,100 on each side in the EVA Bra (Al Masry *et al.*, 2021). The Cyrcadia Breast Monitor (CBM), the iTBra, is an affordable and non-invasive wearable device. It utilizes sixteen sensors to measure thermal data for breast monitoring. During the development phase, 93 individuals with benign and 108 with malignant conditions were included in the study. The model reached 78% accuracy, 83.6% sensitivity, and 71.5% specificity. However, the prototype is yet to be clinically validated, necessitating further investigation (S *et al.*, 2020). Table 2 summarizes the literature on thermal sensors used to diagnose breast cancer.

VI. CONCLUSION

This comprehensive literature review has shed light on the methods used to screen breast cancer, emphasizing the importance of early diagnosis. However, despite the extensive research conducted in this field, there is still a notable absence of an FDA-approved methodology that can reliably detect breast cancer with minimal patient complications. Early detection of breast cancer has long been recognized as a crucial factor in improving patient outcomes and reducing mortality rates. While mammography remains the gold standard for breast cancer screening, other conventional methods, such as breast ultrasound and breast MRI, are used today to diagnose breast cancer. However, according to Table 1, we can see that they all have different limitations, especially the inability to diagnose breast cancer at its early stages. Thermography has emerged as a potential alternative to mammography, offering a non-invasive and radiation-free method for breast cancer detection. However, with the facts stated in Table 1, the evidence supporting the reliability and accuracy of thermography as a standalone screening tool still needs to be more conclusive. While some studies have shown promising results, others have reported limited sensitivity and specificity, preventing its widespread adoption in clinical practice. As a result, thermography still needs to be incorporated into the screening protocols of medical oncologists.

Given the pressing need to detect breast cancer at its earliest stages, there is a call for developing a screening approach that addresses the limitations of current methods. Such an approach should offer reduced complications, minimal radiation exposure, and easy accessibility to patients. Researchers and clinicians must continue to explore innovative technologies and methodologies to achieve these goals. Further research and advancements are necessary to identify a reliable and FDA-approved screening methodology to detect breast cancer at its earliest stages. A few have researched thermal sensor-based prototype devices, yet there has not been a successful innovation that has promising results to diagnose breast cancer at its earliest stages, according to Table 2. The summary in Table 2 shows that almost all research based on thermal sensors has not been validated on breast cancer patients but only tested on phantoms. Despite technological advancements, the gold standard for breast cancer screening and diagnosis remains Mammogrammy. Additionally, ultrasound remains a widely accepted and medically endorsed screening method, prominently employed by medical professionals across the field. Continued collaborative efforts between researchers, healthcare providers, and policymakers are crucial to achieving these objectives and improving breast cancer outcomes for individuals worldwide.

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VIII. AUTHOR BIOGRAPHIES

MKPSS Angelo Perera is currently a final year Biomedical Engineering Undergraduate at the Faculty of Engineering of General Sir John Kotelawala Defence University. His final year research is based on developing a machine-learning algorithm for early breast cancer diagnosis using 3D breast temperature maps.

Dr. MPA Karunaratne is the Strategic Ops & Tech Lead, Softmatter, MAS Holdings, Sri Lanka, and a visiting lecturer at the Department of Mechanical Engineering, University of Moratuwa, Sri Lanka. His research interests include Wearable Technology, Biomechanics, Bio Instrumentation, and Biomaterials

WPLK Wijesinghe is a lecturer in the Department of Electrical, Electronic, Telecommunication & Biomedical Engineering at General Sir John Kotelawala Defence University, Sri Lanka. His research interests include Electronic Sensors, Biomechanics, and Medical Instrumentation.

Dr. Naomal Perera (MBBS, MS, FRCS (Edinb.)) is a consultant Oncological Surgeon based at Kings Hospital, Colombo 05, Sri Lanka. His research interests include Breast Cancer, Thyroid Cancer, and Helicobacter Pylori.