

ORIGINAL RESEARCH ARTICLE

A comprehensive system for breast cancer screening using rotational thermography and dynamic thermal infrared imaging

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Abstract

Integrated rotational thermography and dynamic infrared imaging enable accurate, non-invasive, and early breast cancer (BC) detection. This study presents an integrated framework for a novel BC screening approach that combines dynamic thermal imaging and comprehensive angle coverage. The proposed system aims to achieve high accuracy and a reliable method for BC detection by addressing the limitations of conventional infrared imaging approaches. By integrating innovative camera technologies, rotational thermography, and advanced data analysis techniques, the system overcomes challenges, such as incomplete breast tissue coverage, limited adaptability to diverse patient profiles, and limitations in data analysis and diagnostic yield. The research methodology comprised pilot studies (PS1, PS2, and PS3), followed by a final study, utilizing various data collection techniques and analysis methods. Infrared images were captured using various infrared cameras, including both low-resolution and high-resolution models. Rotational thermography provided multiple-angle imaging, improving abnormality detectability. User-interface-based image processing software and machine learning algorithms were employed for efficient data analysis and feature extraction. The results demonstrated accurate binary classification of normal versus abnormal breast tissue, achieving sensitivity, specificity, and accuracy of 86.67%, 97.30%, and 93.27%, respectively. In addition, this study highlights the importance of considering angiogenesis in BC screening, as infrared imaging can detect hypervascularity and hyperthermia in non-palpable BCs. Integrating angiogenesis-related factors with infrared imaging can facilitate early detection and enhance prognostic outcomes. Overall, the proposed BC screening system overcomes limitations through dynamic temperature-based imaging, comprehensive angle coverage, and consideration of angiogenesis.

Keywords: Breast cancer screening; Dynamic temperature-based imaging infrared imaging; Rotational thermography; Angiogenesis; Biomedical engineering; Machine learning; Data analysis techniques; Early detection

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1. Introduction

Breast cancer (BC) is the most commonly diagnosed malignancy among women worldwide. Traditional BC detection methods, such as mammography and ultrasonography (USG), have been used for decades. However, limitations include false positives and false negatives¹ and variability in sensitivity and specificity by age, breast density, and imaging modality.^{2,3} USG is a popular detection method, but it is less accurate than mammography. Additionally, ultrasound is operator-dependent and can be influenced by the technician's skill and experience. Recently, there has been increased interest in developing new methods for early BC detection, such as rotational thermography and dynamic temperature-based infrared imaging.⁴

This study involved pilot studies and a final phase that employed various infrared camera technologies, including low-resolution forward-looking infrared (FLIR) cameras and higher-resolution FLIR T650Sc and Variocam HD600 cameras. The introduction of rotational thermography enabled imaging from multiple angles, enhancing the system's ability to detect potential abnormalities.⁵ The proposed system addresses incomplete tissue coverage, limited adaptability across diverse patient profiles, and suboptimal analytic pipelines and diagnostic yield.⁶

The effectiveness of the proposed system was evaluated through qualitative and quantitative analyses. The qualitative analysis focused on visual interpretation, identifying thermal patterns indicative of BC. The results demonstrated accurate classification of normal versus abnormal breast tissue, as evidenced by sensitivity, specificity, and accuracy metrics.⁷ The proposed system's quantitative analysis involved machine learning techniques and statistical methods to analyze the thermal data and identify potential abnormalities. The results indicated higher accuracy and reliability than conventional BC screening approaches.⁸ The methods and wavelength bands used with hyperspectral imaging technology to detect BC yielded high sensitivity, specificity, and accuracy. A meta-analysis of eight studies on BC diagnosis using hyperspectral imaging methods reported average sensitivity, specificity, and accuracy scores of 78%, 89%, and 87%, respectively.⁹ Contemporary machine-learning applications support quantitative diagnosis and can reduce inter-observer variability.¹⁰ Meta-analytic estimates for infrared thermography, particularly dynamic/rotational protocols with modern image processing and machine learning, show a pooled sensitivity $\approx 88.5\%$, with a specificity $\approx 71.8\%$. Additionally, rotational/dynamic acquisition improves lesion localization compared to static thermography.¹¹

1.1. Limitations of conventional infrared imaging approaches

Conventional approaches to using infrared image processing for BC screening have limitations that impact their effectiveness. One such limitation is the incomplete coverage of breast tissue, as static imaging techniques may fail to capture abnormalities from certain angles or regions.¹² This lack of adaptability to diverse patient profiles can result in missed diagnoses and delayed interventions.¹³ Furthermore, limitations exist in the data analysis of infrared imaging, which can lead to inaccurate results and further delays in diagnosis and treatment.¹⁴

The limitations of infrared imaging are not unique to this technology, as many different biologically based approaches to detecting BC face similar challenges.¹⁵ Infrared imaging has been approved by the Food and Drug Administration as an adjunct to mammography to detect thermal abnormalities in the breast.¹⁶ Traditional film-based mammography may not adequately cover breast tissue, and other imaging modalities, such as ultrasound and magnetic resonance imaging, have their limitations.¹⁷⁻²⁰

Traditional infrared imaging has the potential to overcome some of the limitations of mammography and other imaging modalities. For example, infrared imaging can selectively optimize contrast in areas of dense tissue that are difficult to visualize with other imaging modalities.²¹ However, traditional infrared imaging needs to be further developed to overcome its limitations, such as its lack of adaptability to different patient situations and failure to capture abnormalities from specific angles or areas.^{6,22} Different imaging modalities and methods may be necessary to enhance the accuracy and effectiveness of BC screening and diagnosis. Improved performance for rotational and dynamic thermography compared to static thermography has been reported, along with details on algorithmic and receiver operating characteristic analysis.⁴ Additionally, a supplementary or Cureus review article may provide a concise background with comparative data and summary tables.²³

1.2. Relation between thermal imaging and angiogenesis

The study highlights the importance of addressing angiogenesis in BC screening. Infrared imaging is a valuable tool in BC detection as it can reveal hypervascularity and hyperthermia in non-palpable BCs.^{24,25} The comprehensive angle coverage of the proposed system enables the detection of potential abnormalities in breast regions that are usually missed by traditional methods.²⁶

1.2.1. Role of angiogenesis in BC progression and prognosis

Angiogenesis is the process of creating new blood vessels, which plays a crucial role in the development and progression of BC.²⁷ Angiogenesis is an independent prognostic indicator in BC²⁸ and is initiated by a hypoxic condition to develop the malignancy, leading to vascular endothelial growth factor production and release.²⁹ Angiogenesis is a crucial step in the progression and spread of BC, facilitating rapid tumor growth by creating new blood vessels.^{29,30}

1.2.2. Prognostic and diagnostic significance of infrared thermography in BC

Infrared imaging demonstrates notable prognostic relevance, correlating with pathological indicators including tumor size, histologic grade, lymph node involvement, and growth-related biomarkers.³¹ It is also an independent risk factor for BC detection and can lead to an early detection of BC, increasing overall survival.³¹ Infrared imaging can identify additional BCs in patients with dense breasts not detected by mammography.³² For each breast, two thermal images are captured: The first aligns with the polarity of the external cooling source, and the second is taken after twice the initial time, representing twice the thermal penetration depth and the opposite polarity.³² It is necessary to recruit existing vascularity and neo-angiogenesis in cellular growth and multiplication.³³ In biomedical engineering, thermography has been established as a valuable tool in identifying standard and neoplastic tissue growth through *in vitro* and *in vivo* studies.³³ Infrared imaging can be instrumental in detecting cancers that are not visible on mammography and can reveal hypervascularity and hyperthermia in 86% of non-palpable BCs.³³

Contemporary clinical evidence indicates that thermal signatures reflect underlying tumor biology, including vascular and metabolic activity, thereby supporting the use of thermography—with appropriate image acquisition and analysis—to aid in the detection of non-palpable cancers and the inference of prognostic information.¹⁴ Hence, infrared imaging may enable early BC detection and provide valuable prognostic information through its correlation with pathological parameters, including tumor size, grade, lymph node involvement, and proliferative markers. Consequently, infrared imaging has significant potential for BC screening.

1.2.3. Detection of angiogenesis using rotational and dynamic thermographic techniques

Rotational thermography and dynamic temperature-based infrared imaging are two emerging technologies that have

the potential to revolutionize BC screening. Rotational thermography involves taking multiple images of the breast from different angles and using a computer algorithm for detection. Dynamic temperature-based infrared imaging involves measuring changes in temperature in the breast tissue over time. Both methods can detect angiogenesis, a key biomarker for BC. The comprehensive system, which utilizes rotational thermography and dynamic temperature-based infrared imaging, has several advantages over traditional methods.

2. Methodology

2.1. Experimental setup design and data collection techniques

This study proposes a novel BC screening system incorporating dynamic temperature-based imaging and comprehensive angle coverage to address the limitations of conventional BC screening approaches. The research methodology involved subject selection, data collection using infrared cameras, data analysis techniques, and performance evaluation.

The study followed a systematic approach, conducting pilot studies (PS1, PS2, and PS3) and a final study (FS) phase. The pilot studies explored different camera technologies, including low-resolution FLIR (United States) cameras in PS1 and a higher-resolution FLIR SC325 (United States) camera in PS2. The rotational thermography technique was introduced in PS3 to enhance the system's ability to detect potential abnormalities. The FS utilized a robotic arm-based automated hardware movement system with a temperature-controlled chamber for data collection.

Table 1 summarizes the data collection techniques used in each phase, the number of patients, the design setup, and the challenges or observations made during data collection. The pilot studies relied on manual data collection and analysis, requiring skilled personnel and facing challenges related to variations in focal length and control of ambient temperature. In contrast, the FS phase implemented automated data collection and analysis systems, standardized protocols, and a controlled environment, resulting in faster data collection and improved accuracy.

In the initial pilot study (PS1), data collection followed a technique described in early studies.¹⁹ Participants were seated in front of a camera with raised hands (Figure 1A), and two cameras captured images at a 45° angle. In the subsequent pilot study (PS2), participants were seated similarly, but only one front-facing camera captured infrared images (Figure 1B).^{25,34}

Modifications were made in accordance with the doctor's guidance. In this setup, thermographic imaging

Table 1. Data collection techniques used in different phases of the study

Phase	Description	No. of patients	Used camera	Number of images for each subject	Setup design	Advantages	Limitations
Pilot study 1 (PS1)	Data collected from July 2015 to June 2016	71	Data acquisition using two low-resolution FLIR 160×120×2 cameras	2	The subject sat in front of the camera with both hands raised upward; IR image acquisition through two cameras placed at two corners, and images captured from a 45° angle	Fast data collection	Insufficient information; requires human expertise for image analysis; no standardization with ambient temperature
Pilot study 2 (PS2)	Data collected from July 2016 to August 2017	10	Data acquisition using one FL SC325 320×240 camera	1	Subject sat in front of the camera with both hands raised upward; angular views captured; challenges in focusing on a specific breast due to patient rotation; unsatisfactory imaging results due to variations in focal length	Fast data collection	Requires human expertise for image analysis; No relation drawn with ambient temperature changes
Pilot study 3 (PS3)	Data collected from October 2017 to November 2018	37	Rotational thermography FLIR T650Sc, Variocam HD600	16	Introduced thermal imaging using a rotational IR camera; the patient was seated in a fixed position, with the camera movement; the IR camera was rotated manually for data collection; a semi-automated software was used for analysis	Fast data collection; automated data collection and analysis system	Data collected in an open space may lead to unreliable results; difficulty in controlling ambient temperature; difficulty in obtaining a standardized protocol; may miss the relationship between ambient temperature and IR breast imaging
Final study	Data collected from November 2019 to January 2023	119	Motorized rotational thermography FLIR T650Sc, Variocam HD600	32	Motorized movement using a robotic arm for the IR camera hardware; used a temperature-controlled chamber; an automated software analysis tool was used for analysis; standardized protocol for data collection in an enclosed environment	Automated data collection and analysis system; detailed and accurate results; considers the relationship between ambient temperature and IR breast imaging	Large data size requires high performance system

Abbreviations: FLIR: Forward-looking infrared; IR: Infrared.

was performed with a stationary camera while the patient was seated on a rotating chair to obtain multi-angle views of the breast. However, the continuous rotation hindered consistent focus on a particular breast, resulting in image distortion and suboptimal diagnostic clarity.

A significant modification was made in PS3 (Figure 1C). The patient remained stationary while the camera moved in a semi-circular arc. A tabletop setup ensured that focus was on one breast at the pivot point, while the other was covered.

The FS used rotational thermography (Figure 1D). The camera rotated in a semi-circular arc while the

patient stayed seated. A breast-shaped hole in an enclosed chamber allowed imaging of one breast at a time. The focal length of the infrared camera was 1 m, which allowed us to set the camera-to-subject distance to 1 m. The system had a clearance of 0.76 m with respect to ground level, ensuring the subjects could comfortably place their legs under the table. Each subject underwent 32 captures of infrared images at different ambient temperatures.

Fourteen breast images and two axilla images were taken for each set of images. A protocol was developed to facilitate the imaging process, which involved positioning

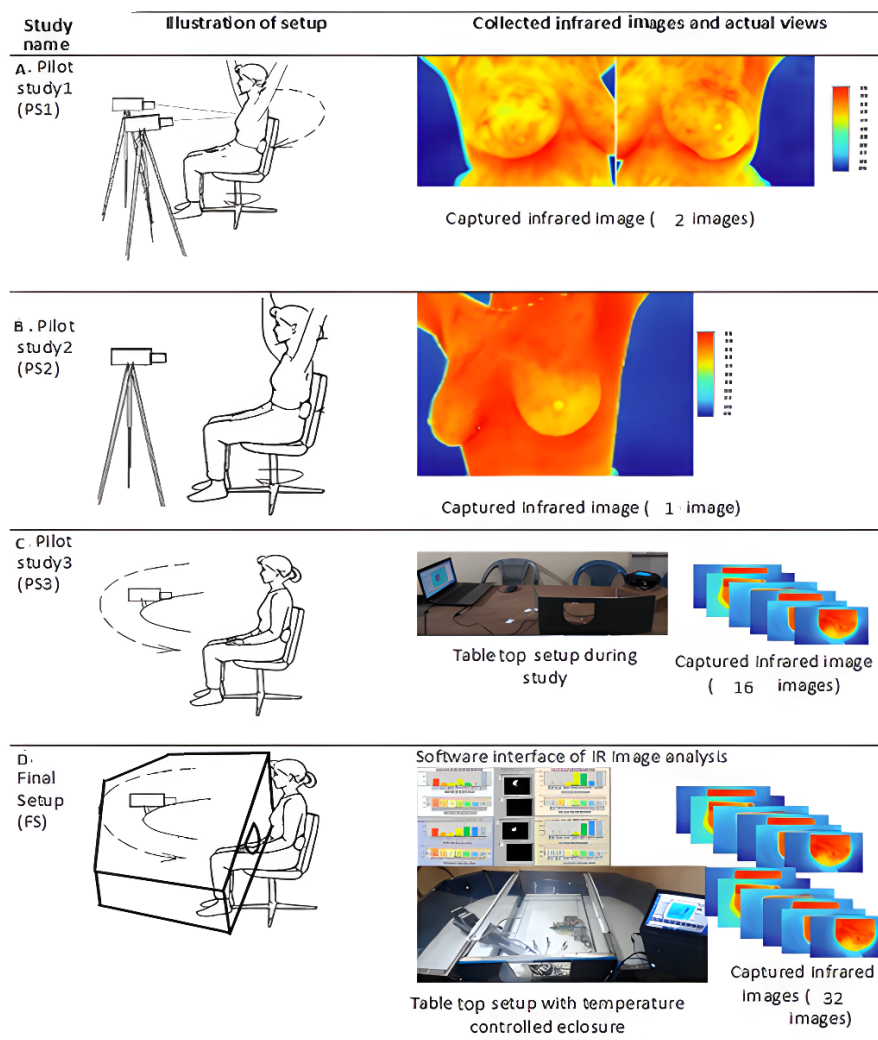


Figure 1. Evaluation of an infrared imaging-based breast cancer screening system through various phases

and focusing the camera through 17 defined steps. A second data set was collected after reducing the temperature by 2°C. A total of 32 infrared breast images were obtained per subject using dynamic temperature-based data collection.

A tabletop setup (Figure 2) enclosed the system in an airtight chamber to control room temperature. External regulation of the chamber's temperature was achieved using a portable AC while the room temperature remained constant.

The inclusion of the enclosed chamber emphasized the system's capability to collect data at two different ambient temperatures, which is essential for dynamic temperature-based data collection related to angiogenesis. Infrared

imaging can detect hypervascularity and hyperthermia in BCs, and it correlates with pathologic prognostic features and can lead to earlier detection of BC.

By considering angiogenesis in the development of the BC screening system, the researchers aimed to enhance the system's ability to identify early signs of BC and improve prognostic outcomes. Infrared imaging, combined with dynamic temperature-based data collection, has significant potential for BC screening, particularly for detecting non-palpable BCs that may not be visible on mammography.

2.2. Data interpretation and analysis techniques

In thermal imaging-based BC screening, the infrared camera serves as the primary device for data acquisition.

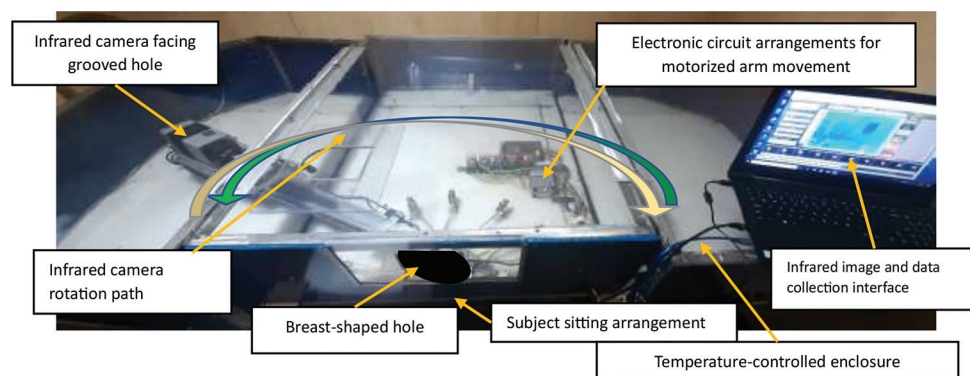


Figure 2. Schematic of the rotational thermography setup enclosed within a temperature-controlled chamber

Prior studies have highlighted challenges in achieving optimal image quality due to misalignment between imaging techniques and system configurations, as well as variations in temperature and other environmental factors. Addressing these limitations requires a detailed understanding of the system and adaptive design. Furthermore, integrating intelligent data acquisition and analysis frameworks is vital for enhancing system performance, refining algorithms, and improving the effectiveness of machine learning models.^{35,36} This system contains integrated infrared image processing techniques at each stage of development, resulting in an efficient system and an effective infrared image processing algorithm. Previous studies used online databases³⁷ to develop infrared imaging algorithms. However, their real-life implementation could have been improved, as the databases have insufficient information. The FS featured an innovative data collection protocol. [Table 2](#) shows the comparison chart of different aspects of data analysis techniques for each study phase. [Table 3](#) summarizes the data analysis techniques used in each phase of the study.

2.3. Infrared image feature extraction and analysis method

In the initial pilot study (PS1) and subsequent pilot study (PS2), conventional analysis techniques were employed, including statistical and distribution-based features (mean, median, mode, standard deviation, histogram, and maximum value). Infrared images were not correlated with results obtained from USG, mammography, or biopsy.

In the subsequent pilot study (PS3), USG and biopsy findings served as the primary reference sources. Infrared image-based clustering was applied for segmentation, using the mean temperature of each region of interest (ROI) as the key feature. The clustering process was refined and optimized through experimental validation and expert

consultation, considering abnormalities reported in the USG and biopsy results.

In the FS, the analysis technique remained similar to PS3, with the addition of a temperature-controlled enclosure. Image segmentation into foreground and background regions was performed using the K-median clustering algorithm. The ROI was divided into seven clusters using fuzzy-C means clustering in PS3 and K-median clustering in the FS. The selection of seven clusters was based on a validation exercise that identified abnormalities in ultrasound and biopsy reports. Additionally, two datasets were acquired under different ambient temperature conditions to determine the key discriminating feature for the analysis.

The temperature area clustering method was employed to analyze infrared images, wherein the number of pixels within each temperature cluster zone (Zones 0–6) was recorded to compute the corresponding area using an efficient infrared image processing and machine learning algorithm.³⁸ This method allowed for the identification of abnormal regions based on temperature variations. The algorithm for this analysis technique was implemented using LabVIEW 2021 SP1. [Figure 3](#) shows the user interface view of the rotational thermographic imaging system displaying infrared images of the affected and normal breast.

The final system incorporated a temperature-controlled enclosure to collect data at two different ambient temperatures, facilitating dynamic temperature-based data collection. This inclusion was crucial in considering the process of angiogenesis. Angiogenesis is associated with hypoxia, and the release of vascular endothelial growth factor, and infrared imaging can detect hypervascularity and hyperthermia in non-palpable BCs. By integrating angiogenesis-related factors into the system, earlier detection of BC and improved prognostic outcomes can be achieved, thereby establishing infrared imaging as an effective modality for BC screening.

Table 2. Comparison of data analysis techniques

Study	IR image analysis method	Reference source	Image segmentation method	Clustering method	Number of clusters	Temperature-controlled enclosure	No. of subjects	Key features
Pilot study 1	Conventional, manual	None	N/A	N/A	N/A	Not integrated	71	Mean, minimum, maximum value
Pilot study 2	Conventional manual	Doctors marking	N/A	N/A	N/A	Not integrated	10	Statistical and distribution-based features (mean, median, mode, standard deviation, histogram, maximum value)
Pilot study 3	IR image-based, software-generated	USG, biopsy reports with the doctor's validation	Clustering and ROI extraction	K-means and fuzzy C-means,	Optimized based on experimental validation and consultation with doctors	Not integrated	37	Mean temperature of each ROI, IR image features
Final study	IR image-based, automated, software-generated	USG, biopsy reports with doctor's validation; higher ambient temperature state	Clustering and ROI extraction	K-median	7	Integrated	119	Mean temperature of each ROI, IR image features

Abbreviations: IR: Infrared; N/A: Not available; ROI: Region of interest; USG: Ultrasonography.

2.4. Performance evaluation and validation

The performance of the developed BC screening system was evaluated using various metrics to assess its effectiveness. These metrics included sensitivity, specificity, accuracy, positive predictive value, negative predictive value, and the area under the curve of the receiver operating characteristic (AUC-ROC).

The developed model was tested on an independent dataset that was not used during the training phase to validate the system's performance. This helped assess the system's ability to generalize and classify new, unseen cases accurately.

Furthermore, comparisons with existing screening methods, such as mammography or ultrasound, were performed to evaluate the proposed system's advantages and limitations. The performance of the system was evaluated in terms of its ability to detect breast abnormalities, its sensitivity in early-stage cancer detection, and its potential to reduce false positives and negatives.

2.5. Ethical considerations

Throughout the study, ethical considerations were considered to ensure patient safety, privacy, and informed consent. The research adhered to ethical guidelines and obtained approval from the relevant institutional review board or ethics committee.

Patient confidentiality and data protection were maintained throughout the study. Measures were implemented to anonymize patient data and ensure its secure storage and transmission.

Informed consent was obtained from all participants after clearly explaining the study's purpose, procedures, potential risks, and benefits. Participants had the right to withdraw from the study at any point without facing any negative consequences.

Researchers also considered the potential biases in the study, such as selection bias, and took steps to mitigate them. They strived for a diverse and representative sample to ensure the generalizability of the findings.

3. Results

3.1. Qualitative and quantitative evaluations

The BC screening system, incorporating dynamic temperature-based imaging and comprehensive angle coverage, showed promising results in improving the accuracy and reliability of BC detection. The results were obtained through qualitative and quantitative evaluations, as discussed below.

Table 3. Summary of data analysis techniques used in each phase of the study

Phase	Data Analysis Technique	Observations
PS1	Conventional analysis based on basic image features	No reference to other imaging modalities
PS2	Conventional analysis based on basic image features	Unsatisfactory imaging results due to variations in focal length
PS3	IR image-based fuzzy C-means clustering, temperature-based feature extraction	Optimization of the clustering method based on consultation with doctors
Final study	IR image-based K-median clustering, temperature-based feature extraction clustering, background-foreground separation, ambient temperature-based analysis	Optimization of the clustering method based on consultation with doctors; improved abnormality detection; integration with data-collection workflow; demonstrates consistency with angiogenesis-related thermal patterns

Abbreviations: IR: Infrared; PS: Pilot study.

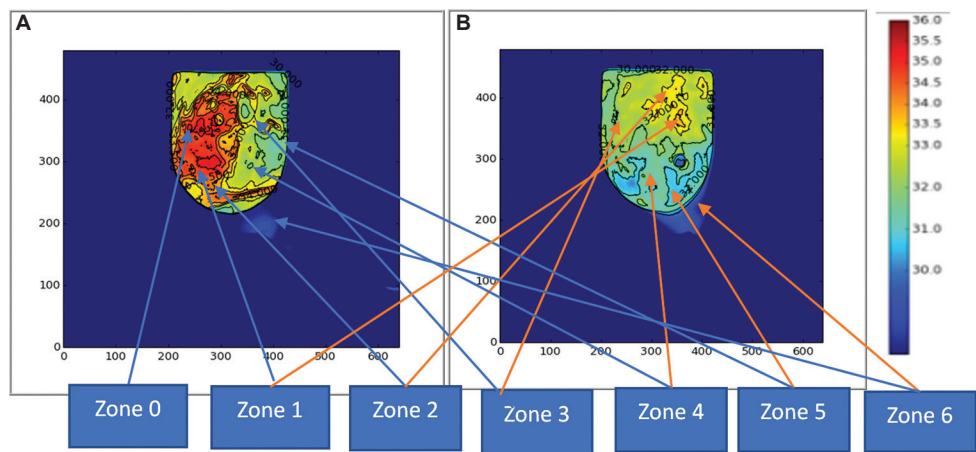


Figure 3. Software interface displaying frontal infrared images of the breasts. (A) Affected breast and (B) normal breast.

Qualitative analysis focused on visually interpreting infrared images to identify thermal patterns and abnormalities indicative of BC. Skilled personnel visually inspected the images for any abnormal temperature patterns or hotspots. The system successfully detected potential abnormalities through visual assessment. Table 4 summarizes the qualitative analysis results for each phase.

Quantitative analysis involves feature extraction and statistical methods to assess the system’s performance. The pre-processed infrared images extracted relevant features, such as temperature distribution, hotspot intensity, size, and spatial relationships. Machine learning algorithms were employed for classification based on the extracted features. Table 5 presents the critical features extracted for quantitative analysis in each phase.

3.2. Performance evaluation

The system’s performance was evaluated using various metrics, including sensitivity, specificity, accuracy, positive predictive value, negative predictive value, and AUC-ROC. Table 6 compares the performance results from each study phase.

The performance evaluation demonstrated an accurate classification of normal and abnormal breast tissue. The

Table 4. Summary of the qualitative statistical analysis

Phase	Methodology	Key findings
PS1	Expert consultation	Visual assessment for abnormalities
PS2	Expert consultation	Software-based assessment for abnormalities
PS3	Software and doctor	An irregular and box-shaped ROI is abnormal
Final study	Software and doctor	Improved detection of abnormalities in irregular and box-shaped ROI, visual assessment for abnormalities shows satisfactory results by concerned experts

Abbreviations: IR: Infrared; PS: Pilot study; ROI: Region of interest.

system achieved high sensitivity, specificity, and accuracy rates, indicating its effectiveness in detecting BC. The positive predictive value and negative predictive value further validated the system’s ability to accurately predict positive and negative cases. Table 7 summarizes the overall performance metrics.

4. Discussion

In phase PS1 (manual, conventional, and qualitative), expert personnel visually assessed abnormalities in the

Table 5. Summary of the quantitative analysis

Phase	Methodology	Key features extracted
PS1	Conventional	Mean, minimum, and maximum temperature
PS2	Conventional	Mean, median, mode, standard deviation, histogram, max value
PS3	IR-based open-air	Mean temperature of ROIs, K-means clustering, fuzzy-C means clustering
Final study	Dynamic temperature-based motorized rotational technique	Mean temperature of ROIs, K-median clustering, background-foreground separation, improved clustering

Abbreviations: IR: Infrared; PS: Pilot study; ROI: Region of interest.

Table 6. Comparison of results from each study phase

Phase	Data collection	Number of subjects	Mode	TP	TN	FP	FN	Sensitivity (%)	Specificity (%)	Accuracy (%)
PS1	Manual	71	Conventional, qualitative	Expert system, data analyzed based on visual perception						
PS2	Manual	10	Conventional, quantitative	1	6	2	1	50	75	70
PS3	Semi-automated	37	IR-based open-air, quantitative	9	19	4	1	90	82.61	84.84
Final study	Automated, protocol-guided software	119	Dynamic temperature-based motorized rotational, both qualitative and quantitative	39	72	2	6	86.67	97.30	93.27

Abbreviations: FN: False negative; FP: False positive; IR: Infrared; PS: Pilot study; TN: True negative; TP: True positive.

Table 7. Summary of overall performance metrics

Phase	Accuracy (%)	Precision (%)	Recall (%)	F1 score
Pilot study 1	-	-	-	-
Pilot study 2	70	33.33	50	39.50
Pilot study 3	84.84	69.23	90	78.12
Final study	93.27	95.12	86.67	90.65

infrared images without using specific numerical metrics for evaluation. While we lacked sensitivity, specificity, and accuracy values for quantitative assessment, this qualitative technique provided meaningful associations between infrared imaging features and BC.

Phase PS2 (manual, conventional, and quantitative) combined manual assessment and software-based evaluation using conventional quantitative methods. The system achieved an accuracy of 70%, indicating that 70% of predictions were correct. The precision of 33.33% suggests that only 33.33% of optimistic predictions were true positives. A recall of 50% shows that the system correctly identified 50% of actual positive cases. The F1 score of 39.50 represents a balanced system performance measure.

Phase PS3 (semi-automated, infrared-based, and quantitative) utilized semi-automated infrared-based methods for quantitative assessment. The system achieved a promising accuracy of 84.84%, representing a significant improvement over PS2, with a precision of 69.23% and a recall of 90%, indicating an effective identification of actual

positive cases. The F1 score of 78.12 demonstrates balanced precision and recall.

The FS phase (automated, dynamic temperature-based, both qualitative and quantitative) incorporated an automated system with dynamic temperature-based imaging and comprehensive angle coverage, integrating qualitative and quantitative approaches. This phase demonstrated the highest accuracy of 93.27%, impressively detecting breast abnormalities. The precision of 95.12% indicates that most predictions were accurate, resulting in a high number of true positives. With a recall of 86.67%, the system effectively identified many positive cases, ensuring comprehensive detection. The high F1 score of 90.65 indicates an outstanding balance of overall precision and recall performance.

This study highlights the advantage of considering angiogenesis as an advanced process in BC screening. Infrared imaging, or thermography, is a valuable tool for detecting BC, as it can reveal hypervascularity and hyperthermia in non-palpable BCs. By integrating angiogenesis-related factors with infrared imaging, the proposed system can facilitate earlier detection of BC and enhance prognostic outcomes.

The proposed BC screening system has demonstrated promise, but certain limitations must be acknowledged. In the pilot studies (PS1, PS2, and PS3), manual data collection and analysis introduced variability and subjectivity, necessitating the involvement of skilled personnel. Challenges, such as focal length variations,

ambient temperature control, and open-space environment were observed during data collection.

In contrast, the FS phase employed automated data collection and analysis, standardized protocols, and a controlled environment, improving accuracy and efficiency. However, data collection in the FS phase was slower due to dual temperature control in the enclosed environment. Further advancements are necessary for faster data collection and more effective data analysis techniques.

Future research should focus on refining data analysis methodologies to enhance accuracy and reliability. The integration of multimodal imaging data and clinical information can enhance diagnostic capabilities. Large-scale clinical trials are necessary to validate the system's performance on diverse populations and assess its impact on BC detection rates and patient outcomes.

5. Conclusion

The integration of rotational thermography and dynamic temperature-based infrared imaging in a comprehensive BC screening system has shown promise in detecting breast abnormalities. Qualitative analysis confirms its ability to visually identify potential indicators of BC, while quantitative analysis and performance metrics demonstrate accurate classification of normal and abnormal breast tissue. Incorporating findings related to angiogenesis enhances the system's diagnostic capabilities. Ongoing research aims to optimize the system and validate its performance in real-world clinical settings.

Implementing this comprehensive system in clinical settings presents several challenges, including the need for specialized equipment and trained technicians, which can limit accessibility and increase costs. However, further research is needed to advance BC screening technologies utilizing rotational thermography and dynamic temperature-based infrared imaging. Improving image analysis algorithms and system accuracy can make a device suitable for clinical use.

Overall, this comprehensive system has the potential to revolutionize BC screening, improving early detection and saving lives. Continued research can address the limitations of traditional methods and enhance patient outcomes.

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Conflict of interest

The authors declare that they have no competing interests.

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Conceptualization: Asok Bandyopadhyay

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Methodology: Asok Bandyopadhyay

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Ethics approval and consent to participate

This study received ethical clearance from the Institutional Review Board (IRB)/Ethics Committee of Cachar Cancer Hospital and Research Centre (Approval No. CCHRC/IRB/01/2019/254). Written consent was obtained from each participant in the study.

Consent for publication

Written consent was obtained from the participants for this experimental study.

Availability of data

All data analyzed have been presented in the paper.

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