Universidade Federal de Pernambuco

Centro de Informática

Graduação em Sistemas de Informação

A systematic review of algorithms for breast cancer diagnosis using thermography.

Trabalho de Conclusão de Curso de Graduação

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Recife, Junho / 2025

Ficha de identificação da obra elaborada pelo autor,
através do programa de geração automática do SIB/UFPE

Nogueira, Gustavo.
A systematic review of algorithms for breast cancer diagnosis using thermography. / Gustavo Nogueira. - Recife, 2025.
21 : il., tab.

Orientador(a): Jamilson Ramalho Dantas
Trabalho de Conclusão de Curso (Graduação) - Universidade Federal de Pernambuco, Centro de Informática, Sistemas de Informação - Bacharelado, 2025.
7.
Inclui referências, apêndices, anexos.

1. Breast cancer. 2. Artificial intelligence. 3. Thermal imaging. 4. Diagnosis. 5. Algorithms. I. Dantas, Jamilson Ramalho. (Orientação). II. Título.

000 CDD (22.ed.)

GUSTAVO NOGUEIRA.

A SYSTEMATIC REVIEW OF ALGORITHMS FOR BREAST CANCER DIAGNOSIS USING THERMOGRAPHY.

Monografia apresentada a Graduação em Sistemas de Informação da Universidade Federal de Pernambuco, Centro de Informática, como requisito para a obtenção do Título de Bacharel em Sistemas de Informação.

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Aprovado em: 11 / 04 / 2025.

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A systematic review of algorithms for breast cancer diagnosis using thermography.

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ABSTRACT

Breast cancer tumorigenesis usually takes place in the cells of the mammary ducts and poses a significant health challenge globally, as it remains the most common cancer type. Early diagnosis and advancements in treatment have substantially enhanced survival rates for breast cancer. Currently, mammography, ultrasound, and magnetic resonance imaging are the primary techniques for early breast cancer detection. In contrast, thermography-based diagnostics, despite its decreased cost when compared to all other techniques, remains underused. This happens largely due to the challenges faced by current computational methods to correctly classify thermography-based images. This study conducts a systematic literature review to identify and understand which artificial intelligence algorithms are currently employed in diagnosing breast cancer using such thermographic images. Additionally, it seeks to map the main challenges stemming from this specific research area. To achieve this, a significant number of international studies were scrutinized, considering criteria such as: employed methodology, databases utilized, publication venues, impact factors, algorithms applied, overall contributions to the field, findings, and conclusions.

Keywords: breast cancer – artificial intelligence – thermal imaging – diagnosis – algorithms

1. INTRODUCTION

Breast cancer is a type of cancer that forms in the cells of the breast, usually in the mammary ducts, which are the tubes that carry milk to the nipple, or in the lobules, which are the glands that produce milk (Silva 2017). Breast cancer occurs at similar rates in both developed and underdeveloped countries. However, mortality rates are higher in underdeveloped countries due to late detection (Santana et al. 2022). Thermography has emerged as a valuable tool for screening breast carcinoma, aiming to reduce associated morbidity and mortality (Gupta et al. 2023). Medical image analysis, a rapidly advancing field, plays a critical role in diagnosis by offering innovative solutions and improved accuracy (Zerouaoui and Idri 2021). Many techniques have been developed for the diagnosis of breast cancer how mammography, ultrasound, MRI, histology, and thermography (Radak et al. 2023).

This paper conducts a systematic literature review to identify the types of artificial intelligence techniques used for diagnosing breast cancer through thermography images and to map the challenges in this field. The main goals include examining current screening strategies and evaluating existing breast cancer screening methods, as well as identifying the strengths and limitations of the methods used. As the main contributions of this paper, we can list:

- Evaluate existing breast cancer screening methods to identify the strengths and limitations of the methods used.
- Comparison between the main studies in the state of the art related to algorithm evaluation, highlighting the databases used and the results obtained.

- Challenges that are still emerging and research opportunities for beginners and researchers interested in applying new algorithmic frameworks for breast cancer diagnosis using thermography.

The organization of the remaining sections of this paper is as follows: Section 2 introduces the fundamental concepts of techniques for diagnosing breast cancer, an overview of thermal cameras and artificial intelligence. Section 3 outlines the methodology used for papers collections. Section 4 reviews the state-of-the-art and compares the evaluated studies. Section 5 discusses key directives and current challenges in diagnosing breast cancer using thermography images. Finally, Section 6 concludes the paper and highlights future directions.

2. FUNDAMENTAL CONCEPTS

2.1. Breast Cancer Detection: An Overview

Types of breast cancer deception: Mammography, breast ultrasound and Magnetic resonance imaging (MRI) of the breast. Then its characteristics, advantages and disadvantages will be shown.

- Mammography is the most common and effective method for the early detection of breast cancer (Thakur et al. 2024). It is an imaging exam that uses low-dose X-rays to create detailed images of breast tissue. Mammography can detect tumors that are too small to be palpated, as well as microcalcifications that may indicate the presence of cancer (Thakur et al. 2024).
- Breast ultrasound uses sound waves to create images of the inside of the breast (Thakur et al. 2024). This exam is often used as a complement to mammography, especially in women with dense breasts, where mammography may be less effective (Silva 2019).
- Breast Magnetic Resonance Imaging (MRI) uses magnetic fields and radio waves to produce detailed images of breast tissue. It is often recommended for women at high risk of breast cancer, such as those with a strong family history of the disease (Rautela et al. 2022).

2.2. Thermal Camera

Infrared cameras are devices that capture images based on the thermal radiation emitted by objects, allowing the visualization of the heat they generate. Unlike conventional cameras, which record visible images, infrared cameras detect radiation in the infrared light spectrum (invisible to the naked eye) (Silva 2017). These devices are widely used in various fields such as security, surveillance, industry, and medicine. One of the main benefits of infrared cameras is the ability to make accurate diagnoses without the need for physical contact (Silva 2017). With technological advancements, their use has expanded, becoming more accessible and offering increasingly higher resolutions(fonte vozes da minha cabeça).

2.3. Artificial Intelligence

The combination of artificial intelligence (AI) with thermography has shown great potential in the medical field, especially in the early diagnosis of breast cancer (Silva 2019). Thermography, which uses infrared cameras to detect temperature variations on the skin's surface, can identify thermal anomalies associated with pathological processes, such as cancer (Santana et al. 2022). These thermal anomalies occur due to the increased cellular metabolism in tumor areas, which generates additional heat, visible in thermal images (Santana et al. 2022). However, analyzing these thermal images can be challenging due to the large amount of data generated and the need to identify subtle patterns indicating the presence of tumors (Silva 2019). This is where artificial intelligence, especially deep learning techniques, comes into play. AI algorithms, such as convolutional neural networks (CNN), can be trained to identify and classify thermal patterns associated with tumors, overcoming the limitations of human analysis, such as subjectivity and interpretation errors (Karthiga and Narasimhan 2021).

3. METHODOLOGY

To conduct this study analysis, a systematic literature review was performed. This method provides an organized and unbiased process to identify the nature and scope of the available empirical studies, with the aim of answering the research questions. This type of study enables the categorization of previously published reports and results, ultimately presenting a visual summary of the findings. The systematic review provides an overview of the area, classifying and identifying the types of research and their respective results (Petersen et al. 2008).

3.1. Planning

Planning began with the definition of the research objective and questions. Then, the search strategy was constructed, determining the research bases, the search terms, and the inclusion and exclusion criteria for selecting papers.

3.2. Research Questions

To achieve this, the following questions were formulated, which will be answered in this paper:

- Q1: What are the most commonly used algorithms?
- Q2: What are the challenges in breast cancer detection using artificial intelligence?
- Q3: Which thermographic image acquisition techniques show the best performance?
- Q4: What are the challenges for large-scale implementation of thermography in breast cancer diagnosis?
- Q5: How does breast cancer detection using deep learning differ from other approaches?

Conducting a systematic review that addresses the raised questions is crucial for the advancement of early breast cancer diagnosis through thermography and artificial intelligence.

3.3. Databases

The databases used in this study were SpringerLink, PubMed, and Nature Publishing Group, as they are prominent digital libraries in the fields of computing and medicine. These sources were selected due to their strong emphasis on biomedical research, machine learning applications, and interdisciplinary scientific studies. PubMed was chosen for its comprehensive coverage of biomedical and life sciences literature, which is essential for identifying medically relevant machine learning research. SpringerLink was included for its vast repository of applied computer science and engineering publications, particularly those related to image processing. Nature Publishing Group was selected for its high-impact journals that frequently feature pioneering studies at the intersection of artificial intelligence and healthcare. Together, these databases provided a comprehensive and relevant foundation for the literature review.

3.4. Search Terms

After defining the databases to find the primary studies, the search string was defined to identify and classify these studies, as can be seen in Figure 1. In the three databases adopted, advanced search resources were used to find the researched keywords contained in the titles and abstracts of the prospected material.

Throughout the research process, the search string was progressively refined to improve the relevance and quality of the retrieved publications. Initially, a broad query was created using general terms related to artificial intelligence and breast cancer detection through thermal imaging. As initial results were reviewed, commonly used expressions such as "machine learning", "thermography", and "breast cancer" were identified as key components, while less effective terms were adjusted. Boolean operators and grouping were used to ensure precise filtering across the selected databases. This iterative refinement helped align the search with the research objectives and improved the retrieval of highly relevant scientific publications.

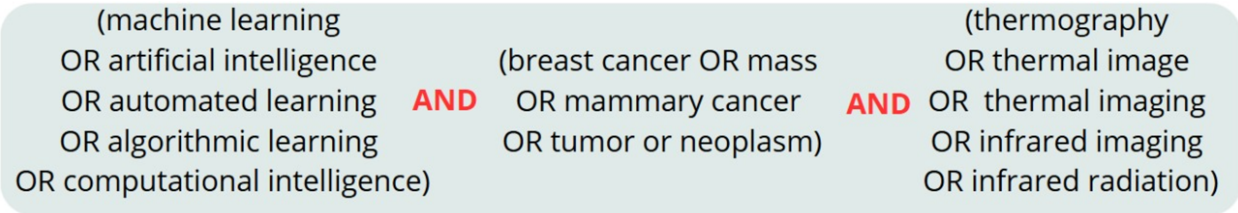

Figure 1. The search string.

As the search encompasses studies from around the world, broad search strings were used to include as many relevant works as possible.

3.5. Inclusion and exclusion criteria

Inclusion and exclusion criteria: Inclusion and exclusion criteria are used to delimit more relevant studies that answer or do not the research questions.

The following inclusion criteria (IC) were defined:

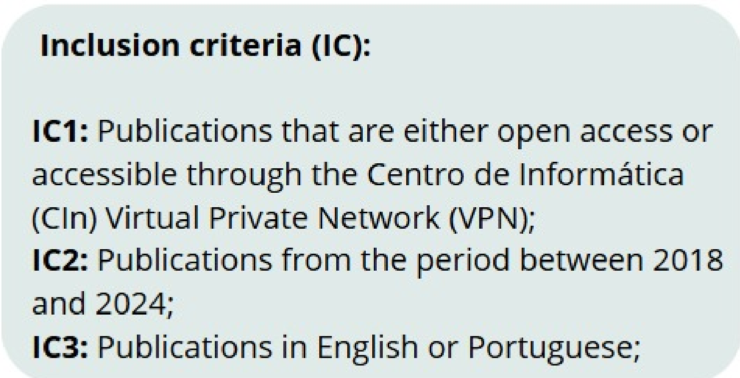

Figure 2. Inclusion criteria (IC) .

The exclusion criteria (EC) were:

Exclusion criteria (EC):

EC1: Publications that are not open access and cannot be accessed through the Centro de Informática (CIn) Virtual Private Network (VPN);
EC2: Duplicate publications;
EC3: Publications prior to 2018;
EC4: Publications that are not in English or Portuguese;
EC5: Publications outside the scope of the research.

Figure 3. Exclusion criteria (EC).

The search for papers was conducted at the beginning of the first half of 2024. The number of papers identified, the filtering method, and data extraction are detailed next.

3.6. Screening of articles

Initially, we sought to find as many articles as possible on the proposed topic. As a result, 917 articles were found in SpringerLink, 454 in the PubMed database and 675 in the Publishing Group, totaling 2046 articles. After applying the exclusion criteria (EC) and considering the objective of this paper, 43 articles remained, which were used to answer the questions outlined in Subsection 3.2.

4. REVIEW OF STATE OF THE ART

In the systematic literature review process, the following data were extracted from all 43 analyzed works: title, number of citations, impact factor, country of publication origin, source, authors' names, access link, publication year, contact email, year and location where the article was published. This information is available in a Google Sheets spreadsheet titled: Article List. [1]. In the following subsections, a brief summary of the 43 articles is presented, divided based on the databases used in this study: SpringerLink, PubMed and Nature Publishing.

4.1. SpringerLink

The first article analyzed was by Gupta et al. (Gupta et al. 2023). They present a new feature selection method using machine learning. An artificial neural network is used for classification, with results varying based on age range and the physiology of each type of breast. The study compares sequential backward selection (SBS), forward selection, and exhaustive techniques, concluding that SBS is significantly effective for breast cancer diagnosis, achieving an accuracy of 88.57% with a computation time of 87.4s.

The authors Ensafi et al. (Ensafi et al. 2022) explore the application of deep learning to improve early detection by integrating multiple thermographic views. Their approach combines frontal-45, lateral-45, and

[1] Article List.

lateral-45 images to enhance the performance of pre-trained deep learning architectures through transfer learning. The study uses the Database for Mastology Research (DMR) and demonstrates that fusing multiple views can improve sensitivity by 2–15% and specificity by 2–30% compared to other handcrafted and deep learning-based techniques. They conclude that their technique is promising and could serve as a foundation for future research.

The brazilian researchers Santana et al. (Santana et al. 2022) presented their expertise in breast cancer diagnosis by exploring the potential of Deep Wavelet Neural Networks (DWNNs) for breast thermography imaging. While mammography remains the primary diagnostic tool, thermography serves as a complementary technique, offering advantages over self-examination. However, interpreting thermal images remains a challenge for radiologists. To address this, the authors propose a deep hybrid architecture based on a five-layer DWNN for feature extraction from regions of interest, combined with a linear kernel support vector machine for classification. Their study evaluates various classifiers, including Bayesian classifiers, multilayer perceptrons, decision trees, and Random Forests. The results demonstrate that their approach achieves an average accuracy of 99% and a kappa score of 0.99. The authors conclude that by leveraging pre-fixed wavelet transform filter banks, their model simplifies the classification process, making deep networks a promising tool for improving breast thermography-based diagnosis.

The article written Yadav et al. (Yadav and Jadhav 2022) by discusses the potential of thermal infrared imaging as an alternative to mammograms for breast cancer diagnosis. The article explores the use of modern machine learning, specifically CNNs, in classifying breast cancer using thermal images, improving upon traditional methods. Two pre-trained models, VGG16 and InceptionV3, were used for transfer learning to enhance the performance of a baseline CNN model. The best results were achieved with InceptionV3 through data augmentation and fine-tuning various parameters. However, the dataset of only 650 images was considered small for CNNs, which are typically trained on millions of images. Many similar images were discarded to avoid issues during training. The article suggests that applying techniques like multi-context ultra aggregation (MCUA) in the future could help improve model performance by using more diverse images.

Aiaidossov et al. (Aidossov et al. 2023) propose a novel intelligent system for breast cancer diagnosis using IR thermal images with Convolutional Neural Networks (CNNs) and Bayesian Networks (BNs). This approach combines transfer learning models like ResNet50 with CNNs and BNs to achieve high diagnostic accuracy with a small dataset. The system offers interpretability, allowing physicians to understand which features are critical for diagnosis. The results show accuracy between 91% and 93%, precision from 91% to 95%, sensitivity from 91% to 92%, and specificity from 91% to 97%. In conclusion, this integrated approach achieves accurate and interpretable breast cancer diagnosis.

This paper by the authors Radak et al. (Radak et al. 2023) makes a comparison of breast cancer diagnostic techniques, focusing on medical imaging modalities: mammography, ultrasound, MRI, histology, and thermography. They discuss popular methods such as Nearest Neighbor, SVM, Naive Bayes, DT, ANN, and CNN. The review highlights that these techniques have achieved high accuracy rates and have the potential to enhance clinical decision-making and patient outcomes.

The authors Karthiga et al. (Karthiga and Narasimhan 2021) propose a novel approach for breast cancer diagnosis using thermography and machine learning. Thermal images are pre-processed to enhance contrast and extract regions of interest. Features such as statistical, geometrical, and texture features from the Gray-

Level Co-Occurrence Matrix (GLCM) are extracted using curvelet transform. Among various machine learning techniques, cubic SVM achieved the highest accuracy of 93.3%, with the combination of statistical, intensity, geometry, and texture features providing the best results.In conclusion, the proposed method offers high accuracy for automated breast cancer diagnosis using thermography.

The researchers Gupta et al. (Gupta et al. 2022) explore the use of breast thermography for early cancer detection, as it can detect heat variations linked to precancerous tissues and tumors. Thermography identifies changes before mammography, offering an advantage in early diagnosis. Key features like energy, information effectiveness, and age are input into neural networks for analysis. The study compares three artificial neural network (ANN)-based algorithms: Gradient Descent, Resilient Backpropagation Algorithm (RBPA), and the newly proposed Extension of RBPA (ERBPA). Results show that ERBPA outperforms the others, achieving 99.90% accuracy for distinguishing between benign and malignant conditions. In conclusion, ERBPA provides a highly effective method for early breast cancer detection.

The authors Nogales et al. (Nogales et al. 2024) evaluates various approaches using thermographic images, focusing on hybrid artificial intelligence models, including convolutional neural networks and evolutionary algorithms. By segmenting thermography into three temperature ranges, the proposed method achieves an accuracy close to 94%. In conclusion, hybrid AI models can significantly enhance the diagnostic value of thermography.

Thakur et al. (Thakur et al. 2024) evaluate machine and deep learning techniques for breast cancer detection, focusing on image modalities, pre-processing, segmentation, and classification. They review studies published from 2010 to 2021, identifying common techniques such as thresholding, region-based, edge-based, clustering, and deep learning (DL) segmentation methods. The most used classifiers are Support Vector Machine (SVM) and convolutional neural network (CNN) variants. Notably, CNN models achieved 100% accuracy in classifying 250 ultrasound images. The review helps identify effective machine and deep learning methods for various datasets and provides insights into significant features for breast cancer detection. Key point, deep learning has largely surpassed traditional machine learning in breast cancer image analysis.

Hakim et al. (Hakim and Awale 2020) discuss the role of thermography in early breast cancer detection, emphasizing its low-risk, non-invasive nature. Although it was initially introduced in 1956, its use declined after 1977 due to its subjective nature and limitations compared to other screening methods. However, with advancements in technology, thermography is regaining attention from biomedical researchers. The review evaluates the various methods used for interpreting breast thermal variations, performance metrics like accuracy, sensitivity, and specificity, and highlights gaps in current research. The paper suggests that thermography, coupled with image processing, mathematical modeling, and AI, could offer a promising solution for early detection, especially in younger women.

The authors et al. (Zerouaoui and Idri 2021) conducted a Structured Literature Review (SLR) on the use of Machine Learning (ML) and Image Processing (IP) in breast cancer (BC) imaging, analyzing 530 papers published from 2000 to 2019. The review highlights that diagnosis was the primary medical task, with Deep Learning (DL) techniques predominantly used for classification. Most studies focused on mammograms, with the MIAS dataset being the most common. Image pre-processing, such as noise reduction and color normalization, was widely used, along with segmentation techniques like thresholding. Feature extraction was often performed using traditional methods (e.g., texture and shape features) or DL models (e.g., VGG16, ResNet). Few studies applied feature selection techniques, primarily filter methods.

This paper written by Mohan (Rai 2024) proposes a computer-aided detection system that uses thermal breast images for cancer detection. The system utilizes the pre-trained DenseNet121 model as a feature extractor, processing the images with edge detectors (Prewitt and Roberts) to create a 3-channel input. The model is evaluated on the Database for Mastology Research (DMR-IR) and achieves a classification accuracy of 98.80%, surpassing many state-of-the-art methods.

This paper, authored by Subhrajit Dey et al. (Dey et al. 2022), proposes a computer-aided system that utilizes thermal breast images for cancer detection. The system employs the pre-trained DenseNet121 model as a feature extractor and integrates edge detection techniques (Prewitt and Roberts) to enhance image input. Using the Database for Mastology Research (DMR-IR), the model achieves an accuracy of 98.80%, surpassing many state-of-the-art methods.

The authors Yang et al. (Yang et al. 2023) proposed a hybrid approach using deep complex neural networks and data mining for breast cancer (BC) diagnosis, aiming to improve accuracy and speed. The methodology incorporates data mining techniques to separate characteristics of healthy and cancerous cells, which are then used as input to deep neural networks for more accurate diagnosis. Thermography, an infrared imaging technique, was utilized alongside deep learning and data mining. The study involved 187 volunteers, including 152 healthy individuals and 35 cancer patients, with a total of 1,870 thermographic images. Four deep complex neural network models (ResNet18, ResNet50, VGG19, and Xception) were employed to classify benign and malignant images. Results showed that the combined method significantly improved the accuracy and speed of breast cancer diagnosis.

The authors Sharm et al. (Sharma and Mehra 2020) conducted a study on automatic multi-classification of breast cancer histopathological images, focusing on magnification-dependent classification using the balanced BreakHis dataset. They explored two machine learning approaches: one based on handcrafted features (Hu moment, color histogram, and Haralick textures) and another using transfer learning with pre-existing networks (VGG16, VGG19, and ResNet50) as feature extractors. The results showed that pre-trained networks outperformed both the baseline and handcrafted feature-based approaches across all magnifications. Additionally, data augmentation significantly improved classification accuracy. The highest accuracy was achieved with VGG16 and linear SVM, providing patch-based accuracies of 93.97% (40×), 92.92% (100×), 91.23% (200×), and 91.79% (400×), as well as patient-based accuracies of 93.25%, 91.87%, 91.5%, and 92.31%, respectively. "Fibro-adenoma" (benign) and "Mucous Carcinoma" (malignant) were identified as the most challenging classes for classification across all magnification levels.

The authors Abhisheka (Abhisheka et al. 2023) reviewed Deep Neural Networks (DNN) for breast cancer (BC) detection, classification, and segmentation using medical imaging. They found mammography and histopathologic images were most common, with 55% of studies using public datasets. Pre-processing techniques like data augmentation, scaling, and normalization were used to reduce variability. Convolutional Neural Networks (CNNs) were widely employed, either through pre-trained models or custom DNNs. The paper identifies key imaging modalities and DNN approaches for reliable predictions, addressing 13 challenges for future BC diagnosis research.

The review written by Koshy et al. (Koshy et al. 2022), covers imaging modalities, publicly available datasets, data augmentation, preprocessing, transfer learning, and deep learning techniques used in early breast cancer detection. It also reviews the performance, challenges, and future research directions of existing algorithms.Methods are compared based on performance metrics like accuracy, sensitivity, specificity, AUC, and F-measure. Many studies report over 90% accuracy in breast cancer detection using histopathological images. In Conclusion, the review identifies limitations, such as incorrect labeling due to observer variations and issues with computation time and memory. These need further exploration to enhance CAD systems for better accuracy.

This study written by Hemavathi et al. (Hemavathi et al. 2022) focuses on early-stage breast cancer prediction using deep learning. Various machine learning algorithms—such as Logistic Regression, K-Nearest Neighbors, Support Vector Machines, Decision Trees, Random Forest, and ensemble methods—were tested on a dataset with 30 features. Random Forest showed the best performance. After feature selection reduced the dataset to 14 attributes using a heat map, the models were re-evaluated, with Random Forest still leading and the reduced model performing similarly to the full-feature version. However, deep learning models can bypass feature selection due to their layered structure. The proposed deep learning model, designed for binary classification (malignant vs. benign), demonstrated superior performance across multiple evaluation metrics.

The authors Manhas et al. (Manhas et al. 2022) did a review examines the application of machine learning techniques on medical imaging modalities for cancer diagnosis between 2008 and 2019. Focusing on five major cancers—cervical, oral, breast, brain, and skin—the study highlights how machine learning, particularly when combined with imaging, has improved early detection. Traditional algorithms like SVM and GMM have shown strong classification results, while deep learning has become dominant in medical image analysis. The review identifies key challenges in feature selection, evaluation metrics, and model performance, and also outlines future research opportunities. Accuracies of up to 100% have been reported in some studies, emphasizing the potential of AI in cancer diagnostics.

The authors Shojaedini et al. (Shojaedini et al. 2024) proposed using Generative Adversarial Networks (GAN) to address the challenge of limited training data in thermography for cancer diagnosis. By estimating the statistical distribution of real thermographic images and generating fake images, they enhanced the dataset to improve deep learning performance. The method led to improvements in sensitivity (3-9%) and accuracy (3-7%), with a slight trade-off in specificity. The results showed that GAN-based augmentation significantly boosted the ability to differentiate between healthy and cancerous thermograms.

This paper written by Rehman et al. (Rehman et al. 2022) reviews state-of-the-art machine learning and deep learning techniques for breast cancer detection, particularly in mammography. It emphasizes the need for computer-aided diagnostic (CAD) systems to support early detection and reduce human error, especially in low-income regions like Asia and Africa where mortality rates are higher. The review analyzes 110 research papers, focusing on methods used for image preprocessing, classification, and the detection of key mammographic features such as breast density, mass, calcifications, and architectural distortion. It also evaluates performance metrics, datasets used, and highlights research gaps to guide future work in improving diagnostic accuracy.

This paper by Houssein et al. (Houssein et al. 2022) proposes a novel breast cancer classification model, IMPA-ResNet50, which combines a pretrained CNN architecture (ResNet50) with an improved meta-heuristic algorithm called the Improved Marine Predators Algorithm (IMPA), enhanced using the opposition-based learning (OBL) strategy for automatic hyperparameter optimization. The model aims to improve diagnostic accuracy in mammographic images by overcoming the challenges of manual hyperparameter tuning. Evaluated on two datasets (CBIS-DDSM and MIAS), the IMPA-ResNet50 achieved 98.32% and 98.88% accuracy, respectively, outperforming the baseline MPA and other meta-heuristics. The study highlights the effectiveness of IMPA for CNN optimization and outlines future work involving more datasets, additional pretrained models, and applications across broader medical and engineering problems.

Authors Olota et al. (Olota et al. 2024) conducted a study to enhance breast cancer classification in thermography using a hybrid system integrating image preprocessing and machine learning. Multi-view thermal images from the DBR dataset (1370 healthy, 645 sick) were preprocessed using Gaussian Filtering and anisotropic diffusion, followed by level-set segmentation and Canny edge detection. Texture features were extracted and reduced via t-test, then classified using Least Square Support Vector Machine (LSSVM) with optimized hyperparameters. The proposed approach achieved 9% higher accuracy, with 5.75% and 7.25% improvements in sensitivity and specificity, respectively, compared to existing methods. The study emphasizes enhanced segmentation and diffusion functions for improved thermogram-based diagnosis.

Authors (Raghavan 2024) proposed an attention-guided Grad-CAM method to enhance trust between AI models and healthcare professionals in breast cancer detection. The system used an ensemble of three pre-trained networks to classify infrared breast images, achieving an accuracy of 98.04%. The attention-guided Grad-CAM visually highlighted tumor regions, helping to explain the AI's predictions. The model's performance was validated with high precision, sensitivity, and specificity, and an ablation study showed a 42.5% drop in performance when explanation maps replaced original images, with an activation score increase of 25.35%.

Authors Shaikh et al. (Shaikh et al. 2020) proposed a Learning Using Privileged Information (LUPI)-based framework to enhance single-modal imaging-based CAD for breast cancer. Although multimodal imaging offers better diagnostic accuracy, single-modal imaging is often favored in rural hospitals due to equipment limitations. LUPI leverages privileged information (PI)—available only during training—to boost model performance without requiring it during testing. The study introduces classifier- and feature-level LUPI strategies, transferring knowledge from PI to the diagnostic modality. Experimental results on two primary datasets demonstrate that all classifier-level and deep learning-based feature-level LUPI methods consistently improve CAD performance in breast cancer diagnosis.

This study written by Nemade et al. (Nemade et al. 2022) focuses on early-stage breast cancer prediction using deep learning. Various machine learning algorithms—such as Logistic Regression, K-Nearest Neighbors, Support Vector Machines, Decision Trees, Random Forest, and ensemble methods—were tested on a dataset with 30 features. Random Forest showed the best performance. After feature selection reduced the dataset to 14 attributes using a heat map, the models were re-evaluated, with Random Forest still leading and the reduced model performing similarly to the full-feature version. However, deep learning models can bypass feature selection due to their layered structure. The proposed deep learning model, designed for binary classification (malignant vs. benign), demonstrated superior performance across multiple evaluation metrics.

Authors Jeyanthi and Mangai (Jeyanthi and Mangai 2019) proposed an ensemble classifier called Population Rescaled Differential Evolution with Weighted Boosting (PRDE-WB) for early breast cancer detection using thermal infrared images. The method involves a novel ROI extraction technique based on Logarithmic Cube-root Shift and PRDE optimization to select essential features. These features are then classified using

Weighted Boosting. Numerical experiments showed that PRDE-WB outperforms state-of-the-art methods in terms of classification accuracy, Peak Signal-to-Noise Ratio, and both detection rate and time for early breast cancer diagnosis.

4.2. PudMed

Authors Sami Ekici and Hushang Jawzal (Ekici and Jawzal 2020) proposed a computer-aided diagnosis (CAD) system for automatic breast cancer detection using thermography, targeting early diagnosis to reduce health and social complications. Given the limitations of mammography in young women due to dense breast tissue, the study focuses on thermal imaging as a non-invasive alternative. A new algorithm extracts breast features from thermal images using bio-data, image analysis, and statistical techniques, followed by classification using CNNs optimized via the Bayes algorithm. Tested on 140 individuals, the system achieved 98.95% accuracy, showing high potential for early detection.

Authors Rakhunde et al. (Rakhunde et al. 2022) conducted a review on the potential of thermography as an emerging modality for early breast cancer detection, highlighting its advantages over traditional techniques like mammography, ultrasound, and clinical breast examination. While mammography remains the gold standard, its limitations—especially in younger women with dense breast tissue—prompt the exploration of alternatives. Through a literature search across PubMed, Google Scholar, and ScienceDirect, the review emphasizes that recent advances in thermal sensors, imaging protocols, and AI-powered diagnostic tools significantly enhance thermography's viability. The findings suggest that thermography, when integrated with AI, holds strong promise as a mainstream breast cancer screening method.

This paper written by Zuluaga et al. (Zuluaga-Gomez et al. 2019) highlights that, while mammography remains the standard screening method, access is limited in many regions due to economic and social barriers. Recent advances in computational methods, infrared imaging, and bio-impedance devices have enabled alternative techniques such as thermography, infrared imaging, and electrical impedance tomography—which are faster, more accessible, and cost-effective. Studies show that these methods, when combined with machine learning models (e.g., logistic regression, decision trees, random forest, CNNs), significantly reduce false positives and false negatives. The integration of 3D simulations, advanced pre-processing, and tumor prediction models further enhances diagnostic accuracy. These techniques show great promise as complementary tools in breast cancer detection, especially in underserved areas.

Authors Diniz et al. (Diniz et al. 2018) proposed a CNN-based method for automatic mass detection in mammography images using the DDSM dataset. The approach includes classification of breast tissue (dense/non-dense) and mass detection through a multi-step training and testing pipeline. The method achieved up to 97.72% accuracy for tissue classification and 94.8% accuracy for mass detection in dense breasts, demonstrating the effectiveness of CNNs in assisting breast cancer diagnosis.

Authors Wang et al. (Wang et al. 2023) developed and validated a mobile phone-based AI infrared thermography (AI-IRT) system for breast cancer screening. Using two datasets from over 2,200 patients, the AI-IRT system achieved high diagnostic accuracy (AUC up to 0.9487), outperforming human readers. It is worth mentioning that this is the article in this systematic review with the highest impact factor 15.3. The results confirm the potential of AI-IRT to enhance early detection and expand access to screening, especially in resource-limited settings.

This review, authored by Mambou et al. (Mambou et al. 2018), examines the use of infrared digital imaging for identifying thermal variations between healthy and cancerous breast tissues, with a particular focus on the elevated thermal activity observed in precancerous regions and their surrounding areas. The study further underscores the importance of employing appropriate models, such as the widely recognized hemispheric model, to enhance the performance of Computer-Aided Diagnosis (CAD) systems based on infrared imaging. The primary contribution of this work lies in a comprehensive comparative analysis of multiple breast cancer detection techniques, incorporating advanced computer vision methods and deep learning architectures.

This paper, authored by Resmini et al. (Resmini et al. 2021), discusses various techniques proposed for the detection of abnormalities, including the analysis of thermal images to identify potential tumors. In this study, specific protocols were employed to acquire thermal data, which was subsequently processed using temperature time series and texture analysis, with advanced techniques such as genetic algorithms. By clustering the time series and extracting relevant features, the study achieved a high level of accuracy in detecting breast abnormalities using classifiers such as K-Star and Support Vector Machines (SVM). Although this hybrid methodology demonstrated significant potential, it also presented certain limitations. The dataset used was relatively small, and regions of interest were manually segmented, which may introduce bias. Future improvements should focus on incorporating automated segmentation techniques, enhancing feature extraction methods, and exploring alternative kernel functions for the SVM classifier.

4.3. Nature Publishing Group

The present study written by Lozano et al. (Lozano III et al. 2020) developed a computational thermal model of breast cancer based on high-resolution IR images, real 3D breast geometries, and real tumor definition from a breast cancer subject. The novelty of the study was its use of clinical data to construct and calibrate the model. The goal of the study was to quantify the thermal characteristics of breast cancer. The results reported herein represent a first step toward the accurate computational thermal modeling of breast cancer. Clearly, the female breast is a complex, inhomogeneous tissue. Thus, results provide estimates of the ranges expected regarding the metabolic heat generation rate of breast cancer. Future directions of this study include validating the calibrated model with future female subjects presenting with similar breast cancer characteristics and incorporating the real 3D breast vasculature.

In the present study written by Gutierrez et al. (Gutierrez et al. 2024) the IRI-Numerical Engine is introduced as a complementary tool for breast cancer detection based on surface temperature data. This approach employs a computerized inverse heat transfer method grounded in Pennes's bioheat transfer equations. The enhanced algorithm was validated using data from twenty-three patients with biopsy-confirmed breast cancer, following informed consent under an approved protocol. The algorithm accurately predicted the size and location of tumors in twenty-four breasts and correctly identified twenty-two contralateral breasts as cancer-free, with one patient presenting bilateral cancer. Tumors were characterized as highly perfused and metabolically active heat sources, which influence surface temperature patterns used in the heat transfer model. Notably, findings from the twenty-four biopsy-confirmed cases suggest that breast density does not impact the algorithm's detection capability. These results highlight the potential of the IRI-Numerical Engine as an effective adjunct to mammography. However, large-scale clinical trials with statistically significant sample sizes are required prior to its integration into standard diagnostic protocols.

This paper written by Zhou et al. (Zhou et al. 2024) investigates the role of the ANXA9 protein in breast cancer. The researchers found that ANXA9 is highly expressed in metastatic breast cancer tissue and that its expression correlates with disease progression. This study was included in this systematic review to demonstrate that there are other ways to diagnose breast cancer and to demonstrate the relevance of biopsy.

Authors Neumann et al. (Neumann et al. 2022) proposed an automated approach to allergy recognition using neural networks, aiming to address subjectivity in human-based classification. The method classifies prick allergic reactions using correlated visible-spectrum and thermal images of a patient's forearm. Tested on a dataset of 100 patients, the model achieved 93.6% accuracy, with a 0.98 ROC AUC and 0.97 AP. The approach also includes a segmentation method to isolate allergen injection areas, potentially reducing examination time and enhancing accuracy compared to human assessment.

5. RESULTS AND DISCUSSIONS

This section presents the results of the systematic review analysis. The extracted data is showcased, analyzed, and discussed. To facilitate comprehension and enhance visualization, the section is organized into subsections based on the publication year, the geographic origin of the studies, and the research questions (RQs).

5.1. The publication year

The distribution of the final set of selected studies over the years is shown below:

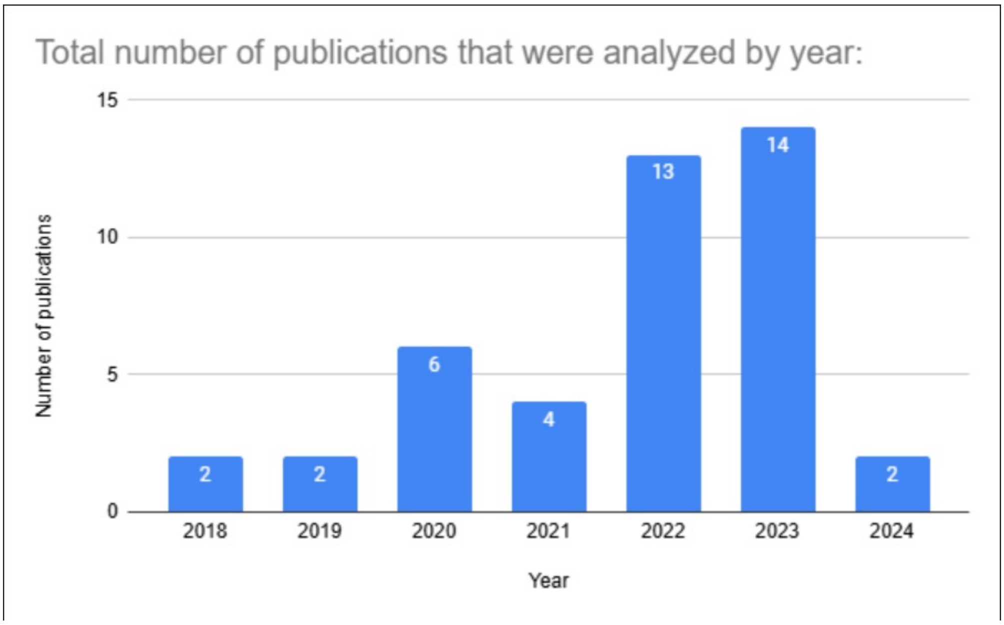

Figure 4. Total number of publications that were analyzed by year.

Analyzing the data, a decline in the number of articles in 2024 is noted, which is likely due to there may be a delay in indexing new articles in scientific databases. Additionally, very recent articles are often not freely available and are therefore discarded, as stated in Selection Criterion EC1: Publications that are not open access and cannot be accessed through the Centro de Informática (CIn) Virtual Private Network (VPN).

5.2. The geographic origin of the studies

The distribution of the countries of origin of the selected papers is shown below:

India	19
Iran	4
Brazil	4
China	4
USA	2
Singapore	1
Spain	1
Morocco	1
South Korea	1
Egypt	1
Australia	1
Peru	1
France	1
Malaysia	1
Poland	1

Table 1. Distribution of articles by country of origin

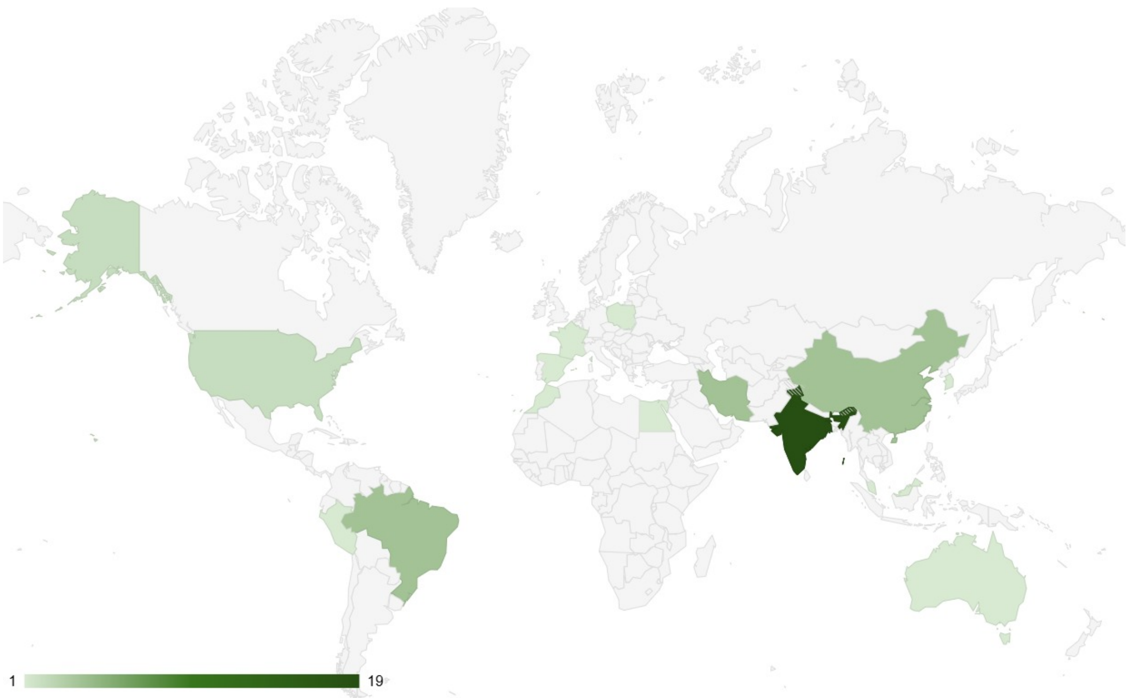

Figure 5. Distribution map of publications by country.

As seen in the table, India has the highest number of studies on breast cancer. This is because the disease is one of the most common types of cancer among Indian women and a leading cause of cancer-related deaths in the country. Additionally, as a developing nation with limited healthcare resources, India faces challenges in providing widespread access to early diagnosis and treatment. This makes investing in more affordable technologies, like thermography, a promising solution to help improve breast cancer detection.

5.3. The research questions (RQs)

- **Q1: What are the most commonly used algorithms?** After analyzing all 43 articles, it was concluded that the most commonly used algorithms are Support Vector Machine (SVM), Convolutional Neural Network (CNN), and Random Forest.

  – SVM (Support Vector Machine) is a machine learning technique primarily used for classification and regression problems. It is a supervised learning algorithm that aims to classify a given set of data points, which are mapped to a multidimensional feature space using a kernel function, employed for problem classification (Karthiga and Narasimhan 2021).

  – CNN (Convolutional Neural Network) is an intelligent model capable of automatically learning and extracting important features from medical images. CNN offers high accuracy and a low error rate in classifying tumors as benign or malignant. Convolutional neural networks consist of convolutions with weights and biases. CNN is the most commonly used classifier (Rai 2024). The main challenges we observed include the problem of data imbalance, the variety of feature extraction techniques, small medical datasets, classifier parameter optimizations, execution time, adaptive classifiers, and a common technique for segmentation and classification. In particular, convolutional neural network (CNN)-based architectures have been used more frequently than other deep learning-based architectures in this field (Rai 2024). CNNs are neural network structures that model the joint distribution between data and hidden layers, leading to the potential for hierarchical representation extraction from training thermograms. This capability enables them to provide a better diagnosis regarding the type of high-level features to be detected. Unfortunately, the performance of CNNs in breast analysis using thermograms is hindered by their strong need for large training datasets.

  – The Random Forest model constructs multiple decision trees during training. Each tree is created from a random subset of the training data and a random subset of features. This helps ensure that each tree is slightly different from the others. It is a form of ensemble learning, which combines multiple models to improve overall performance (Chauhan et al. 2022). The main advantages of using Random Forest include ease of human interpretation, the ability to handle a variety of input labels in the dataset, good performance with minimal effort, and the possibility of implementation on various platforms. Thus, this method serves as a good alternative for extracting reliable information while remaining easy to interpret (Chauhan et al. 2022).

- **Q2: What are the challenges in breast cancer detection using artificial intelligence?**

  – Data Availability: There are still limitations and challenges in the diagnosis and classification of breast cancer that can be addressed using machine learning techniques. One of the main challenges is the lack of comprehensive training datasets for training deep learning models on medical images. AI requires large datasets to train effective models. In the case of breast cancer, obtaining sufficiently comprehensive datasets is not always easy, especially in regions where access to medical exams may be limited. Due to the small number of training images, it is common to expand the dataset using the Data Augmentation process (Brasileiro 2021), which aims to create new samples from existing data to improve the model's performance and robustness.

  – Data Quality: Even when data is available, it may be unbalanced, incomplete, or contain errors. Data quality can significantly impact the performance of AI models in breast cancer detection. Two

Indian studies, Yadav and Jadhav (Yadav and Jadhav 2022) and Karthiga and Narasimhan (Karthiga and Narasimhan 2021), used the dataset from the PROENG[2] online project: Brazilian dataset from the Department of Computer Science at the Federal Fluminense University in Rio de Janeiro. Although this dataset is considered high quality, researchers have pointed out some issues, such as duplicate patients, overly blurred images, and incomplete classifications. These obstacles hinder part of the research process and must be addressed by researchers.

– Model Interpretability: Many AI models used in breast cancer detection, such as deep neural networks, are complex and difficult to interpret. This can make it challenging for doctors to understand how the model arrived at a particular conclusion, potentially affecting trust in the technology. It is common for studies to report accuracy rates above 90% (Shaikh et al. 2020). While this level of accuracy is impressive, it may also lead to skepticism among medical professionals. However, it is important to emphasize that thermography should only be used as a diagnostic support tool alongside other methods. The final diagnosis should always be made by a doctor, considering other medical tests and patient evidence.

– Energy Consumption: Training AI models can consume large amounts of energy, especially when running on high-performance hardware (Radak et al. 2023). This not only increases operational costs but also has a negative environmental impact due to the associated carbon footprint.

– Hardware Requirements: Complex AI algorithms, such as deep neural networks, often require powerful hardware, such as GPUs (graphics processing units), for efficient training and inference (Radak et al. 2023). The cost of acquiring and maintaining this hardware can be financially unfeasible for many institutions, especially those in developing countries.

- **Q3: Which thermographic image acquisition techniques show the best performance?**

– One of the most innovative techniques for acquiring thermographic images is 3D mapping (Lozano III et al. 2020). The present study developed a computational thermal model of breast cancer based on high-resolution infrared (IR) images, real 3D geometries of the breast surface, and internal tumor definition from a woman histologically diagnosed with breast cancer. A state-of-the-art IR camera captured IR images of the patient's breasts, a 3D scanner recorded surface geometries, and standard imaging diagnostic procedures provided tumor sizes and spatial locations within the breast.
Procedures and Equipment: Patients entered the examination room, sat down, and removed clothing from the upper body. They had been thermally acclimated to the environment beforehand. High-resolution infrared images were recorded using a FLIR A655sc infrared camera.

– The infrared camera had a resolution of 640 × 480 and a sensitivity of 30 mK (0.030 °C). The standard lens on the infrared camera was used (25° field of view, 24.6 mm focal length), and individuals were positioned approximately 1 meter away from the infrared camera. The infrared images were processed using FLIR ResearchIR Max 4.40.8.28, a proprietary software provided by the manufacturer. Additionally, the infrared images were post-processed using MATLAB 2019b.

Next, the 3D surface scans of the breast were captured using an Artec Eva Lite (Artec Europe SARL, Luxembourg), a handheld 3D scanner.

The 3D scanner was held approximately 50 to 60 cm away from the subjects' breasts and smoothly swept in an airbrush-like motion for about 30 to 60 seconds to fully capture the 3D topography of both breasts.

[2] http://visual.ic.uff.br/

The 3D scans were processed using Artec Studio 13 Professional, a proprietary software provided by the manufacturer. Finally, the ambient temperature in the clinical examination room was measured, ranging between 22.0 to 24.0°C. The temperature was recorded using a digital thermometer Omega HH506RA, which had a resolution of 0.1°C and an accuracy of ±0.3°C. Real 3D breast surface geometries offer significant advantages compared to 2D representations. 3D models provide a more realistic and detailed representation of objects, allowing for accurate visualization of shapes, textures, and depths that are not possible with 2D models. Additionally, 3D models can be manipulated and viewed from different angles, offering an interactive experience that enhances the understanding of tumor locations. This directly assists in biopsy or surgical procedures, improving precision and effectiveness.

- **Q4: What are the challenges for large-scale implementation of thermography in breast cancer diagnosis?**

– Limited Scientific Evidence: Although thermography has been studied as a screening tool for breast cancer, its effectiveness has not yet been fully proven. The lack of robust evidence may make it difficult to convince healthcare professionals and regulators about the clinical utility of thermography in breast cancer diagnosis (Lovett and Liang 2011). In light of this situation, it is important to emphasize the role of thermography as an aid in the screening process, rather than as a definitive diagnostic tool. According to the U.S. Food and Drug Administration (FDA), "thermography does not replace screening mammography and should not be used alone to diagnose breast cancer." Furthermore, it is not considered an effective screening tool for any medical condition, including the early detection of breast cancer or other breast diseases. Similarly, major health insurers in the United States and the Centers for Medicare and Medicaid Services do not cover thermography as a procedure for any indication, as they have stated, "the FDA is not aware of any valid scientific data showing that thermographic devices, when used alone, are an effective screening tool for breast cancer.

– Standardization and Interpretation of Results: The regulation of thermography for breast cancer diagnosis may vary between countries, and a broader standardization of procedures and interpretation criteria may be necessary to ensure its effectiveness and safety (Radak et al. 2023). The interpretation of thermographic images can also be subjective and require specialized training. Furthermore, the lack of standardization in imaging acquisition protocols and result interpretation can lead to variations in diagnostic accuracy among different healthcare providers.

– Awareness and Acceptance: Thermography is still not widely known or accepted as a screening tool for breast cancer in many communities (Silva 2019). The lack of awareness about its potential benefits may affect patients' willingness to adopt it and healthcare professionals' willingness to prescribe it. Overcoming these challenges will require a collaborative effort between researchers, healthcare professionals, regulators, and the industry to increase the evidence base, develop standardized protocols, reduce costs, and raise awareness about the role of thermography in breast cancer diagnosis.

- **Q5: How does breast cancer detection using deep learning differ from other approaches?**

The detection of breast cancer using deep learning differs from other approaches primarily due to the ability of deep learning models to learn complex and hierarchical representations of data (Thakur et al. 2024). Here are some ways in which breast cancer detection using deep learning differs from other approaches:

– Automatic Feature Extraction: Instead of relying on manually designed features, such as specific textures or shapes, deep learning models can automatically learn relevant features directly from the data (Abhisheka et al. 2023). This reduces the need for domain experts to design and select relevant features.

– Generalization Capability: Deep learning models have the ability to generalize from large datasets, meaning they can learn patterns that are useful for breast cancer detection, even if these patterns are not obvious to humans (Radak et al. 2023). This can lead to higher sensitivity and specificity in breast cancer detection.

– Adaptation to Different Imaging Modalities: Deep learning is flexible enough to handle a variety of imaging modalities, such as mammograms, ultrasounds, and magnetic resonance imaging (MRI) (Radak et al. 2023). This allows the models to be trained on different types of image data and integrated into multi-modality breast cancer detection systems.

– Continuous Improvement with More Data: As more data becomes available and the models are trained with this additional data, the accuracy of deep learning models tends to improve (Radak et al. 2023). This contrasts with traditional approaches, which often have a limit to their improvement as the data increases.

– Automation of the Detection Process: Once trained, deep learning models can be implemented in automated breast cancer detection systems, allowing for rapid and accurate detection on a large scale (Silva 2019). This can help reduce the workload of radiologists and improve diagnostic efficiency.

6. CONCLUSION AND FUTURE DIRECTIONS

In summary, the application of artificial intelligence algorithms, such as Support Vector Machine, Convolutional Neural Network, and Random Forest, has shown excellent results in breast cancer detection, with a focus on the high performance rates achieved by these approaches. However, challenges persist, mainly related to the quality and availability of data, as well as difficulties in normalizing images from different sources. Regarding image acquisition, the 3D mapping technique has proven to be superior to the 2D method, especially in high-resolution computational thermal models. Thermography, although promising, faces challenges in being widely adopted, primarily due to a lack of awareness and acceptance among both healthcare professionals and patients. Finally, the use of deep learning stands out by enabling automation in feature extraction from the data, reducing reliance on specialists and increasing diagnostic accuracy. The continuous learning capability of these models promises a more efficient and scalable future in breast cancer detection.

Future research should prioritize improving data quality, tackling challenges related to image normalization, and encouraging the widespread adoption of advanced imaging techniques, such as 3D mapping and thermography. Furthermore, deeper exploration of deep learning models could pave the way for more automated, accurate, and accessible methods of breast cancer detection.

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