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Artificial intelligence in breast cancer detection: Advances across imaging modalities and clinical integration

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Abstract
Breast cancer remains a major global health challenge, where timely and accurate detection is critical for improving survival outcomes. Recent advances in artificial intelligence (AI), encompassing machine learning and deep learning techniques, have transformed breast cancer screening and diagnosis by enhancing image interpretation across multiple imaging modalities, including mammography, ultrasound, magnetic resonance imaging (MRI), and thermography. AI-driven models particularly convolutional neural networks, hybrid radiomics-deep learning frameworks, and transfer learning architectures enable automated feature extraction, precise lesion detection, segmentation, and classification, often achieving diagnostic performance comparable to or exceeding expert radiologists. The incorporation of explainable AI approaches, such as saliency maps and attention mechanisms, further improves transparency, interpretability, and clinical trust. Beyond detection, AI supports risk stratification, workflow prioritization, biomarker prediction, and personalized clinical decision-making, addressing challenges of inter-observer variability and limited expert availability, especially in resource-constrained settings. Although issues related to data heterogeneity, standardization, and regulatory validation persist, growing clinical integration and robust evidence highlight AI's potential to complement conventional imaging, optimize screening programs, and advance precision medicine in breast cancer care.

Keywords: Artificial intelligence, breast cancer detection, medical imaging, machine learning, deep learning, mammography, computer-aided diagnosis, precision medicine, clinical decision support

Introduction
Breast cancer is a leading cause of cancer-related morbidity and mortality in women globally, with early detection fundamentally improving patient outcomes (Giaquinto *et al*., Sung *et al*., 2021; Kim *et al*., 2025) [39, 21]. Conventional breast cancer screening and diagnosis primarily involve mammography, ultrasound, and MRI, interpreted by radiologists and pathologists (Mann *et al*., 2020; Sardanelli *et al*., 2024) [37, 36]. While effective, these modalities are subject to inter-observer variability and limited availability of expert interpretation in resource-constrained settings (Bitencourt *et al*., 2024; Lehman *et al*., 2019) [9, 43]. The integration of AI encompassing machine learning (ML) and deep learning (DL) promises to overcome these limitations by automating intricate pattern recognition and extracting subtle imaging cues beyond human perception (Sechopoulos *et al*., 2024; Carriero *et al*., 2024; Al Khalil *et al*., 2023) [37, 10, 4].

2. AI in Breast Imaging: Core Concepts and Models
AI algorithms for breast cancer detection typically leverage supervised learning, wherein models are trained using annotated medical images to recognize patterns associated with malignant and benign tissues (Sechopoulos *et al*., 2024; Carriero *et al*., 2024) [37, 10]. Among AI methods, convolutional neural networks (CNNs) are particularly prominent due to their ability to learn hierarchical features directly from imaging data without manual feature engineering (An *et al*., 2025; Wahed *et al*., 2025) [6, 42]. Other models include support vector machines (SVM), random forests (RF), and transfer learning architectures that repurpose pre-trained networks (e.g., ResNet, DenseNet, VGG) for medical imaging tasks (Minnoor &

Baths, 2023) [28]. Explainable AI (XAI) is increasingly incorporated to enhance model transparency, interpretability, and clinical trust, with SHapley Additive exPlanations (SHAP) emerging as a leading explainability tool alongside techniques like LIME, Grad-CAM, and saliency maps (Ghasemi *et al*., 2024; Bai *et al*., 2024; Alom *et al*., 2025) [18, 7, 5].

3. Imaging Modalities and AI Applications

3.1 Mammography

Mammography remains the **cornerstone** of population-based breast cancer screening due to its proven effectiveness in early tumor detection and mortality reduction (Duffy *et al*., 2020) [14]. In recent years, artificial intelligence has significantly enhanced the diagnostic capabilities of mammographic imaging by improving lesion detection, classification, and risk stratification (Sechopoulos *et al*., 2024; Carriero *et al*., 2024) [37, 10]. Deep learning-based models, particularly convolutional neural networks (CNNs), are highly effective in identifying subtle radiographic features such as microcalcifications, architectural distortions, and asymmetries that are often challenging for human readers, especially in dense breast tissue (Tan *et al*., 2025; Lauritzen *et al*., 2023) [40, 23]. Multi-view and multi-scale CNN architectures that simultaneously analyze craniocaudal and mediolateral oblique views have demonstrated superior performance, achieving high sensitivity and specificity with area under the receiver operating characteristic curve (AUC) values frequently exceeding 0.93 in distinguishing malignant from benign lesions (Tan *et al*., 2025) [40]. Additionally, AI-driven mammography systems support automated breast density assessment and personalized risk prediction, thereby enabling more tailored screening strategies (Gastounioti *et al*., 2022; Yala *et al*., 2019) [17, 43]. When integrated into clinical workflows, these AI tools function as decision-support systems, reducing radiologist workload, minimizing false positives and false negatives, and enhancing overall screening efficiency and diagnostic confidence (Lauritzen *et al*., 2024) [23].

3.2 Ultrasound

Breast ultrasound is a valuable adjunct imaging modality, particularly for women with dense breast tissue where the sensitivity of mammography is diminished (Thigpen *et al*., 2018). The incorporation of artificial intelligence has markedly improved the diagnostic utility of ultrasound by enhancing lesion detection, segmentation, and classification accuracy (An & Li, 2025; Alom *et al*., 2025) [6, 5]. Deep learning models such as U-Net and its variants (e.g., DBU-Net, Attention U-Net) have been widely applied for precise tumor boundary delineation, enabling better differentiation between benign and malignant lesions based on morphological and textural features (Punn and Agarwal, 2022; Kormpos *et al*., 2025) [34, 22]. In addition, transfer learning approaches using pre-trained convolutional neural networks (e.g., DenseNet, EfficientNet) have reduced the need for large annotated datasets while maintaining high diagnostic performance (Moursi *et al*., 2025) [30]. AI-enhanced ultrasound systems also facilitate automated feature extraction and standardized reporting, reducing operator dependency one of the major limitations of conventional ultrasound (Carriero *et al*., 2024; Fu *et al*., 2024) [10, 15]. Furthermore, emerging ultrasound-AI frameworks offer real-time diagnostic decision support, making them suitable for integration with handheld and point-of-care ultrasound devices (Clarius, 2025) [25]. These advancements expand access to early breast cancer detection, particularly in low-resource and rural settings, and support more accurate, rapid, and user-independent clinical assessments (An & Li, 2025) [6].

3.3 Magnetic Resonance Imaging (MRI)

Magnetic resonance imaging (MRI) offers superior soft-tissue contrast and functional imaging capabilities, making it particularly valuable for breast cancer screening in high-risk populations and for resolving equivocal findings from other imaging modalities (Mann *et al*., 2019; Al Khalil *et al*., 2023; Olviedo *et al*.) [27, 4]. The application of machine learning (ML) and deep learning (DL) techniques to breast MRI has significantly enhanced lesion characterization by enabling automated analysis of complex, multiparametric datasets, including dynamic contrast-enhanced (DCE) and diffusion-weighted imaging (DWI) (Zhao *et al*., 2023; Carriero *et al*., 2024; Hirsch *et al*., 2025) [44, 10, 35]. Advanced convolutional neural networks and hybrid radiomics-DL models have demonstrated excellent performance in differentiating malignant from benign lesions, improving sensitivity while maintaining high specificity (Al Khalil *et al*., 2023; Olviedo *et al*., 2025; Abdullah *et al*., 2025) [27, 4, 1]. Moreover, AI-driven feature extraction allows identification of subtle spatial and temporal enhancement patterns that may be overlooked by human observers (Müller-Franzes *et al*., 2023; Hirsch *et al*., 2025) [31, 35]. Systematic evidence across multiple studies reports strong diagnostic accuracy and consistent performance, highlighting the robustness and generalizability of MRI-based AI models across diverse datasets and imaging protocols (Al Khalil *et al*., 2023; Carriero *et al*., 2024; Abdullah *et al*., 2025) [27, 10, 1]. These advancements support more accurate risk stratification, reduce false positives, and contribute to personalized diagnostic decision-making in clinical breast imaging (Bitencourt *et al*., 2024; Sechopoulos *et al*., 2024) [9, 37].

3.4 Thermography

Thermography is a non-invasive, radiation-free, and relatively low-cost imaging modality that measures surface temperature variations associated with underlying vascular and metabolic changes in breast tissue, making it particularly feasible for screening in remote or resource-limited settings (Singh & Singh, 2020; Goñi-Arana *et al*., 2024; Al Husaini *et al*., 2024) [38, 19, 3]. The integration of artificial intelligence has improved the interpretability of thermographic images by enabling automated feature extraction, pattern recognition, and classification of abnormal thermal asymmetries (Bansal *et al*., 2023; Mirasbekov *et al*., 2024) [8, 29]. Machine learning and deep learning models, including support vector machines and convolutional neural networks, have shown promising results in distinguishing suspicious from normal thermal patterns; however, reported diagnostic performance varies considerably across studies (Aidossov *et al*., 2023; Civilibal, 2023; Goñi-Arana *et al*., 2024) [2, 11, 19]. This variability is largely attributed to differences in image acquisition protocols, environmental conditions, and limited availability of high-quality, labeled datasets. Future progress and broader clinical adoption of thermography-based AI systems may depend on the development of robust unsupervised and self-learning algorithms capable of adapting to heterogeneous data and generalizing effectively from limited annotated samples, thereby improving reliability and clinical confidence (Al Husaini *et al*., 2024; Mirasbekov *et al*., 2024) [3, 29].

4. Clinical Applications and Integration

AI systems assist radiologists in workflow prioritization, reducing interpretive fatigue, and improving efficiency (Lauritzen *et al.*, 2024; Leibig *et al.*, 2022) [23, 25]. When incorporated into clinical workflows, AI can pre-screen normal examinations, flag critical cases, and provide adjunctive measures like BI-RADS categorization and compression of report turnaround times (Tan *et al.*, 2025; Dratsch *et al.*, 2023) [40]. Clinical implementation is seen in both high-income health systems and emerging programs aimed at democratizing access to diagnostic tools (Al Husaini *et al*., 2024) [3].

Table: 1: Summary of Imaging Modalities, Artificial Intelligence Models, and Their Clinical Applications in Breast Cancer Detection

Imaging Modality	Common AI Models	Key Advances	Typical Performance (AUC/Accuracy)	Clinical Applications	References
Mammography	CNNs (e.g., ResNet, DenseNet), Multi-view CNNs, Transfer Learning	Lesion detection, microcalcifications identification, risk stratification, BI-RADS categorization	AUC > 0.93; Accuracy 90-99%	Workflow prioritization, reducing false positives/negatives, pre-screening normal cases	Sechopoulos *et al.* (2024) [37]; Carriero *et al.* (2024) [10]; Tan *et al.* (2025) [40]
Ultrasound	U-Net variants, Transfer Learning (e.g., DenseNet, EfficientNet), CNNs	Lesion segmentation, classification, real-time decision support	Accuracy up to 100%; AUC 0.95+	Adjunct for dense breasts, operator-independent assessment, point-of-care devices	An & Li (2025) [6]; Alom *et al.* (2025) [5]
MRI	Hybrid Radiomics-DL, CNNs, Multimodal models	Lesion characterization, multiparametric analysis (DCE, DWI)	AUC 0.92-0.97	High-risk screening, equivocal findings resolution, risk stratification	Al Khalil *et al.* (2023) [4]; Abdullah *et al.* (2025) [1]; Zhao *et al.* (2023) [44]
Thermography	SVM, CNNs, Hybrid ML-DL	Thermal asymmetry detection, pattern recognition	Variable; Accuracy 85-95% (promising but inconsistent)	Non-invasive screening in resource-limited settings, adjunct tool	Goñi-Arana *et al.* (2024) [19]; Bansal *et al.* (2023) [8].

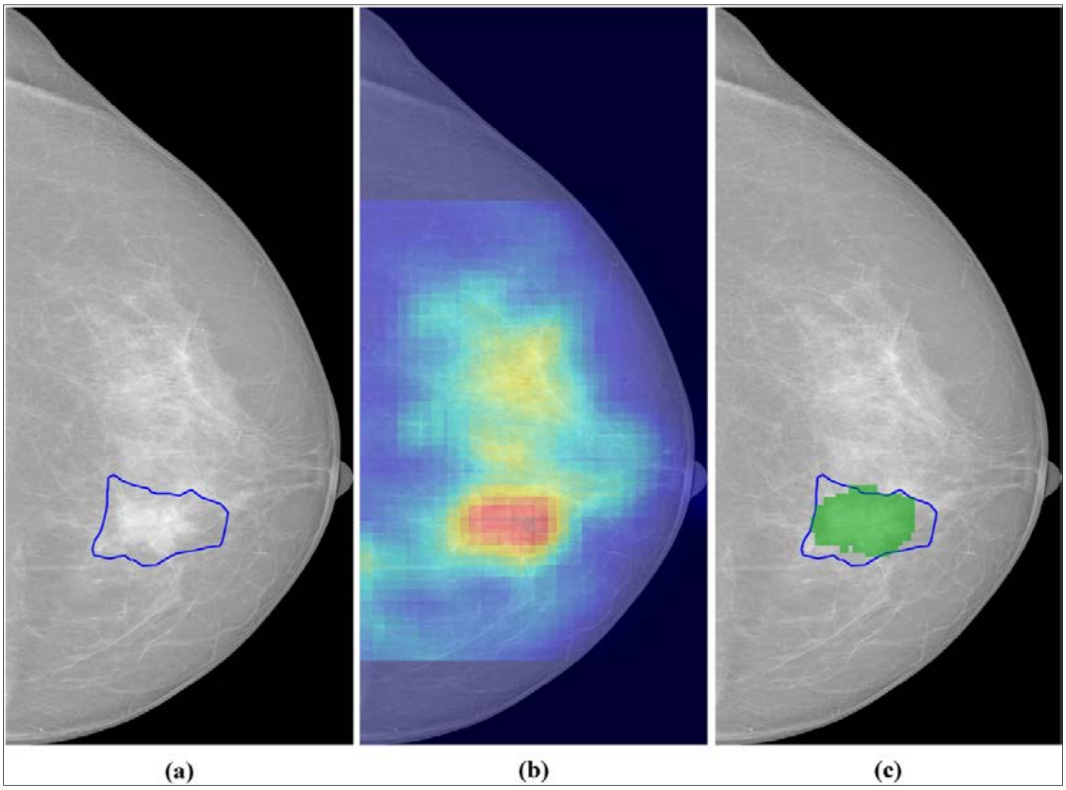

Fig 1: AI saliency/heatmaps highlighting breast lesions on mammograms (Pertuz *et al*., 2023) [33].

Figure 1 illustrates the application of AI-based saliency and heatmap techniques for highlighting suspicious breast lesions on mammograms, as reported by Pertuz *et al*. (2023) [33]. Panel (a) shows the original mammographic image with a radiologist-defined lesion boundary, serving as the ground truth, while panel (b) presents the AI-generated saliency/heatmap overlay, where warmer colors (yellow-red) indicate regions with higher model attention and likelihood of malignancy. Notably, the heatmap concentrates on the lesion area rather than irrelevant surrounding tissue, demonstrating the model's ability to capture diagnostically meaningful features such as mass density and architectural distortion. Panel (c) further compares AI-guided lesion localization with manual annotation, showing strong spatial agreement between the predicted region and expert-defined contours. This visual correspondence highlights the potential of explainable AI methods to enhance transparency, build clinical trust, and support radiologists by clearly indicating why a model flags a region as suspicious. Overall, the figure underscores how saliency maps can function as effective decision-support tools, improving interpretability and facilitating the integration of AI into routine mammographic assessment.

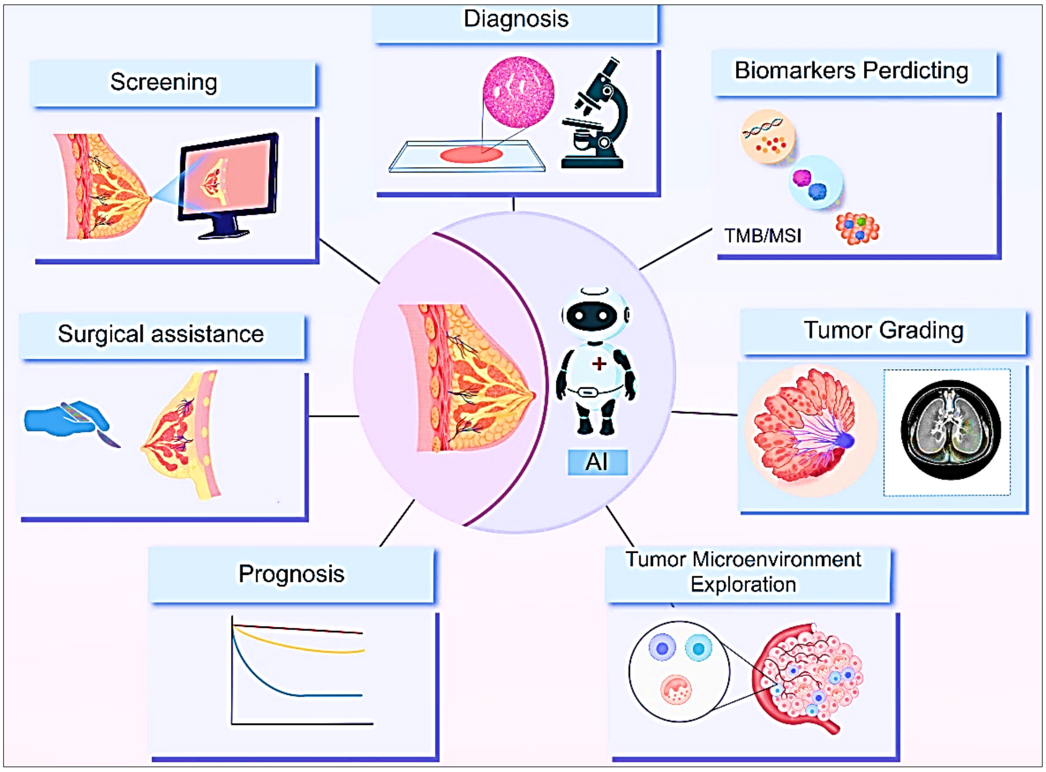

Fig 2: Futuristic visualization of AI integrating multiple imaging modalities (mammography, MRI, ultrasound) with neural network overlays (Ran *et al*., 2025) [35]

Figure 2 presents a futuristic conceptual framework illustrating the integrative role of artificial intelligence across the breast cancer care continuum by combining multimodal imaging data mammography, ultrasound, MRI, and digital pathology with advanced neural network architectures (Ran *et al*., 2025) [35]. The visualization highlights how AI functions as a central analytical engine, supporting key clinical stages including screening, diagnosis, tumour grading, biomarker prediction (such as TMB/MSI), surgical assistance, prognosis estimation, and tumour microenvironment exploration. By fusing heterogeneous imaging and biological data, AI enables comprehensive feature extraction and cross-modal learning, leading to more accurate lesion characterization and personalized risk assessment. The depiction of neural network overlays emphasizes the shift from single-modality interpretation toward holistic, data-driven decision-making, where AI augments clinician expertise rather than replacing it. Overall, the figure underscores the transformative potential of AI in enabling precision oncology, streamlining clinical workflows, and advancing individualized breast cancer management through seamless integration of imaging, pathology, and predictive analytics.

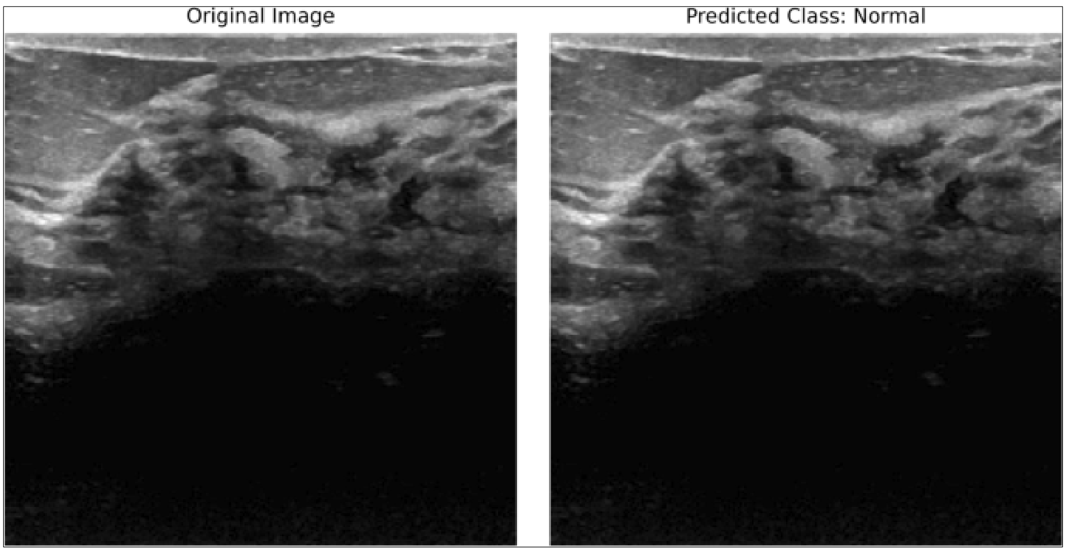

Fig 3: Explainable AI output: Deep learning model with attention maps for accurate breast cancer classification (Alom *et al*., 2025) [5]

Figure 3 demonstrates the application of explainable artificial intelligence (XAI) in breast ultrasound analysis, showcasing how a deep learning model classifies breast tissue while providing transparent visual justification for its prediction (Alom *et al*., 2025) [5]. The figure compares the original ultrasound image with the model's predicted output, labeled as "Normal," accompanied by attention or activation maps that highlight regions most influential in the classification process. The focused attention on relevant tissue structures, rather than background artifacts, indicates that the model is learning clinically meaningful features such as tissue homogeneity and echo patterns. This interpretability is crucial for enhancing clinician confidence, as it allows radiologists to verify that AI decisions are grounded in valid anatomical and pathological cues. Overall, the figure underscores the importance of explainable AI frameworks in improving diagnostic reliability, facilitating clinical adoption, and ensuring responsible integration of deep learning models into breast cancer screening and diagnostic workflows.

Conclusion

AI is revolutionizing breast cancer detection by enhancing performance across imaging modalities and supporting clinical decision-making. Deep learning models, especially in mammography, ultrasound, and MRI, have achieved high diagnostic accuracy and show potential to reduce false positives and negatives compared to traditional methods. Explainable AI and transfer learning further advance model reliability and interpretability. While challenges remain, including dataset standardization and clinical validation, ongoing research and integration efforts are poised to transform early detection paradigms and improve patient outcomes worldwide.

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