Advancements and Applications of Artificial Intelligence in Breast Cancer Diagnosis and Treatment: A Comprehensive Review

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Background: Breast cancer remains the most prevalent malignancy among women worldwide and a leading cause of cancer-related mortality. Recent advances in artificial intelligence (AI) have transformed approaches to detection, diagnosis, prognosis, and management of breast cancer. AI techniques, particularly deep learning and radiomics, enable earlier detection and more precise risk stratification by analysing complex imaging and pathological data. This narrative review summarises current applications, advances, and limitations of AI in breast cancer care, highlighting its potential to enhance personalised medicine.

Keywords: Artificial intelligence, Breast cancer, Machine learning, Deep learning, Radiomics, Diagnosis

Introduction

Breast cancer remains the most frequently diagnosed malignancy and a leading cause of cancer-related death among women worldwide (1). For breast surgeons and oncologists, early and accurate detection is crucial not only for improving survival but also for enabling less invasive surgical approaches and preserving quality of life (2).

Traditional diagnostic workflows-including mammography, ultrasound, magnetic resonance imaging (MRI), and histopathological evaluation- are highly dependent on radiologist and pathologist expertise. Although these methods have advanced substantially over recent decades, they remain limited by inter-observer variability, subjective interpretation, and time- intensive analysis. From a surgical standpoint, accurate preoperative localization and characterization of breast lesions are vital for determining appropriate surgical margins, identifying candidates for breast-conserving surgery, and planning sentinel lymph node biopsy. However, distinguishing benign from malignant lesions, identifying multifocal disease, and assessing tumor response to neoadjuvant therapy remain ongoing challenges that directly influence surgical outcomes and recurrence rates (3, 4).

Artificial intelligence (AI), particularly through machine learning (ML) and deep learning (DL) frameworks, has emerged as a powerful adjunct to traditional diagnostic and decision-making processes. By leveraging vast datasets from imaging, pathology, and genomic sources, AI can detect subtle patterns and correlations that may be imperceptible to the human eye (5–7). Convolutional neural networks (CNNs) and radiomics-based algorithms enhance lesion detection, improve diagnostic accuracy, and provide quantitative assessments of tumor heterogeneity (8). For breast surgeons, AI integration offers transformative potential-ranging from automated image interpretation and intraoperative margin assessment to personalized

treatment planning based on tumor biology and patient-specific risk profiles. These advances support the shift towards precision surgery, where therapeutic decisions are guided by data-driven insights rather than subjective interpretation alone. Moreover, AI-based prognostic models can help predict treatment response and recurrence risk, enabling surgeons to collaborate more effectively within multidisciplinary oncology teams to tailor interventions for optimal outcomes (9, 10).

Applications of AI in Breast Cancer

Screening and Early Detection

Early detection of breast cancer significantly reduces mortality (11). Mammography remains the standard screening tool; however, its interpretation is influenced by breast density, lesion characteristics, and radiologist experience, resulting in variable sensitivity and specificity (12). AI-assisted mammography—particularly using deep learning models such as CNNs—has demonstrated notable improvements in detection rates while reducing false positives and radiologist workload. These models are trained on large annotated datasets to recognize subtle abnormalities, including microcalcifications, architectural distortions, and small masses often missed by human readers.

Integration of AI with digital breast tomosynthesis (DBT) enables volumetric analysis, improving lesion localization and classification. AI algorithms can segment lesions, assign malignancy probabilities, and prioritize high-risk cases, facilitating more accurate and efficient interpretation (13). Furthermore, models combining imaging features with patient demographics, genetic profiles, and prior imaging can support individualized risk assessment and screening strategies, identifying women at higher risk of interval cancers who may benefit from adjunctive imaging modalities.

Diagnosis and Classification

Accurate diagnosis and classification of breast lesions are essential for guiding management and prognosis. AI models have been developed to differentiate benign from malignant lesions using mammography, ultrasound, and MRI. Deep learning algorithms extract high-dimensional radiomic features correlating with tumor biology, grade, and aggressiveness (14). Multimodal imaging integration enhances diagnostic precision by combining structural and functional data (15).

In pathology, AI applied to whole-slide image analysis enables automated detection, segmentation, and classification of histological features, improving grading accuracy and receptor-status prediction. AI systems can also quantify tumor-infiltrating lymphocytes and stromal characteristics, offering additional prognostic insight. By integrating imaging and pathological AI outputs, clinicians gain a more comprehensive and objective assessment, facilitating personalized decisions regarding surgery and systemic therapy, while potentially reducing unnecessary biopsies and improving workflow efficiency (16).

Prognosis and Risk Stratification

Prognostic assessment is essential for optimizing treatment and improving outcomes. Traditional indices such as the Nottingham Prognostic Index or TNM staging often fail to capture tumor heterogeneity fully (17, 18). AI-based models integrate genomic, imaging, and clinical data to predict recurrence, survival, and treatment response more accurately. Machine learning frameworks stratify patients into risk categories, enabling tailored surveillance and follow-up (19, 20).

AI algorithms can also predict response to chemotherapy, targeted therapy, and radiotherapy, supporting selection of patients most likely to benefit from specific regimens and reducing exposure to ineffective treatments (21). Radiomic and molecular features extracted from imaging and pathology provide insights into tumor behavior, enhancing individualized therapeutic planning (22). Despite these advances, AI prognostic models require large, high-quality datasets, multicenter validation, and careful consideration of potential biases to ensure reliability and generalizability.

Treatment Planning and Follow-up

AI applications extend to treatment optimization and longitudinal monitoring. In radiotherapy, AI facilitates automated target delineation, organ-at-risk segmentation, and dose optimization, reducing variability and improving efficiency (23).

In surgery, image-guided AI systems assist in margin assessment and lymph-node evaluation, minimizing the risk of residual disease. Integration of multi-omics data enables prediction of patient-specific responses to systemic therapies, supporting precision oncology (20).

AI further contributes to dynamic follow-up, adjusting surveillance intensity based on individual risk profiles to detect recurrence at an earlier stage (9, 24). These applications highlight AI's potential to enhance personalized care, improve outcomes, and optimize resource utilization, although challenges regarding data quality, validation, and clinical implementation persist.

Challenges and Limitations

Despite its transformative potential, AI integration into breast cancer care faces notable barriers. Data quality and standardization are critical, as variations in imaging protocols, scanner models, and annotation practices affect model reproducibility and generalizability. Interpretability remains a key concern, as many deep learning models operate as "black boxes," limiting clinician trust (25).

Ethical and legal considerations-including patient privacy, data security, and algorithmic bias-must also be rigorously addressed.

Most AI tools remain in the research or early clinical phases, necessitating large-scale, multi- institutional validation before routine adoption. Cost, infrastructure demands, and limited technical resources may further hinder implementation, particularly in low- and middle-income settings.

Future Directions

The future trajectory of AI in breast cancer management centers on multimodal integration, explainable AI, real-time clinical decision support, and adaptive learning systems. Combining radiological, pathological, genomic, and clinical data promises a holistic view of tumor biology and enhanced predictive accuracy. Explainable AI frameworks aim to increase transparency, strengthen clinician confidence, and facilitate informed decision-making. Real-time AI assistance can refine intraoperative guidance, lesion detection, and radiotherapy adaptation. Continuously learning systems that evolve with new patient data will further improve algorithmic performance over time, while AI-driven dynamic follow-up protocols may optimize surveillance resources and enable earlier relapse detection.

Conclusion

Artificial intelligence has emerged as a powerful adjunct in breast cancer care, enhancing early detection, diagnostic precision, prognostic assessment, treatment planning, and follow-up. By integrating imaging, pathology, genomic, and clinical data, AI enables truly personalized medicine—tailoring interventions to individual disease profiles and improving patient outcomes. Addressing challenges in data standardization, interpretability, ethics, and clinical validation remains essential for safe and effective implementation. Future advancements promise fully integrated, adaptive, and patient-centered AI applications capable of revolutionizing breast cancer management, augmenting clinical expertise, and supporting the evolution of precision oncology.

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