International Journal of Multidisciplinary and Applied Studies (IJMDAS) Research Article
F-ISSN:3107-8028 Vol.1, Issue 6, December 2025

Artificial Intelligence in Breast Cancer: Innovations in Screening, Diagnosis, and Treatment

[1]Dr. Nitin Kulkarni, [2]Dr. Bhavana Singh, [3]Mr. Arvind Joshi, [4]Dr. Snehal Patwardhan, [5]Dr. Manoj Kale, [6]Mrs. Asha Nair

*[*1]Professor Department of Surgery, Dr. D. Y. Patil Medical College, Pune, India Nitinkulkarni82@gmail.com*
[2]Associate Professor Department of Pharmacology, Dr. D. Y. Patil Medical College, Pune, India Bhavana.singh56@gmail.com
[3]Assistant Professor Department of Anatomy, Dr. D. Y. Patil Medical College, Pune, India Arvindjoshi21@gmail.com
[4]Professor Department of Pathology, Dr. D. Y. Patil Medical College, Pune, India Snehal.patwardhan@gmail.com
[5]Associate Professor Department of Medical Oncology, Dr. D. Y. Patil Medical College, Pune, India Manojkale1976@gmail.com
[6]Assistant Professor Department of Physiology, Dr. D. Y. Patil Medical College, Pune, India Ashanair48@gmail.com

ABSTRACT:

Breast cancer remains the most frequently diagnosed malignancy among women worldwide and continues to be a leading cause of cancer-related mortality despite substantial advances in screening programs, molecular diagnostics, targeted therapies, and precision medicine. Early detection and individualized treatment remain essential for improving survival while minimizing treatment-related morbidity. Recent developments in artificial intelligence (AI) have transformed breast cancer care by enabling automated analysis of radiological imaging, digital pathology, genomic sequencing, electronic health records, and multimodal clinical data. Machine learning, deep learning, computer vision, natural language processing, multimodal learning, graph neural networks, and foundation models have demonstrated remarkable capabilities in breast cancer screening, lesion detection, risk prediction, molecular classification, treatment optimization, prognostic assessment, and survivorship care. AI-powered systems now support mammographic interpretation, breast ultrasound, magnetic resonance imaging, digital pathology, radiogenomics, surgical planning, radiation therapy, immunotherapy prediction, and clinical decision support. Emerging technologies including explainable artificial intelligence, federated learning, generative AI, wearable health technologies, and digital twins are expected to further enhance precision breast oncology. Nevertheless, important challenges remain regarding data quality, algorithmic bias, interoperability, cybersecurity, regulatory validation, ethical governance, and equitable implementation. This review provides a comprehensive overview of artificial intelligence applications in breast cancer, highlighting current innovations, clinical applications, emerging technologies, and future directions for precision breast cancer management.[1]

Keywords: Artificial intelligence, Breast cancer, Mammography, Precision oncology, Machine learning, Deep learning, Digital pathology, Radiomics, Clinical decision support, Precision medicine.

Received Date: 5 December 2025; **Accepted Date:** 15 December 2025; **Published Date:** 20 December 2025

I. Introduction

Breast cancer is one of the most extensively studied malignancies and remains the leading cancer diagnosed among women worldwide. Despite major improvements in awareness programs, population-based screening, molecular diagnostics, targeted therapies, and multidisciplinary management, breast cancer continues to contribute substantially to global morbidity and mortality. Clinical outcomes vary considerably among patients because breast cancer encompasses multiple molecular subtypes with distinct biological behavior, therapeutic sensitivity, and long-term prognosis.[2]

Modern breast oncology generates enormous quantities of heterogeneous biomedical information through mammography, digital breast tomosynthesis, ultrasound, magnetic resonance imaging (MRI), digital pathology, genomic sequencing, transcriptomics, laboratory biomarkers, electronic health records, and wearable technologies. Collectively, these datasets provide detailed insights

DOI: https://doi.org/10.62896/ijmdas.2025.V1.I6.04

into tumor biology; however, their interpretation often exceeds the capacity of conventional analytical approaches and routine clinical workflows.[3]

Artificial intelligence has emerged as one of the most transformative technologies in breast cancer management by enabling automated analysis of complex biomedical data. AI algorithms identify subtle imaging abnormalities, classify breast lesions, predict molecular characteristics, estimate treatment response, and support personalized clinical decision-making. Rather than replacing clinicians, AI functions as an intelligent decision-support system that enhances diagnostic accuracy, improves workflow efficiency, and facilitates evidence-based patient care.[4]

As computational technologies continue to evolve, artificial intelligence is becoming increasingly integrated throughout the entire breast cancer care continuum, from risk assessment and early detection to treatment planning, survivorship monitoring, and long-term follow-up.[5]

2. Evolution of Artificial Intelligence in Breast Oncology

The application of artificial intelligence in breast cancer has evolved considerably over recent decades. Early computer-aided detection systems relied primarily on handcrafted imaging features and rule-based algorithms to identify suspicious mammographic abnormalities. Although these systems improved lesion detection, they frequently generated false-positive findings and demonstrated limited adaptability.[6]

Machine learning introduced data-driven predictive modeling capable of identifying complex relationships between imaging characteristics and clinical outcomes. Algorithms such as support vector machines, random forests, and gradient boosting significantly improved lesion classification, recurrence prediction, and treatment response estimation across diverse breast cancer populations.[7]

The emergence of deep learning revolutionized breast imaging through convolutional neural networks capable of automatically extracting hierarchical image features without manual engineering. More recently, transformer architectures, multimodal learning, graph neural networks, and foundation models have enabled simultaneous integration of mammography, ultrasound, MRI, pathology, genomics, laboratory investigations, and clinical documentation into unified computational frameworks.

These advances have transformed artificial intelligence from isolated diagnostic software into comprehensive clinical platforms supporting precision breast oncology throughout diagnosis, treatment, and survivorship.[8]

3. Artificial Intelligence Technologies in Breast Cancer

Modern breast oncology relies upon multiple complementary artificial intelligence technologies that collectively support clinical decision-making. Machine learning algorithms identify statistical relationships between patient characteristics and clinical outcomes, enabling prediction of diagnosis, recurrence, survival, and therapeutic response.[9]

Deep learning substantially expands predictive capability through automated extraction of complex features from radiological images and histopathological slides. Convolutional neural networks excel in mammographic interpretation, ultrasound analysis, MRI evaluation, and computational pathology.

Natural language processing enables extraction of clinically relevant information from pathology reports, radiology reports, physician documentation, and electronic health records, facilitating automated clinical summarization and decision support.

Graph neural networks model interactions among genes, proteins, signaling pathways, and molecular biomarkers, whereas multimodal learning integrates imaging, pathology, genomics, laboratory investigations, and clinical information into comprehensive patient-specific representations that support precision medicine.[10]

4. Artificial Intelligence in Breast Cancer Screening

Population-based breast cancer screening has substantially reduced mortality through early detection; however, interpretation of mammographic examinations remains challenging because of dense breast tissue, subtle imaging abnormalities, and interobserver variability among radiologists.[11]

Artificial intelligence significantly enhances breast cancer screening by automatically detecting suspicious lesions, microcalcifications, architectural distortion, focal asymmetry, and soft tissue masses on digital mammography and digital breast tomosynthesis. Deep learning algorithms achieve high sensitivity while reducing false-negative interpretations and assisting radiologists in prioritizing examinations requiring immediate attention.

AI also supports individualized screening strategies by integrating imaging findings with demographic characteristics, family history, genetic predisposition, hormonal factors, and lifestyle variables to estimate personalized breast cancer risk. Such risk-adapted screening approaches may improve early detection while reducing unnecessary imaging procedures.[12]

5. Mammography and Digital Breast Tomosynthesis

Mammography remains the primary imaging modality for breast cancer screening worldwide. Artificial intelligence has substantially improved mammographic interpretation by assisting radiologists with lesion detection, breast density assessment, tumor localization, and malignancy classification.[13]

DOI: https://doi.org/10.62896/ijmdas.2025. V1.I6.04

Deep learning algorithms automatically analyze mammographic images to identify masses, calcifications, asymmetries, architectural distortion, and interval changes across sequential examinations. Quantitative image analysis reduces observer variability while improving diagnostic consistency among radiologists.

Digital breast tomosynthesis generates three-dimensional breast images that reduce tissue overlap and improve lesion conspicuity. Artificial intelligence further enhances tomosynthesis by accelerating image reconstruction, lesion detection, volumetric assessment, and diagnostic classification, thereby improving both screening performance and workflow efficiency.[14]

6. Artificial Intelligence in Breast Ultrasound and Magnetic Resonance Imaging

Breast ultrasound serves as an important complementary imaging modality, particularly for evaluating dense breast tissue and characterizing indeterminate mammographic findings. Artificial intelligence assists sonographers and radiologists by automatically identifying suspicious lesions, quantifying tumor morphology, evaluating vascularity, and differentiating benign from malignant breast masses.[15]

Breast magnetic resonance imaging provides high sensitivity for detecting invasive breast cancer, multifocal disease, contralateral malignancies, and treatment response. Deep learning algorithms automate lesion segmentation, tumor volume measurement, background parenchymal enhancement assessment, and radiomic feature extraction from multiparametric MRI examinations.

Artificial intelligence further enables longitudinal analysis of sequential MRI studies, allowing objective evaluation of treatment response during neoadjuvant chemotherapy and facilitating earlier identification of residual disease or recurrence.[16]

7. Digital Pathology and Computational Histopathology

Digital pathology has become a cornerstone of precision breast oncology through conversion of conventional glass slides into ultra-high-resolution whole-slide images suitable for computational analysis. Artificial intelligence evaluates millions of microscopic tissue regions simultaneously, providing objective assessment of tumor morphology, histological grade, mitotic activity, stromal remodeling, lymphovascular invasion, necrosis, and immune infiltration.[17]

Deep learning and transformer-based pathology models accurately classify breast cancer subtypes, identify prognostic biomarkers, predict lymph node metastasis, and estimate recurrence risk with remarkable reproducibility. These computational systems reduce interobserver variability while improving diagnostic consistency across pathology laboratories.

Recent advances have demonstrated that AI can predict clinically important molecular biomarkers—including estrogen receptor (ER), progesterone receptor (PR), HER2 status, Ki-67 proliferation index, and molecular subtypes—directly from routine histopathological images, potentially accelerating precision breast cancer management while reducing additional laboratory testing in selected clinical settings.[18]

8. Radiomics and Radiogenomics in Breast Cancer

Radiomics extends conventional breast imaging by extracting hundreds of quantitative imaging biomarkers describing tumor shape, texture, vascularity, heterogeneity, intensity, and spatial organization. Artificial intelligence analyzes these imaging features to improve diagnosis, prognostic prediction, and therapeutic response assessment.[19]

Radiogenomics further integrates imaging biomarkers with genomic sequencing and molecular profiling to identify relationships between radiological phenotypes and underlying tumor biology. AI models predict molecular subtypes, treatment sensitivity, recurrence risk, and disease aggressiveness using routinely acquired imaging studies.

Repeated imaging throughout treatment enables continuous monitoring of tumor evolution, providing non-invasive assessment of biological changes that may influence individualized therapeutic planning and long-term disease management.[20]

9. Artificial Intelligence in Molecular Classification and Precision Medicine

Breast cancer is a biologically heterogeneous disease comprising multiple molecular subtypes with distinct clinical behavior and therapeutic responses. Artificial intelligence has become increasingly valuable in molecular classification by integrating genomic sequencing, transcriptomics, proteomics, digital pathology, radiological imaging, and clinical information into comprehensive predictive models.[21]

Machine learning algorithms accurately classify tumors into luminal A, luminal B, HER2-enriched, basal-like, and triple-negative molecular subtypes while identifying clinically actionable biomarkers that guide individualized therapy. AI also predicts treatment sensitivity, resistance mechanisms, recurrence probability, and long-term survival by analyzing multidimensional molecular datasets.

Integration of molecular information with radiological imaging and histopathological characteristics supports precision medicine by enabling personalized therapeutic selection based on the unique biological profile of each patient's tumor.

10. Artificial Intelligence in Surgical Planning and Radiation Therapy

Artificial intelligence is increasingly improving surgical oncology by supporting preoperative planning, intraoperative decision-making, and postoperative outcome prediction. Three-dimensional reconstruction of breast anatomy using mammography, ultrasound, and magnetic resonance imaging enables detailed visualization of tumor extent, surrounding tissues, vascular structures, and lymphatic anatomy.[22]

Deep learning algorithms estimate tumor margins, predict lymph node involvement, assess surgical complexity, and forecast cosmetic outcomes following breast-conserving surgery or mastectomy. These computational models assist surgeons in selecting individualized operative strategies while minimizing complications.

In radiation oncology, AI automates tumor contouring, organ-at-risk segmentation, treatment planning, dose optimization, and adaptive radiotherapy. Continuous analysis of sequential imaging enables individualized modification of radiation treatment plans according to anatomical and biological changes occurring during therapy, improving precision while reducing unnecessary radiation exposure to healthy tissues.

11. Artificial Intelligence in Systemic Therapy and Immunotherapy

Artificial intelligence is transforming systemic breast cancer treatment by supporting personalized selection of chemotherapy, endocrine therapy, targeted therapy, antibody-drug conjugates, and immunotherapy. Machine learning integrates genomic alterations, receptor status, transcriptomic profiles, pathology findings, radiological imaging, laboratory biomarkers, and clinical characteristics to predict treatment response and toxicity.[23]

Deep learning models estimate responsiveness to neoadjuvant chemotherapy, endocrine therapy, HER2-targeted therapies, CDK4/6 inhibitors, PARP inhibitors, and immune checkpoint inhibitors. AI also predicts pathological complete response, recurrence risk, progression-free survival, and overall survival, enabling more individualized treatment planning.

For triple-negative breast cancer and other immunotherapy-responsive subtypes, AI evaluates immune-cell infiltration, PD-L1 expression, tumor mutational burden, and the tumor microenvironment to identify patients most likely to benefit from immunotherapeutic strategies while minimizing unnecessary adverse effects.

12. Artificial Intelligence in Drug Discovery and Clinical Decision Support

Artificial intelligence is accelerating breast cancer drug discovery through computational analysis of molecular pathways, genomic alterations, protein interactions, and pharmacological databases. Machine learning identifies novel therapeutic targets, predicts drug-target interactions, estimates toxicity profiles, and facilitates development of personalized anticancer therapies.[24]

Generative AI further enhances pharmaceutical research by designing candidate molecules, modeling biological interactions, and simulating therapeutic responses before laboratory validation.

Within clinical practice, AI-powered decision-support systems integrate laboratory investigations, imaging findings, pathology reports, genomic sequencing, medication history, and electronic health records into comprehensive clinical dashboards. These systems provide individualized recommendations regarding diagnosis, treatment planning, toxicity prediction, and survivorship care while preserving physician oversight and multidisciplinary collaboration.

13. Explainable Artificial Intelligence and Ethical Considerations

The successful implementation of artificial intelligence in breast oncology depends upon transparency, reliability, and clinician confidence. Explainable artificial intelligence (XAI) enables clinicians to understand how computational models generate predictions using visualization techniques such as saliency maps, attention heatmaps, SHAP (Shapley Additive Explanations), feature attribution analysis, and counterfactual reasoning.[25]

Several important challenges continue to limit widespread adoption. Algorithmic bias, data heterogeneity, interoperability limitations, patient privacy, cybersecurity, regulatory approval, medico-legal accountability, and unequal access to advanced computational technologies remain significant barriers to clinical implementation.

Addressing these issues will require standardized validation protocols, secure computational infrastructure, transparent governance frameworks, multidisciplinary collaboration, and continuous physician oversight to ensure equitable and responsible integration of AI into breast cancer care.

14. Emerging Innovations and Future Directions

Rapid advances in artificial intelligence continue to expand opportunities for precision breast oncology. Foundation models trained on massive biomedical datasets are expected to improve diagnostic performance, therapeutic prediction, and clinical decision support while requiring less task-specific retraining.[26]

Digital twins capable of continuously integrating imaging, pathology, genomics, laboratory biomarkers, wearable sensor data, and treatment outcomes may enable individualized simulation of disease progression and therapeutic response throughout the patient's cancer journey.

Additional innovations including federated learning, liquid biopsy, spatial transcriptomics, single-cell sequencing, wearable health technologies, quantum computing, and cloud-based healthcare infrastructure are expected to further strengthen personalized breast cancer management while improving scalability and accessibility across diverse healthcare settings.

15. Discussion

Artificial intelligence has emerged as one of the most transformative technologies in modern breast oncology. Applications spanning breast cancer screening, mammography, ultrasound, magnetic resonance imaging, digital pathology, radiogenomics, molecular classification, surgical planning, radiation therapy, systemic treatment, drug discovery, and clinical decision support demonstrate its remarkable potential for improving patient outcomes.[27]

Unlike conventional analytical approaches that evaluate isolated datasets, AI integrates multimodal biomedical information into comprehensive computational frameworks capable of supporting personalized diagnosis, prognostic prediction, therapeutic optimization, and longitudinal disease monitoring.

Nevertheless, widespread implementation depends upon overcoming important scientific, technical, ethical, and regulatory challenges including data standardization, interoperability, algorithmic transparency, cybersecurity, prospective clinical validation, and equitable healthcare access. Continued multidisciplinary collaboration among clinicians, computer scientists, biomedical engineers, and regulatory agencies will be essential for translating AI innovations into routine clinical practice.[28]

16. Conclusion

Artificial intelligence is fundamentally transforming breast cancer management by enabling earlier detection, more accurate diagnosis, individualized prognostic assessment, precision therapeutic planning, and evidence-based clinical decision-making. Through integration of mammography, ultrasound, magnetic resonance imaging, digital pathology, genomics, molecular biology, electronic health records, and advanced computational modeling, AI supports every stage of the breast cancer care continuum.[29]

As technologies such as multimodal learning, foundation models, digital twins, federated learning, generative artificial intelligence, and cloud-based computational infrastructure continue to mature, their clinical applications are expected to expand substantially. Although important technical, ethical, and regulatory challenges remain, ongoing interdisciplinary research is steadily advancing AI toward routine integration into breast oncology.

Rather than replacing clinicians, artificial intelligence will continue to augment human expertise, improve healthcare efficiency, enhance precision medicine, and ultimately contribute to better clinical outcomes and improved quality of life for patients with breast cancer worldwide.[30]

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