

From Big Data to Smart Health: Machine Learning Approaches Shaping the Future of Biomedicine

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Abstract

The convergence of artificial intelligence, machine learning, and big data analytics continues to revolutionize healthcare delivery and biomedical research, creating unprecedented opportunities for precision medicine, enhanced diagnostic accuracy, and personalized therapeutic interventions. This comprehensive review examines the latest developments in AI-driven healthcare, incorporating breakthrough innovations from 2024 and 2025 that are fundamentally reshaping medical practice across diverse applications and clinical specialties. From generative AI and foundation models to digital twins, quantum computing, and ambient intelligence systems, these technologies are establishing new paradigms for healthcare delivery that prioritize predictive, personalized, and proactive medical care. The global AI healthcare market, valued at \$20.9 billion in 2024, is projected to reach \$148.4 billion by 2029, representing a compound annual growth rate of 48.1% and reflecting the transformative impact of these technologies across diagnostic imaging, clinical decision support, drug discovery, surgical robotics, and patient care delivery. Generative AI in healthcare is expected to reach \$2.7 billion in 2024 and approximately \$17 billion by 2034, while 85% of healthcare leaders are now exploring or have already adopted generative AI capabilities. These advancements represent a paradigm shift toward more intelligent, predictive, and personalized healthcare delivery systems that extend far beyond traditional machine learning applications. The integration of ambient intelligence technologies, robotic surgical systems, and Internet of Medical Things devices is creating comprehensive healthcare ecosystems that enhance both clinical outcomes and operational efficiency.

1. Introduction

The healthcare industry is experiencing a paradigm shift driven by the rapid integration of artificial intelligence and machine learning technologies across all aspects of medical practice (Bajwa *et al.* 2021). Recent developments in 2024 and 2025 demonstrate remarkable progress in AI capabilities, with foundation models achieving new benchmarks in clinical reasoning and diagnostic accuracy (Mahesh *et al.* 2024). Healthcare organizations globally are recognizing the transformative potential of AI to address persistent challenges including physician burnout, diagnostic accuracy, treatment personalization, and operational efficiency while improving patient outcomes and reducing healthcare costs (Bekbolatova *et al.* 2024). The convergence of multiple advanced technologies, including foundation models, digital twins, quantum computing, neuromorphic systems, and ambient intelligence, is creating a comprehensive ecosystem of intelligent healthcare solutions that extend far beyond traditional machine learning applications (Figure.1 and Figure 2) (Papachristou *et al.* 2024). The digital twins are known as virtual duplicates of a patient's organ or clinical system from clinical records, imaging and sensors, and they simulate real-time behaviour using data sources. The term 'ambient intelligence' stands for unique AI technology that works silently and automatically in the background. This technology contributes to the daily clinical tasks by collecting the information, supporting doctors and handling routine work without disturbing or interrupting patient care. And another term is Neuromorphic Systems are artificial human brain made by the computers and software, which can use less energy, work faster, adapt or learn better than normal computers by using the artificial neurons and synapses.

2. Methodology

In this Review, the excellent literature search was done by the usage of some popular databases like PubMed, Scopus and Web of Science, focusing the published of articles on time duration from year of 2020 to 2025 (August). Combination of terms like 'artificial intelligence in healthcare,' 'machine learning,' 'digital twins,' 'precision medicine,' 'clinical decision support systems,' 'generative AI,' and 'AI ethical challenges' are used as primary search in the databases. And also searched terms which more relevant to the topic like 'ambient clinical intelligence,' 'robotic

surgery, and AI implementation barriers. The review encloses with both peer-reviewed original research and review articles and listed the Reference of Key articles were screened for the supplementary sources. can calculated. The method's foundation respites on a statistical analysis of relationships between pairs of homologous structures, formerly resultant from a database of 105 family alignments that included 416 proteins with known 3D structure. This analysis predicts the various correlations including relationships between equivalent Ca-Ca distances or equivalent mainchain dihedral angles from associated proteins (Janson *et al.* 2019).

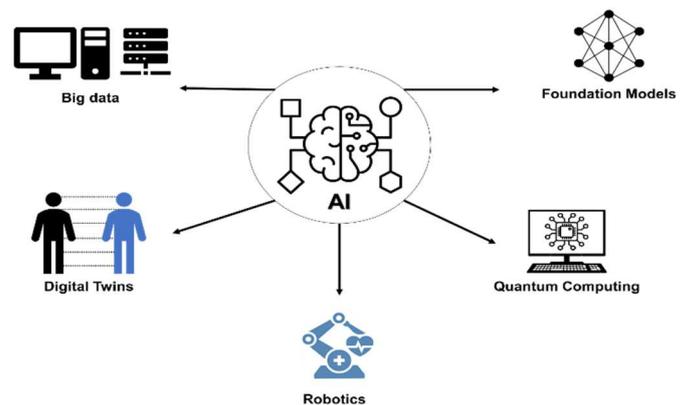


Figure.1. The integration of AI, machine learning, and cutting-edge technologies

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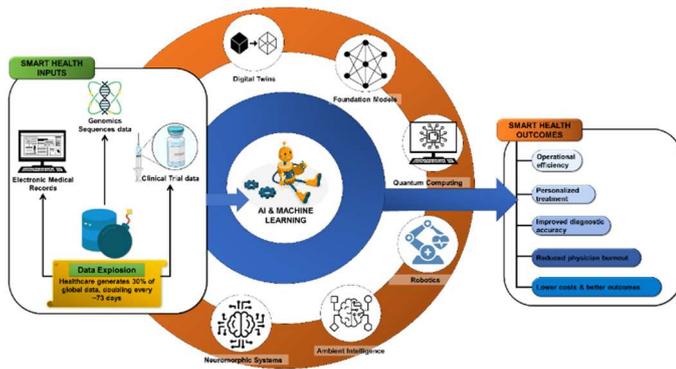


Figure 2. Ecosystem of AI and Emerging Technologies in Healthcare

3. Foundation Models and Generative AI in Healthcare

3.1. Evolution and Clinical Applications

Foundation models represent a revolutionary advancement in AI capabilities, characterized as large-scale deep learning models trained on massive datasets using self-supervised learning techniques. These versatile models serve as robust bases for diverse downstream tasks, demonstrating remarkable adaptability across clinical applications (Huang et al. 2025). Foundation models are transforming healthcare by enabling more sophisticated natural language processing, medical image analysis, and omics research capabilities that significantly outperform traditional machine learning approaches. The emergence of foundation models in biomedical research represents a fundamental shift from traditional machine learning approaches toward more comprehensive and adaptable AI systems (Li et al. 2024). These models leverage multi-modal data integration, combining genomic, transcriptomic, proteomic, and clinical data to provide comprehensive insights into biological processes. Foundation models enable researchers to identify previously unknown patterns and relationships across different biological systems, facilitating breakthrough discoveries in disease mechanisms and therapeutic targets (Sanchez et al. 2024). The integration of diverse data types through foundation models creates opportunities for more holistic understanding of complex biological phenomena, moving beyond reductionist approaches to embrace systems-level analysis (Figure 3).

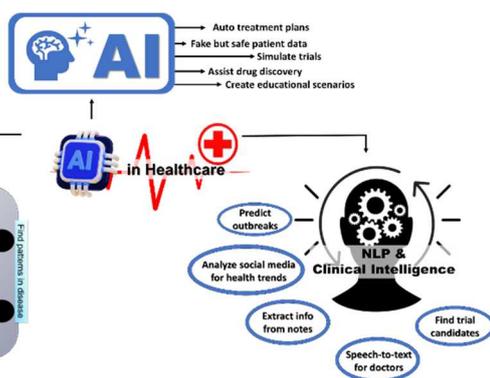


Figure 3. Role of Foundation Models and NLP in AI-Driven Healthcare

Generative AI has demonstrated transformative potential across numerous clinical applications, fundamentally changing how healthcare providers approach patient care, documentation, and decision-making processes (Chen and Esmailzadeh 2024). In clinical settings, generative AI supports the creation of customized treatment plans by analysing extensive patient data to identify optimal therapeutic strategies. The technology excels at generating synthetic data for research purposes, enabling researchers to overcome data scarcity challenges while

maintaining patient privacy. Advanced generative models can create realistic patient populations for clinical trial simulations, drug discovery applications, and medical education scenarios (Bhuyan et al. 2025).

3.2. Clinical Documentation and Decision Support

Clinical documentation represents one of the most immediate and impactful applications of generative AI in healthcare settings. Large language models demonstrate remarkable capabilities in automating medical record creation, generating discharge summaries, and producing referral letters with accuracy comparable to human clinicians. These applications significantly reduce administrative burden on healthcare providers, allowing them to focus more time on direct patient care. Studies indicate that AI-assisted documentation can reduce documentation time while improving completeness and accuracy of medical records (Oliveira et al. 2025). The integration of generative AI in diagnostic support systems showcases the technology's potential to enhance clinical decision-making capabilities. Med-PaLM 2 achieved accuracy levels comparable to or exceeding human experts on clinical knowledge assessments, demonstrating the sophisticated reasoning capabilities of advanced language models. However, current large language models face limitations in clinical judgment and integrative capacities essential for complex clinical practice. These models excel at information retrieval but require continued development to achieve the sophisticated clinical reasoning necessary for autonomous medical decision-making (Wong et al. 2024). Ambient clinical intelligence represents a significant advancement in healthcare technology, employing sophisticated voice-recognition AI to capture and record patient-doctor conversations as they naturally occur. The technology aims to streamline care delivery, enhance efficiency, and provide personalization while allowing physicians to maintain undivided focus on their patients (Balloch et al. 2024). Ambient AI was associated with 7 times greater odds of clinicians reporting a higher level of agreement that their documentation workflow is easy and 5 times greater odds of clinicians reporting a higher level of agreement that they can complete documentation before the next patient encounter. Most clinicians surveyed agreed that using ambient AI platforms increased satisfaction at work, decreased documentation burden, decreased time spent documenting outside of clinical hours, and decreased risk for burnout (Albrecht et al. 2025).

3.3. NLP and Clinical Intelligence

Natural language processing technologies are becoming increasingly prevalent in healthcare, with the global NLP market in healthcare expanding from \$2.7 billion in 2023 to a projected \$11.8 billion by 2028. NLP enables healthcare organizations to extract vital data from documents quickly, organizing uncategorized clinical information and providing valuable insights while streamlining manual workflows (Jerfy et al. 2024). NLP algorithms can differentiate between various elements in medical documents, such as distinguishing between patient names and medical conditions and identifying whether information pertains to single or multiple patients. Healthcare systems generate vast amounts of unstructured text data through clinical notes, discharge summaries, and research papers (Sagheb et al. 2021). Automating labour intensive and tedious tasks with language processing algorithms, using text analytics systems and machine learning to analyse social media data and extracting insights from unstructured data allows for better public sentiment analysis, enhancement of risk prediction models, improved patient communication, and informed treatment decisions. Advanced language processing techniques such as Speech Recognition and Natural Language Understanding tools can help overcome linguistic barriers and facilitate efficient communication between patients and healthcare providers (Jerfy et al. 2024). The application of NLP in electronic health record screening, speech-to-text technology for extracting EHR data from point of care,

patient communications, and accelerated identification of eligible clinical trial candidates through automated searches demonstrates the technology's versatility in healthcare applications (Van Bulck et al. 2025). Recent studies have applied NLP tools to social media posts to evaluate public sentiment regarding COVID-19 vaccine use, while social media data has the capacity to be harnessed to develop pandemic prediction models based on reported symptoms (Al-Garadi et al. 2022).

4. Digital Twins and Precision Medicine

4.1. Advanced Digital Twin Technologies

Digital twins represent virtual replicas of physical entities that enable real-time monitoring, simulation, and optimization of healthcare systems. In healthcare, digital twins create dynamic, patient-specific virtual models that combine medical imaging, physiological data, and computational simulations to replicate and predict real-world health outcomes. These virtual models continuously update with real-time data, enabling predictive analysis, scenario simulation, and personalized healthcare interventions that were previously impossible (Papachristou et al. 2024). The global digital twin market in healthcare is experiencing remarkable growth, estimated to reach \$1.37 billion in 2025 and \$6.80 billion by 2032, exhibiting a compound annual growth rate of 25.7%. This rapid expansion reflects the increasing recognition of digital twins' potential to transform personalized medicine, surgical planning, and clinical decision-making. As of 2024, approximately 40% of clinical trial simulations involve digital twin technology, effectively decreasing trial costs by 25% to 30% while improving research efficiency and patient outcomes (Lee and Kim 2024). Digital twins are revolutionizing multiple aspects of healthcare delivery through sophisticated modeling and simulation capabilities. In cardiovascular medicine, virtual heart models enable real-time cardiac monitoring and arrhythmia prediction, allowing clinicians to intervene before serious complications arise. These models integrate electrocardiogram data, imaging studies, and patient history to create comprehensive cardiovascular profiles that guide treatment decisions and predict treatment responses (Trayanova and Prakosa 2024). The technology demonstrates particular promise for personalized cancer treatment, where digital twins can predict cancer treatment responses by modeling tumour behaviour, drug interactions, and patient-specific factors that influence therapeutic outcomes (Figure. 4) (Giansanti and Morelli 2025).

complications, and improve surgical outcomes (Asciak et al. 2025). The scope of digital twin applications continues to expand as the technology matures and computational capabilities improve. Immune digital twins are being developed to model immune system responses to therapeutic interventions, providing insights into personalized immunotherapy approaches. These models can predict how individual patients will respond to specific treatments, enabling more precise therapeutic selection and dosing strategies (Niarakis et al. 2024). Population health applications of digital twins extend beyond individual patient care to address broader public health challenges. Digital twins can model disease transmission patterns, predict epidemic spread, and optimize resource allocation during public health emergencies. These applications became particularly relevant during the COVID-19 pandemic, where digital twin models helped predict healthcare system capacity and guide policy decisions (Rehan and Rehan 2025). The integration of digital twins with artificial intelligence and machine learning capabilities is creating opportunities for more sophisticated predictive modeling through AI-powered digital twins that can continuously learn from new data, improving their predictive accuracy over time and adapting to changing patient conditions (Chaparro-Cardenas et al. 2025).

4.3. Quantum Computing Applications in Biomedicine

Quantum computing represents an emerging frontier in healthcare technology with transformative potential for medical research and clinical applications. Quantum computing's ability to process vast datasets and model complex biological systems positions it as a revolutionary tool for drug discovery, genomics, personalized medicine, and medical imaging optimization. The unique properties of quantum systems, including superposition and entanglement, enable quantum computers to solve problems that are computationally intractable for classical computers (Chow 2024). Recent advances in quantum computing demonstrate significant promise for healthcare applications. Quantum-enhanced algorithms show potential for improving diagnostic accuracy in medical imaging, optimizing treatments in oncology, and enabling real-time clinical decision-making. The ability to process and analyze vast amounts of medical data simultaneously makes quantum computing particularly valuable for applications requiring massive computational power, such as drug discovery and genomic analysis (Figure 5) (Fairburn et al. 2025).

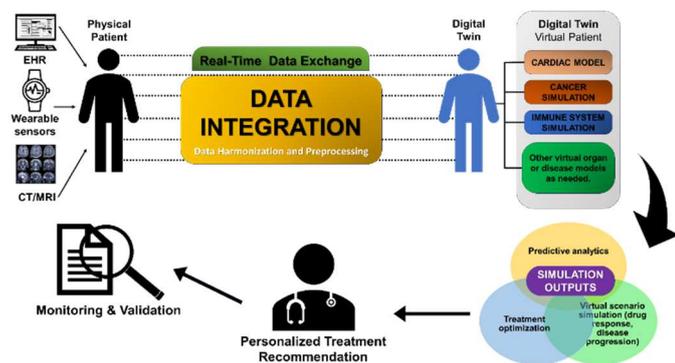


Figure 4. Digital twin framework for precision medicine

4.2. Clinical Implementation and Emerging Applications

Surgical planning represents a transformative application of digital twin technology, enabling surgeons to practice complex procedures using patient-specific digital twins. Surgeons can gain insights into anatomical variations and potential complications before entering the operating room, providing detailed three-dimensional representations of patient anatomy that allow for optimal surgical approach planning and anticipation of potential challenges. The integration of digital twins in surgical planning has been shown to reduce operative time, minimize

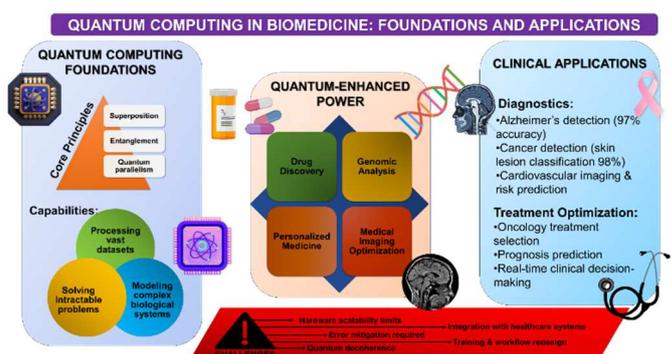


Figure 5. Quantum Computing Foundations and Applications in Biomedicine

Quantum computing applications in clinical care demonstrate remarkable potential for enhancing diagnostic accuracy and treatment optimization. Hybrid classical-quantum neural networks for Alzheimer's detection achieved over 97% classification accuracy when trained on balanced datasets of MRI scans, significantly outperforming classical-only models. These quantum-enhanced systems leverage quantum parallelism for efficient feature extraction, enabling the identification of subtle patterns in medical imaging that might be missed by traditional approaches (Fairburn et al. 2025). Cardiovascular applications of quantum

computing show particular promise for improving cardiac imaging analysis and risk prediction. Quantum algorithms can process complex cardiac imaging data more efficiently than classical methods, providing more detailed insights into cardiac function and identifying potential complications earlier. The ability to analyse multiple cardiac parameters simultaneously through quantum computing enables more comprehensive cardiovascular assessment and treatment planning (Jeyaraman *et al.* 2024). Cancer diagnosis and treatment represent another area where quantum computing demonstrates significant potential. Quantum-enhanced models have improved skin lesion classification accuracy to 98%, outperforming traditional CNN models that typically achieve 81-97% accuracy. The superior performance of quantum models in cancer detection applications suggests broader potential for oncology applications, including treatment selection and prognosis prediction (Sun *et al.* 2025). Despite promising advances, quantum computing in healthcare faces significant challenges that must be addressed for widespread clinical adoption. Hardware limitations, including scalability issues and quantum decoherence, currently restrict the practical implementation of quantum computing systems. Error mitigation techniques and the development of more stable quantum hardware are essential for realizing the full potential of quantum computing in healthcare applications. The integration of quantum computing with existing healthcare infrastructure presents additional challenges requiring new workflows and training programs to effectively utilize quantum computing capabilities (Suvvari *et al.* 2025).

5. Surgical Robotics and AI-Enhanced Procedures

5.1. Advanced Robotic Surgery Systems

The integration of robotics and artificial intelligence in surgery represents a transformative advancement in modern healthcare, promising enhanced precision, efficiency, and patient outcomes. Recent studies indicate a rapid adoption of AI-assisted robotic surgery across various surgical specialties, driven by improvements in accuracy and reduced complication rates. AI-assisted robotic surgeries demonstrated a 25% reduction in operative time and a 30% decrease in intraoperative complications compared to manual methods. Surgical precision improved by 40%, reflected in enhanced targeting accuracy during tumor resections and implant placements (Wah 2025). The successful use of imitation learning to train surgical robots eliminates the need to program robots with each individual move required during a medical procedure and brings the field of robotic surgery closer to true autonomy, where robots could perform complex surgeries without human help. The team used imitation learning to train the da Vinci Surgical System robot to perform fundamental surgical procedures including manipulating a needle, lifting body tissue, and suturing. The model combined imitation learning with the same machine learning architecture that underpins ChatGPT, working with kinematics that breaks down the angles of robotic motion into mathematical representations (Knudsen *et al.* 2024). Machine learning applications in robotic-assisted surgery demonstrate exciting potential across multiple domains including surgical performance assessment and skill training, surgical candidate selection, and autonomous surgery. Autonomous segmentation and classification of surgical data serve as stepping-stones for providing real-time surgical assessment and ultimately improving surgical safety and quality. Predictive machine learning models guide appropriate surgical candidate selection, while intraoperative machine learning algorithms provide 3D augmented reality and real-time surgical margin checks (Ma *et al.* 2020).

5.2. Neurosurgical Robotics and AI Integration

Artificial intelligence in neurosurgery, highlighting AI's promise in multiple domains including operating room and hospital efficiency, learning, education, and performance, as well as novel tools and

technologies (Han *et al.* 2025). Neurosurgical robotics and artificial intelligence are revolutionizing the field of neurosurgery by enhancing precision, improving patient outcomes, and reducing recovery times. The integration of AI algorithms with robotic systems allows for more accurate surgical planning, real-time adjustments, and minimally invasive procedures. Robotics paired with AI offers neurosurgeons the ability to perform complex surgeries with greater confidence and efficiency (Kok Wah 2025). AI-driven robotic platforms are expected to enhance surgical planning, real-time intraoperative decision-making, and post-operative monitoring, offering highly personalized treatment strategies for patients. The continuous development of minimally invasive robotic systems allows for even more precise interventions with smaller incisions, reduced recovery times, and fewer complications (Abdalla Osman *et al.* 2025). Despite substantial advances in engineering, robotics, and artificial intelligence, autonomous robots have yet to revolutionize neurosurgery. Economic, regulatory, liability, and cultural hurdles limit their adoption, requiring cautious optimism and thoughtful integration of robotics to enhance, not replace, the neurosurgeon's critical judgment. The development of neurosurgical robotics requires addressing these multifaceted challenges through collaborative efforts between engineers, clinicians, and regulatory bodies (Kazemzadeh *et al.* 2023).

5.3. Autonomous Surgery and ML Integration

Reinforcement learning strategies have been utilized in autonomous robotic surgery, with the combination of expert demonstrations and trial-and-error learning by the robot itself representing a promising approach toward autonomy. Machine learning enhances robotic surgery by using computer vision models to perceive surgical environments and reinforcement-learning methods to learn from a surgeon's physical motions (Shahkoo and Abin 2023). The unique ability of machine learning to learn from prior experience enables robots to process novel data, similar to how surgeons deal with different anatomical variances among patients (Ma *et al.* 2020). Autonomous camera positioning represents one practical application of machine learning in robotic surgery. Three sources of data have been utilized by machine learning algorithms to achieve autonomous camera positioning including instrument kinematics, laparoscopic video, and surgeon eye-tracking. By using kinematic data from surgical instruments, these algorithms avoid visual occlusion in the operative field, though they require accurate instrument positions that may not be feasible in traditional laparoscopic surgery (Wagner *et al.* 2021). The intersection of machine learning and robotics-derived big data represents a rapidly evolving area of study that harbors the potential to optimize surgical safety and quality. Multiple studies have utilized machine learning models to provide objective and efficient surgical assessment, with the ultimate goal of providing timely and meaningful surgical feedback intraoperatively to prevent adverse events (Morris *et al.* 2024). Machine learning empowers surgical robots to learn procedures autonomously through expert demonstrations, trial-and-error approaches, or hybrid combinations of these methods (Ma *et al.* 2020).

6. IoMT and Remote Patient Monitoring

6.1. AI-Driven Remote Patient Monitoring

The integration of artificial intelligence with remote patient monitoring represents a transformative advancement in healthcare delivery, enabling continuous oversight of patient health outside traditional clinical settings. AI algorithms amplify RPM's potential by analysing vast datasets to detect trends, anomalies, and risks in real-time, converting passive data collection into meaningful clinical insights (Dubey and Tiwari 2023). By 2025, AI-enabled home testing kits are gaining traction, allowing patients to conduct tests for conditions using AI-powered smartphone apps. This technology promises quicker diagnoses and treatment without the need

for office visits, enhancing patient convenience (Thacharodi et al. 2024). Predictive analytics and machine learning models form the core of any AI-enabled remote monitoring system. These algorithms continuously evaluate patient data, identifying early warning signs of deterioration such as cardiac irregularities or respiratory distress before clinical symptoms become evident. This enables early intervention and improves outcomes in chronic disease management (Muralitharan et al. 2021). Wearable devices and biosensors have evolved into clinical-grade tools, with devices such as ECG-enabled smartwatches, continuous glucose monitors, and smart inhalers collecting health data while feeding AI systems to detect anomalies and personalize alerts. The convergence of healthcare with the Internet of Things and Artificial Intelligence is reshaping medical practice with enhanced data-driven insights, automated decision-making, and remote patient monitoring. The integration of IoT and AI in healthcare offers significant advancements including remote patient monitoring, personalized medicine, and operational efficiency. Wearable sensors, cloud-based data storage, and AI-driven algorithms enable real-time data collection, disease diagnosis, and treatment planning (Figure 6) (Sharma et al. 2021).

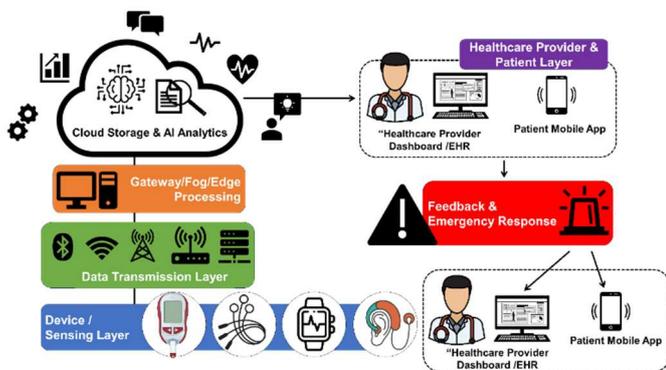


Figure 6. Internet of Medical Things (IoMT) framework for remote patient monitoring

6.2. Wearable Devices and Machine Learning Integration

Wearable devices have emerged as promising tools for personalized health monitoring, utilizing machine learning to distil meaningful insights from the expansive datasets they capture. These devices employ biosignal data such as electro cardiograms, electro myograms, and electroencephalograms to monitor and assess health, focusing on devices measuring physiological signals including glucose levels and electrolytes to offer a holistic understanding of the wearer's physiological state. Motion and physical activity data provide valuable insights into an individual's physical activity and behaviour patterns. The integration of machine learning algorithms within wearable devices illuminates their potential to revolutionize healthcare through early detection, timely intervention, and the provision of personalized lifestyle recommendations. The amalgamation of advanced machine learning techniques with wearable devices paves the way for more effective and individualized healthcare solutions (Olyanasab and Annabestani 2024). Recent advances showcase the integration of machine learning algorithms to enable personalized health monitoring and intervention systems that leverage data from various sensors embedded in wearable devices. Many countries around the world are facing a shortage of healthcare resources, especially during the post-epidemic era, leading to a dramatic increase in the need for self-detection and self-management of diseases (Rani et al. 2025). The popularity of smart wearable devices such as smartwatches and the development of machine learning bring new opportunities for the early detection and management of various prevalent diseases including cardiovascular diseases, Parkinson's disease, and diabetes (Moshawrab et al. 2023). This comprehensive approach encompasses objectives, wearable device and sensor data, machine learning techniques, and wearing

locations to address privacy concerns, security considerations, transmission latency and reliability, energy consumption, and multimodality requirements.

6.3. AIoT and Healthcare Ecosystem Integration

Artificial Intelligence of Things in healthcare merges the power of artificial intelligence with the Internet of Things, creating a transformative impact on medical care. While AI primarily focuses on processing pre-collected data, AIoT collects real-time data from connected devices such as wearables and medical sensors, processing it using AI algorithms to provide real-time insights and predictions (Pise et al. 2022). AIoT enables continuous patient health monitoring, allowing treatment plans to be dynamically adjusted based on real-time data, whereas traditional AI personalizes care based on historical data. AIoT shifts preventive care from identifying risks based on historical data to predicting and preventing health issues by detecting early signs and symptoms (Belbase et al. 2024). Applications include continuous patient monitoring, wearable health devices, AI-powered medical imaging analysis, accelerated drug discovery, and personalized treatment plans. AIoT leverages the strengths of AI and IoT, allowing healthcare to become more efficient, personalized, and proactive in addressing patient needs and health outcomes (Shajari et al. 2023). The rapid advancement of the Internet of Medical Things has revolutionized remote healthcare monitoring, enabling real-time disease detection and patient care. A novel AI-driven telemedicine framework integrates IoMT, cloud computing, and wireless sensor networks for efficient healthcare monitoring. The Transformer-based Self-Attention Model enhances disease classification by replacing conventional convolutional layers with transformer layers, effectively extracting spatial and spectral features from patient health data while optimizing classification accuracy (Abdulmalek et al. 2022).

7. Decision Support Systems and Ambient Intelligence

7.1. AI-Enhanced Clinical Decision Support

Artificial intelligence-based clinical decision support has the potential to augment high-stakes clinical decisions across healthcare settings, particularly in emergency departments where rapid decision-making is critical. AI has moved beyond hype in healthcare, becoming embedded in the clinical decision-making process from diagnostics and risk prediction to workflow optimization and real-time patient insights. Recent developments demonstrate AI tools helping pathologists diagnose diseases in seconds rather than minutes, reducing backlogs and improving speed to care. AI for doctors represents partnership rather than replacement, offering a second layer of insight that supports faster, safer, and more confident decisions (Kareemi et al. 2025). Machine learning in healthcare increases precision, reduces burden, and shifts the entire clinical model from reactive to predictive approaches. Wearable AI technology provides clinicians with real-time clinical decision guidance based on continuous patient monitoring, reshaping how proactive care is defined and delivered (Maleki Varnosfaderani and Forouzanfar 2024). Clinical Decision Support Systems are essential tools in contemporary healthcare, enhancing clinicians' decisions and patient outcomes through the integration of artificial intelligence technologies. The integration of AI technologies into CDSS includes machine learning algorithms like neural networks and decision trees, natural language processing, and deep learning capabilities. AI applications within CDSS demonstrate real-life examples of AI-driven diagnostics, personalized treatment recommendations, risk prediction, early intervention, and AI-assisted clinical documentation (Elhaddad and Hamam 2024).

7.2. Ambient Clinical Intelligence Technologies

Ambient clinical intelligence employs artificial intelligence to automate the detailed documentation required during medical encounters, using

voice recording, voice recognition, natural language processing, speech-to-text contextual transcription, and data collection methods to create comprehensive patient notes. ACI technologies free clinicians from manual transcription, data collection, and EHR data entry, allowing them to focus their full attention and medical expertise on their patients while developing stronger relationships and reducing personal stress and burnout (Ng *et al.* 2025). The effectiveness of ambient AI depends on foundational components that ensure data becomes more than just numbers on a dashboard. Seamless integration with electronic health records and telehealth platforms is critical, as without interoperability, AI insights remain siloed and fail to inform clinical decision-making. Integration ensures that clinicians can access consolidated and meaningful data in real-time, supporting more informed clinical decision-making processes (Nahar and Kachnowski 2023). Ambient AI was associated with decreased time in notes per appointment and improved clinician satisfaction at work while decreasing cognitive load. Ambient AI represents a potential solution to improve the experience of work for clinicians by decreasing the burden of clinical documentation. The technology demonstrates that ambient AI platforms not only reduce documentation burden and risk of burnout among primary care clinicians but also benefit medical and surgical subspecialists across different healthcare settings (Stults *et al.* 2025).

7.3. Clinical Documentation and Workflow Integration

Natural language processing enables healthcare organizations to extract vital data from documents quickly, organizing uncategorized clinical information and providing valuable insights while streamlining manual workflows. NLP algorithms can accurately differentiate between various elements in medical documents, such as distinguishing between patient names and medical conditions and identifying whether information pertains to single or multiple patients (Aramaki *et al.* 2022). The global NLP market in healthcare is expanding rapidly, with applications spanning public sentiment analysis in relation to health policies, electronic health record screening, speech-to-text technology for extracting EHR data from point of care, patient communications, and accelerated identification of eligible clinical trial candidates through automated searches. Advanced language processing techniques such as Speech Recognition and Natural Language Understanding tools help overcome linguistic barriers and facilitate efficient communication between patients and healthcare providers (Jerfy *et al.* 2024). Clinical notes which are generated by the artificial intelligence are not accepted directly. Before the acceptance, a doctor must check, verify and approve everything in the AI-generated clinical notes. To keep these notes accurate and safe, follow the activities like system-based accuracy checks, audit trails and medical terminology rules to avoid mistakes or hallucinations. At last, to avoid the legal or liability risks in the hospitals, it is only done by following the clear policies and understanding the term that AI is not responsible for the final notes. AI-driven clinical decision support systems analyze comprehensive medical data in seconds, providing doctors with evidence-based recommendations for diagnosing and treating patients. This comprehensive analysis helps healthcare providers make informed decisions based on data, leading to fewer medical mistakes and better patient outcomes. The use of AI in clinical decision-making represents a crucial step towards personalized medicine and tailored healthcare delivery approaches (Elhaddad and Hamam 2024).

8. Regulatory Frameworks

8.1. Global Regulatory Landscape Evolution

The regulatory landscape for AI in healthcare continues to evolve rapidly as regulatory agencies worldwide develop frameworks to address the unique challenges posed by AI technologies. The FDA has authorized 950 AI or machine learning-enabled devices as of August 2024, representing

dramatic growth from just 6 devices in 2015. This exponential increase reflects both technological advancement and regulatory adaptation to accommodate the growing complexity and sophistication of AI applications in healthcare (Babic *et al.* 2025). The United States has introduced several significant regulatory updates to oversee AI integration in healthcare during 2025. The Department of Health and Human Services introduced its 2025 AI Strategic Plan, providing a comprehensive roadmap for AI adoption across health, human services, and public health sectors. This strategic plan emphasizes catalyzing health AI innovation, promoting trustworthy and ethical AI development, democratizing access to AI technologies, and cultivating an AI-ready workforce (Bajwa *et al.* 2021). The European Union's AI Act represents one of the most comprehensive regulatory frameworks for AI applications, with healthcare AI systems typically classified as high-risk applications requiring strict compliance measures. The AI Act establishes risk-based categories for AI systems, with most healthcare applications falling under high-risk classifications that require extensive validation, monitoring, and documentation. The United Kingdom is developing a sector-specific regulatory framework that depends on existing regulators to create tailored rules for healthcare AI (Busch *et al.* 2024).

8.2. Implementation Barriers and Healthcare Challenges

Healthcare organizations face multiple barriers to AI implementation including data quality issues, interoperability challenges, security concerns, skill gaps, infrastructure limitations, and cost considerations. Data security and privacy concerns stand as significant challenges in the integration of AI into healthcare, with healthcare organizations handling vast amounts of sensitive patient data making them prime targets for cyberattacks. The consequences of data breaches can be severe, potentially leading to identity theft, financial fraud, and compromising patient care. AI algorithms depend heavily on data to make accurate predictions and recommendations, yet healthcare data is often fragmented across different systems, leading to inaccuracies and inconsistencies. These inaccuracies can adversely affect the performance and reliability of AI models, leading to flawed insights and recommendations. The lack of sufficient or poor-quality data available to train AI algorithms effectively represents a limitation that can hinder the performance and accuracy of AI systems (Ahmed *et al.* 2023). The healthcare workforce requires significant training and education to effectively utilize AI technologies. Healthcare organizations must address challenges including understanding AI and setting strategy, creating AI teams to guide deployments, overcoming data fragmentation, dealing with regulatory compliance, and managing change among healthcare professionals. The initial obstacle for healthcare organizations considering AI adoption involves grasping the essentials of the technology and developing an AI strategy and vision (Bajwa *et al.* 2021).

8.3. Addressing Barriers Through Training and Education

AI is revolutionizing healthcare training by enhancing workforce skills and improving patient care through personalized learning paths that analyse workers strengths and knowledge gaps. AI-driven upskilling solutions provide on-demand virtual simulations enabling healthcare professionals to practice real-world scenarios using AI-powered virtual patients, reducing the need for costly in-person training while providing real-time feedback and assessments. Healthcare institutions require highly skilled and adaptable workforces to navigate rapidly changing medical landscapes. Traditional training methods often struggle to keep pace with rapid advancement, with curriculums becoming outdated quickly and standardized approaches failing to cater to individual learning styles. AI personalizes the learning experience by analysing multiple factors including educational background, previous experience, strengths, weaknesses, and preferred learning styles to create targeted learning paths.

Generative AI excels in crafting customized learning paths tailored to individual healthcare professionals by analyzing performance data and identifying knowledge gaps. AI tools create dynamic modules that align with professional expertise and goals, providing real-time updates to ensure relevance as medical knowledge evolves. AI-driven feedback systems highlight strengths and areas for growth, enabling precise and actionable professional development through simulation and scenario-based learning (Hamilton 2024).

9. Smart Health Systems and Urban Integration

Smart health represents a unified system of care that interconnects people, the environment, and infrastructure within highly technologically advanced and interconnected frameworks. Smart cities and digital intelligence sustain resilient, future-ready environments where smarter healthcare improves the lives and health of citizens through advanced disease monitoring and surveillance, health risk mitigation, and connected health ecosystems that deliver the right care to the right person at the right time. The fusion of smart cities and electronic health is altering the landscape of urban existence, with smart cities expanding beyond merely enhancing transportation, utilities, and governance to become sophisticated ecosystems where digital healthcare is becoming a fundamental aspect of urban planning (Saba Raoof and Durai 2022). Urban areas are progressing beyond conventional care models by utilizing AI, IoT, and real-time data analytics to enhance patient outcomes and improve healthcare accessibility (Maleki Varnosfaderani and Forouzanfar 2024). Smart health technologies refer to digitally enabled tools and systems that automate, augment, or optimize clinical and operational workflows. This includes remote patient monitoring, AI-powered diagnostics, telemedicine platforms, smart ICUs and EHR integration, wearables and mobile health apps, and healthcare IoT and cloud storage systems. These tools work together to help hospitals deliver care beyond hospital walls, improve operational efficiency, and empower both patients and providers (Rani et al. 2025).

10. Future Healthcare Infrastructure Development

The future of hospitals lies in smart health technologies that tackle staff burnout and shortages through smart systems that reduce burden on overworked healthcare professionals by automating repetitive tasks, tracking vitals remotely, and enabling early interventions (Kaldoudi 2024). Remote patient monitoring devices continuously track vitals post-discharge including blood glucose, blood pressure, and oxygen levels, helping prevent complications and avoid unnecessary hospital visits. Smart ICU setups centralize patient data, alert staff to warning signs early, and support AI-driven clinical decision-making to help save lives in real time. Virtual consultations remove geographic and mobility barriers, reduce waiting times, and help hospitals serve rural or remote patients more efficiently while meeting rising patient expectations for digital, responsive, and personalized care (Ko et al. 2023). Technology that learns and systems that adapt enable hospitals to anticipate health risks before they escalate, reduce operational bottlenecks, automate documentation and audits, and personalize treatments using data trends. Hospitals that fail to adopt smart health technologies risk higher patient dissatisfaction, regulatory non-compliance, increased operating costs, low staff retention, and slower emergency response rates (Maleki Varnosfaderani and Forouzanfar 2024). The future of healthcare AI lies in the convergence of multiple advanced technologies creating comprehensive intelligent healthcare ecosystems. The integration of AI with augmented reality, virtual reality, and 5G networks enables real-time AI processing at the point of care, transforming how healthcare is delivered. These technologies create immersive training environments, enhance surgical precision, and enable more interactive patient education and engagement (Bhagat and Kanyal 2024). Much lies on the horizon for healthcare as AI

continues to evolve and mature. New forms of AI including generative AI and large language models will be applied to problems in healthcare, while the metaverse represents an emerging concept with applications being seen in clinical services and operational matters. Opportunities envisaged for healthcare include improving clinical outcomes, clinical trials, improving the efficiency of service delivery and resource utilization, and various communication channels. The evolution toward truly personalized medicine will be driven by the integration of multi-modal data sources including genetic, clinical, lifestyle, and real-time sensor data. AI systems will become increasingly sophisticated in their ability to predict individual treatment responses and optimize therapeutic strategies based on patient-specific characteristics. This personalized approach will extend beyond treatment selection to encompass prevention, early detection, and lifestyle modification recommendations throughout the patient care continuum (Molla and Bitew 2024).

11. Challenges and Future Directions

Despite significant advances in healthcare AI, several technical challenges must be addressed for widespread adoption. Data quality and interoperability remain major barriers, with healthcare data often characterized by inconsistency, incompleteness, and lack of standardization across different systems. The heterogeneous nature of healthcare data requires sophisticated preprocessing and harmonization techniques to ensure that AI systems can effectively utilize information from diverse sources while maintaining accuracy and reliability (Ahmed et al. 2023). Model interpretability and explainability present ongoing challenges for healthcare AI applications, particularly with the complexity of modern AI systems and deep learning models making it difficult for healthcare providers to understand how AI systems arrive at their recommendations. This lack of transparency can undermine trust and acceptance of AI systems in clinical practice, particularly in high-stakes medical decisions where understanding the reasoning process is crucial for patient safety and clinical confidence (Ennab and McHeick 2024). The integration of AI systems with existing healthcare infrastructure requires careful planning and coordination across multiple organizational levels. Healthcare organizations must develop new workflows, training programs, and quality assurance processes to effectively incorporate AI technologies. The need for specialized expertise in AI implementation may create barriers for smaller healthcare organizations with limited resources, requiring collaborative approaches and shared expertise across healthcare networks (Wei et al. 2025).

The integration of AI in healthcare raises significant ethical challenges that require careful consideration and proactive solutions throughout the development and implementation lifecycle. AI systems can perpetuate or exacerbate existing biases, often resulting from non-representative datasets and opaque model development processes. The potential for AI to amplify existing healthcare disparities requires systematic approaches to bias detection and mitigation throughout the AI development lifecycle (Weiner et al. 2025). The Health Equity Across the AI Lifecycle framework provides comprehensive guidance for healthcare organizations to assess and mitigate AI's potential impact on health inequities. This framework evaluates five equity domains across eight key decision points in the AI adoption lifecycle including accountability, fairness, fitness for purpose, reliability and validity, and transparency. Understanding these relationships is crucial for developing AI systems that truly advance health equity rather than simply achieving algorithmic fairness (Kim et al. 2024). Strategies to improve AI equity include developing diverse training datasets, implementing algorithmic fairness testing, and establishing continuous monitoring systems across demographic groups. The importance of diverse representation in AI training data cannot be overstated, as models trained on homogeneous datasets may perform poorly for underrepresented populations.

Systematic approaches to data collection and curation are essential for ensuring that AI systems perform equitably across all patient populations while addressing historical healthcare disparities (Chen *et al.* 2023). High expenses, uncertain reimbursement, rigorous rules, physician scepticism, workflow misalignment, lack of training, and legal or cultural issues are some of the biggest obstacles to AI implementation. These challenges are widely reported in real-world implementation reviews.

This generation of artificial intelligence in healthcare is probably facing many ethical challenges, like data privacy reasons, algorithmic biases, and a lack of transparency in decision-making. So, these result in the direct damage in the clinical trust and provide the unequal outcomes. There must be assurance that AI is used safely and fairly, which can be achieved through strict monitoring, established rules, supervision, and prevention of misuse. The rapid pace of AI development challenges traditional regulatory frameworks that were designed for static medical devices rather than adaptive AI systems that learn and evolve over time. Adaptive AI systems require new regulatory approaches that can accommodate continuous improvement while maintaining safety and efficacy standards. The development of predetermined change control plans represents one approach to addressing this challenge, allowing AI systems to update their algorithms within predefined parameters without requiring complete revalidation (Santra *et al.* 2024). Global harmonization of AI regulations presents ongoing challenges as different countries develop varying approaches to AI governance. The need for international cooperation and standardization becomes increasingly important as AI systems are deployed across multiple jurisdictions. Collaborative efforts between regulatory agencies can help ensure consistent standards while accommodating regional differences in healthcare systems and regulatory priorities. Ethical considerations in AI development require ongoing attention as technologies evolve and new applications emerge. The development of comprehensive ethical frameworks that address emerging challenges while maintaining flexibility for future innovations is essential. Healthcare organizations must establish robust governance structures that can adapt to changing ethical considerations and emerging best practices in AI development while ensuring patient safety and maintaining public trust (Pham 2025).

12. Conclusion

The transformation of healthcare through artificial intelligence and machine learning represents one of the most significant paradigm shifts in modern medicine, creating unprecedented opportunities for precision medicine, enhanced diagnostics, and personalized treatment strategies. The systematic evidence presented in this comprehensive review demonstrates that AI-driven healthcare solutions consistently improve patient outcomes, reduce costs, and enhance operational efficiency across diverse clinical applications and healthcare settings. The convergence of foundation models, digital twins, quantum computing, neuromorphic systems, and ambient intelligence technologies is creating comprehensive healthcare ecosystems that extend far beyond traditional machine learning applications. The global AI healthcare market's projected growth to \$148.4 billion by 2029 reflects the transformative potential of these technologies across all aspects of healthcare delivery, from diagnostic imaging and surgical robotics to remote patient monitoring and clinical decision support systems. Recent breakthroughs in 2024 and 2025, including the development of sophisticated foundation models achieving new benchmarks in clinical reasoning, the expansion of digital twin applications enabling real-time patient simulation, and the emergence of quantum computing demonstrating superior performance in medical imaging analysis, represent fundamental shifts in healthcare technology capabilities. These advances are not merely incremental improvements but constitute revolutionary changes in how healthcare is conceptualized, delivered, and optimized for individual patient needs. The success of AI

implementation in healthcare requires addressing fundamental challenges through collaborative efforts between healthcare providers, technology developers, regulators, and policymakers. The establishment of robust governance frameworks, comprehensive regulatory oversight, and ethical guidelines is essential for ensuring that AI technologies are deployed safely and effectively while maintaining the highest standards of patient care and safety. The integration of generative AI, ambient intelligence, and robotic surgery systems represents more than technological evolution; it constitutes a healthcare revolution that will define the future of medicine for generations to come. As healthcare systems worldwide grapple with aging populations, rising healthcare costs, and increasing complexity of medical care, AI technologies provide practical solutions that can address these systemic challenges while improving patient outcomes and enhancing healthcare accessibility. The future of healthcare will be increasingly characterized by intelligent systems that can predict health problems before they occur, provide personalized treatment recommendations based on individual patient characteristics, and optimize healthcare delivery at both individual and population levels. The convergence of AI technologies with ethical frameworks and regulatory oversight ensures that this transformation will benefit all populations while maintaining the highest standards of patient safety and care quality. The journey from big data to smart health represents a fundamental transition toward predictive, personalized, and proactive healthcare delivery systems. As these technologies continue to mature and integrate into clinical practice, they promise to revolutionize not only how diseases are diagnosed and treated but also how healthcare is accessed, delivered, and experienced by patients worldwide. The systematic evidence presented demonstrates that we are witnessing a transformation in biomedicine where computational power, algorithmic sophistication, and ethical considerations converge to create a future where intelligent health technologies enhance human capability and improve global health outcomes. This transformation represents not just technological advancement but a fundamental reimagining of healthcare delivery, creating a future where smart health technologies enhance clinical decision-making, improve patient safety, reduce healthcare disparities, and ensure that high-quality medical care is accessible to all populations regardless of geographic location or socioeconomic status. The convergence of AI technologies with human expertise promises to create healthcare systems that are more efficient, effective, and equitable than ever before in medical history.

13. Disclosure Statements

13.1. Author Contribution

VS: Writing – Original Draft Preparation; **CP:** Writing – Review and Editing; Validation; **JM:** Writing – Review and Editing; Validation; Conceptualization; Correction and Supervision. All the authors have read and approved the final manuscript.

13.2. Declaration of Generative AI

The authors declare that no generative AI tools were used in the drafting, writing, or editing of the manuscript. All scientific interpretations and conclusions are the author's own. AI-based tools were used only for language grammar refinement and formatting purposes, and the final content was verified and approved by the authors.

13.3. Ethics approval (for clinical/animal studies)

This study did not involve the participation of human subjects, the use of identifiable human data or tissue, or any experiments on live animals. Consequently, the requirement for ethical approval or informed consent did not apply.

13.4. Informed Consent Statement

Not applicable.

13.5. Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

13.6. Acknowledgment

None

13.7. Funding Statement

None

13.8. Conflicts of Interest

The authors declare that they have no known financial, personal, academic, or other relationships that could inappropriately influence, or be perceived to influence, the work reported in this manuscript. All authors confirm that there are no competing interests to declare.

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