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Artificial intelligence in healthcare (Review)

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Abstract. The potential of artificial intelligence (AI) to significantly transform numerous aspects of contemporary civilization is substantial. Advancements in research show an increasing interest in creating AI solutions in the healthcare sector. This interest is driven by the broad spectrum and extensive nature of easily accessible patient data-including medical imaging, digitized data collection, and electronic health records - and by the ability to analyze and interpret complex data, facilitating more accurate and timely diagnoses. This review's goal is to provide a comprehensive overview of the advancements achieved by AI in healthcare, to elucidate the present state of AI in enhancing the healthcare system and improving the quality and efficiency of healthcare decision making, and to discuss selected medical applications of AI. Furthermore, the barriers and constraints that may impede the use of AI in healthcare are outlined, and the potential future directions of AI-augmented healthcare systems are discussed.

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1. Introduction

Artificial intelligence (AI) has become increasingly significant in the realm of innovation in the healthcare industry in the last few years (1). AI, in its broadest sense, is a branch of computer science that aims to replace human intelligence using computer systems (2). This replication is achieved through sophisticated pattern recognition, often at speeds and scales that surpass human abilities. Proponents ardently argue that AI will fundamentally transform healthcare for individuals and communities (3). Alongside AI, subsets such as machine learning (ML) and deep learning (DL) have seen significant advancements in recent years, leading to groundbreaking developments. Currently, AI is predominantly employed to enhance the pace and quality of healthcare. Some of the present applications of AI in this particular field include AI-assisted algorithms to analyze and interpret medical imaging data, including X-rays, MRIs and CT scans, to aid healthcare professionals in rapid and accurate diagnoses (4). The digitization of health-related data, coupled with rapid technological advancements, is driving the advancement of AI applications in healthcare (5). There is a substantial number of reviews that discussed the impact of AI on healthcare (4,5). One of them is a review by Rajpurkar *et al* (5) on AI in personalized medicine, which shows how AI is revolutionizing healthcare by tailoring therapies to individuals' genetic, environmental and lifestyle data. AI may improve the diagnosis of health conditions, treatment choices and health outcomes, notably in genomics and precision medicine (PM); the review also highlights how AI may save healthcare costs, boost efficiency and improve patient care, but it also raises data privacy and clinical validation issues (5).

The implementation of AI in healthcare systems represents a complex integration of multimodal systems that necessitates fundamental advancements in areas such as privacy, large-scale machine learning, optimization and model performance (6). To successfully incorporate AI into healthcare, two key concepts must be addressed: Data with security and analytics with insights. Regarding data and security, complete transparency and trust are essential for effective integration. Similarly, the role of data analytics and insight is crucial. AI has the capability to synthesize inputs from diverse unstructured and structured sources to aid in making more informed decisions, finding better solutions and fostering reasoned discussions in multimodal applications - for instance, enabling clinicians to make more accurate diagnoses and nurses to develop sensible care and follow-up plans (7). Over the past decade, rapid advancements in AI have unlocked the possibility of using aggregated healthcare data to construct sophisticated models. These models may automate diagnosis processes and enable a more precise approach to healthcare by tailoring treatments and allocating resources with utmost efficiency in a timely,

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effective and dynamic manner (7,8). The development of such advanced AI models that deliver high-quality healthcare applications requires skilled professionals equipped with cutting-edge technology.

An enormous amount of untapped data that could significantly impact our health exists outside the medical system. For instance, factors such as lifestyle, diet, environment, medical history and population health have significantly influenced health outcomes and collectively account for ~60% of the determinants of health. By contrast, genetics are responsible for only ~30% and the actual health care received contributes only 10% (9). Throughout an individual's lifetime, huge amounts of personal and health data are being generated. If utilized appropriately, these data can unlock unique insights leading to a longer and healthier life. Taking cancer as an example, it involves complex interactions among cancer cells, normal cells, surrounding tissue, the immune system and the underlying molecular changes.

In the near future, it will likely be possible to create dynamic visualizations of tumor development by employing computer modeling and data integration techniques to amalgamate these layers of information for more accurate diagnoses and improved prognoses (10,11). With optimism, it can be predicted that the advent of sophisticated AI technology and computational systems will bring a more comprehensive understanding of tumor biology within our grasp. The healthcare ecosystem is beginning to recognize the critical role that AI-powered tools will play in next-generation healthcare technologies. AI can enhance almost every aspect of healthcare applications and delivery (12). For instance, the cost reductions that AI may bring to the healthcare system are a significant motivator of AI application adoption. In 2026, it is predicted that AI applications would save the United States alone $150 billion in yearly healthcare expenses (5). A significant portion of these cost savings comes from shifting from a reactive to a proactive strategy, with an emphasis on health prevention of illnesses rather than treatment (13). In the present review, the aim is to provide a comprehensive analysis of the current knowledge of AI applications in healthcare, with a particular focus on novel and emerging trends. Unlike previous reviews that often focus on a specific application, this article uniquely integrates insights from multiple domains, including diagnostic AI, patient care optimization and personalized medicine. Furthermore, the evolving regulatory and ethical considerations are highlighted, enabling readers to grasp the multifaceted impacts of AI on the future of healthcare.

2. AI

It is widely agreed that the term 'AI' indicates the execution by computer of activities that are typically associated with intelligent humans (4). ML algorithms are at the heart of AI. Algorithms are converted to code, which contains instructions for fast analysis and translation of input into conclusions, information or other outputs. AI is fueled by massive amounts of data and the ability to analyze that data in a short period of time. An AI system is a machine-based system that, given a set of human-defined goals, can make a prediction, suggestion or choice that may have an impact on real or virtual surroundings. Automated intelligence systems are intended to function with various degrees of autonomy. When it comes to data definition and analysis, ML is a subset of AI methods that is based on the application of statistical and mathematical modeling techniques (3). These newly acquired patterns are then used to execute or steer specific activities, as well as to create predictions.

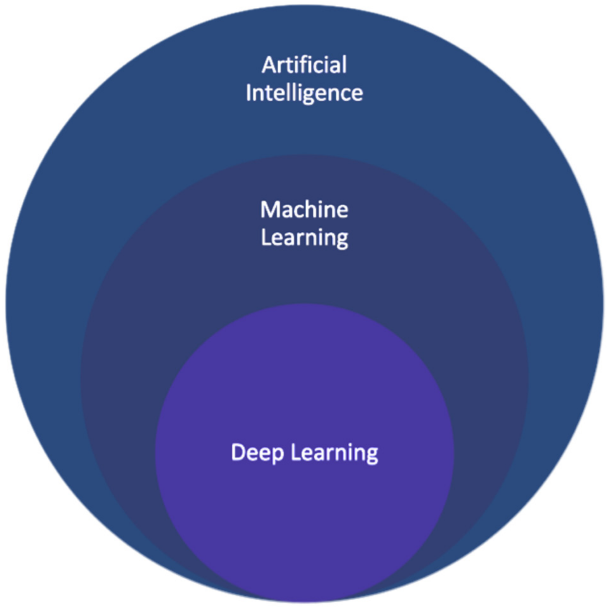

Figure 1. Schematic outlining the relationship between artificial intelligence, machine learning and deep learning.

ML may be divided into three types of learning based on how it learns from data: Supervised learning, unsupervised learning and reinforced learning (14). A model is trained using labeled data (where the outcome variable is known) and the model infers a function from the data that can be used to predict various outputs based on different inputs. In contrast to supervised learning, unsupervised learning includes the detection of hidden patterns in data by a computer rather than the labeling of data. Reinforcement learning is a method of teaching a machine to learn through trial and error in order to achieve a goal, for which the machine is either 'rewarded' or 'punished' based on whether its conclusions help or hinder goal achievement (5).

DL, also known as 'deep structured learning', is a subset of machine learning that utilizes multi-layered neural networks to extract features from data in a hierarchical fashion manner (Fig. 1). DL can be conducted under supervised, unsupervised or semi-supervised settings. It is commonly associated with the need for large volumes of data to effectively train models. Many machine learning techniques are rooted in data-driven methodologies that depend on vast quantities of high-quality data, often referred to as 'big data' (BD) to yield accurate results. Consequently, complex information is rapidly accumulated, resulting in the need for terabytes or even petabytes of storage capacity (15).

3. Medical applications of AI

AI is rapidly becoming an important component of contemporary healthcare, due to recent advancements in computer science and informatics, among other factors. AI algorithms and applications

Table I. Applications of artificial intelligence that have the greatest potential in the healthcare industry.

Application	Description	AI techniques used	Benefits
Medical imaging and diagnostics	AI algorithms can analyze medical images to detect diseases (e.g., cancer, fractures)	DL (CNNs) and computer vision	Improved accuracy and faster diagnosis
Drug discovery and development	Accelerates identification of potential drug candidates and purposing existing drugs	ML and predictive analytics	Reduced time and cost in drug development
Personalized medicine	Tailoring treatment plans based on individual genetics and health data	DM, genomic analysis and ML	More effective treatments and better outcomes
Predictive analytics	Predicts patient outcomes and disease risks based on data patterns	ML and statistical modeling	Proactive care and risk reduction
Patient monitoring and care	Real-time monitoring of patient vital signs with alert systems	IoT devices and ML algorithms	Early issue detection and improved safety
Robotic surgery	AI-assisted robots enhance precision in surgical procedures	Robotics, computer vision and ML	Minimally invasive surgery and better outcomes
Disease outbreak prediction	Uses data analysis to predict and track disease outbreaks	Big data analytics and epidemiological modeling	Early intervention and public health planning
EHR management	Organizes and analyzes EHR data for clinical insights	NLP, DM	Improved data accessibility and decision-making
Telemedicine and remote care	Delivers medical care remotely via AI platforms	Video Analytics, ML and NLP	Increased access and patient convenience
Clinical decision support	Aids clinicians with evidence-based recommendations	Expert systems, ML and NLP	Improved patient outcomes and care quality
Health chatbots	Offers patients information and symptom checking	NLP, ML and conversational AI	24/7 engagement and reduced healthcare workload

AI, artificial intelligence; CNN, convolutional neural network; DL, deep learning; DM, data mining; EHR, electronic health records; ML, machine learning; NLP, natural language processing.

powered by AI are being utilized to assist medical practitioners in clinical settings and ongoing research (Table I). Currently, clinical decision support and image analysis are the most commonly encountered applications of AI in medical contexts (3). Treatment, medication and other patient requirements are all addressed through clinical decision support systems, which provide clinicians with fast access to up-to-date information and research that is relevant to the patient's situation (3,16).

AI opens up an array of possibilities for the development of intelligent medical products, innovative services and new business models. There are numerous different types of AI technologies in medicine, spanning from virtual to physical. The ability of AI technologies to identify complex patterns and hidden structures has allowed image-based detection and diagnostic systems in healthcare to perform similarly or at times even better than a clinician in certain instances, according to recent research (17). Furthermore, clinical decision-support systems that are powered by AI have the potential to minimize human diagnostic errors, enhance decision-making support, increase reproducibility and assist physicians in making better use of data and documentation (18).

In medical imaging, for instance, AI technologies are being used to detect abnormalities that may otherwise be overlooked by a human radiologist in CT scans, X-rays, MRIs and other imaging systems (19). Several studies have already shown that AI can diagnose diseases as well as or better than humans.

Recent advances in AI have shown significant promise in medical diagnosis, particularly in the early detection of diseases. In a study conducted by Esteva *et al* (20) a DL-algorithm was developed and trained to identify skin cancer using images of skin lesions. The model achieved an accuracy comparable to that of certified dermatologists, with the ability to distinguish between malignant and benign skin lesions (20).

Another study by Abràmoff *et al* (21) conducted a pivotal study to evaluate the effectiveness of an autonomous AI system in detecting diabetic retinopathy (DR) from retinal images. DR is a leading cause of vision loss in adults, and early detection is crucial for preventing progression. Traditional screening methods require specialized ophthalmologists, which can be limited in accessibility, especially in primary care settings (21). In another study they created an AI model that achieved a sensitivity of over 90%, indicating a high true positive rate in detecting early DR. Specificity was also high, reducing the number of false positives and unnecessary referrals. Their AI model demonstrated high sensitivity and specificity, outperforming traditional diagnostic methods (21).

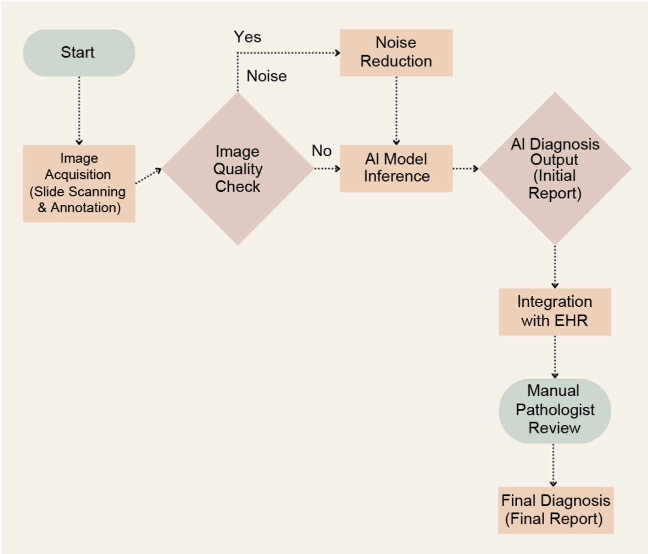

Figure 2. Workflow chart depicting the utilization of AI in digital pathology. AI, artificial intelligence; EHR, Electronic Health Record.

AI has exceeded radiologists in detecting tumors and has aided researchers in building cohorts for clinical studies (22). For instance, in a study conducted by Akselrod-Ballin *et al* (23), a breast cancer prediction algorithm trained on 38,444 mammography images from 9,611 women and integrated with related health data, was able to predict biopsy malignancy with an accuracy comparable to expert radiologists. This algorithm could distinguish between benign and malignant screening findings and had the potential to significantly reduce the number of missed breast cancer diagnose. Radiologists, oncologists and pathologists are poised to benefit from this synergy of AI, ML and DL, which has been trained on a dataset of integrated imaging and matched clinical records. It will assist them in improving diagnoses and could help in the early detection of diseases when intervention and treatment are most effective.

To investigate whether AI can reduce interval cancer in mammography screening, Lång *et al* (24) conducted a significant study on the use of artificial intelligence (AI) in mammography, which was published in The Lancet Digital Health in 2020 and further discussed in The Lancet Oncology in 2021. Their research focused on evaluating the effectiveness of AI in breast cancer screening programs by performing a study to analyze initial screening mammograms of 429 sequential cases of women diagnosed with interval cancer with a deep learning-based AI system. They found that the AI system was able to spot 19% of interval cancers at the preceding mammograms that showed negligible signs of malignancy. Of note, these malignancies were accurately located and ranked as 'high risk' by AI, thus avoiding additional screening.

Chaurasia *et al* (25) presented a breast cancer detection system based on three data mining techniques (RepTree, RBF Network and Simple Logistic). These algorithms were used to forecast the survival rate of breast cancer data collection. The three categorization methods were evaluated in order to determine which was the most accurate in predicting the cancer survival rate in another patient group.

Litjens *et al* (26) investigated the ability of DL to enhance histopathologic slide analysis objectivity. To evaluate the effectiveness of deep neural networks (DLN) in accurately detecting prostate cancer from digitized H&E-stained histopathology slides. Using DLN, the authors digitized histopathology in prostate cancer detection in biopsy specimens with good accuracy.

Weng *et al* (27) developed a prediction method for cardiovascular disease (CVD) utilizing ML on data collected from >350,000 individuals exhibiting symptoms of CVD and the dataset of 5,209 patients with CVD from the Framingham research, in which the Framingham risk score was experimentally tested and compared. They suggested a system that can predict the CVD risk with outstanding accuracy. The implementation of ML techniques has been shown to yield notable enhancements in the precision of CVD risk assessment. This results in a greater number of patients being identified as potential candidates for preventive treatment, while concurrently reducing the incidence of unnecessary treatment.

In the field of digital pathology, with integration of digital slides into the pathology workflow, advanced algorithms and computer-aided diagnostic techniques extend the frontiers of the pathologist's view beyond a microscopic slide and enable true utilization and integration of knowledge beyond human limits and boundaries. AI has already enabled pathologists to identify unique imaging markers associated with disease processes with the goal of improving early detection, determining prognosis and selecting treatments most likely to be effective. This allows pathologists to serve more patients while maintaining diagnostic and prognostic accuracy. Automated image analysis tools offer a higher level of precision and reliability in quantification compared to traditional light microscopy techniques. For instance, the utilization of computer-aided diagnosis is prevalent in the evaluation of estrogen and progesterone receptor and HER2/neu in breast cancer, Ki67 assessment in carcinoid tumors and various other clinical and research stains (28).

For digital slide analysis, Senaras *et al* (29) presented a new DL architecture, named DeepFocus™, which allows the automated detection of unclear areas in digital slides for rapid re-scan in order to enhance image quality for pathologists and image analysis algorithms. Janowczyk *et al* (30) introduced an open-source program called HistoQC to evaluate color histograms, brightness and contrast of each slide and to detect cohort-level outliers. These techniques have an important role in the quality control of whole-slide scans to standardize the quality of images in computational pathology (Fig. 2).

Niazi *et al* (31) employed DL techniques to detect tumor regions in pancreatic neuroendocrine tumors. Their methodology utilized transfer learning, a technique in which the characteristics of a pre-existing DL-algorithm that has been trained on a different classification task are adjusted and retrained to classify regions of tumors and stroma. Tumor cells exhibiting both Ki67 positivity and negativity were employed. Using AI, pathologists can now be relieved from the heavy manual annotations for each slide scan thanks to improvements in various smart image-recognition algorithms. Campanella *et al* used ML methods based on CNN and recurrent neural networks to evaluate programmed cell

Table II. Summary of studies on AI applications in healthcare.

Author(s), year	Title of study	Findings	(Refs.)
Esteva *et al*, 2017	Dermatologist-level classification of skin cancer with deep neural networks	Developed a deep learning algorithm that identifies skin cancer from images of skin lesions with accuracy comparable to certified dermatologists, effectively distinguishing between malignant and benign lesions.	(20)
Abràmoff *et al*, 2018	Pivotal trial of an autonomous AI-based diagnostic system for detection of diabetic retinopathy in primary care	Evaluated an autonomous AI system for detecting diabetic retinopathy from retinal images. The AI model achieved >90% sensitivity and high specificity, outperforming traditional diagnostic methods and reducing false positives and unnecessary referrals.	(21)
Akselrod-Ballin *et al*, 2019	Predicting breast cancer by applying deep learning to linked health records and mammograms	Created a breast cancer prediction algorithm trained on 38,444 mammography images and integrated health data from 9,611 women. The algorithm predicted biopsy malignancy with accuracy comparable to expert radiologists, potentially reducing missed breast cancer diagnoses.	(23)
Lång *et al*, 2020	Can artificial intelligence reduce the interval cancer rate in mammography screening?	Analyzed initial screening mammograms of 429 women diagnosed with interval cancer using an AI system. Found that AI could detect 19% of interval cancers in prior mammograms, accurately locating and ranking them as 'high risk', which could reduce missed diagnoses in screening programs.	(24)
Chaurasia *et al*, 2018	Data mining technique approach to predict breast cancer using machine learning	Presented a breast cancer detection system using three data mining techniques (RepTree, RBF Network and Simple Logistic) to forecast survival rates. Evaluated these methods to determine the most accurate in predicting cancer survival rates in different patient groups.	(25)
Litjens *et al*, 2016	Deep learning as a tool for increased accuracy and efficiency of histopathological diagnosis	Investigated the use of deep learning to enhance objectivity in histopathological slide analysis. Using deep neural networks, they achieved good accuracy in detecting prostate cancer from digitized H&E-stained histopathology slides, improving diagnostic precision.	(26)
Weng *et al*, 2017	Can machine-learning improve cardiovascular risk prediction using routine clinical data?	Developed a machine learning-based method for cardiovascular disease risk prediction using data from >350,000 individuals. Their system showed outstanding accuracy compared to traditional methods, identifying more candidates for preventive treatment while reducing unnecessary interventions.	(27)
Senaras *et al*, 2018	DeepFocus: Detection of out-of-focus regions in whole slide digital images using deep learning	Introduced DeepFocus™ , a deep learning architecture for automated detection of unclear areas in digital slides. This allows rapid re-scanning to enhance image quality for pathologists and image analysis algorithms, improving the overall efficiency of digital pathology workflows.	(29)
Janowczyk *et al*, 2019	HistoQC: An open-source quality control tool for digital pathology slides	Developed HistoQC, an open-source program that evaluates color histograms, brightness and contrast of each slide to detect cohort-level outliers. This tool plays a crucial role in the quality control of whole-slide scans, standardizing image quality in computational pathology.	(30)
Niazi *et al*, 2019	Leveraging transfer learning in deep neural networks for tumor classification using non-small cell lung cancer	Employed deep learning techniques with transfer learning to detect tumor regions in pancreatic neuroendocrine tumors. Adjusted a pre-existing deep learning algorithm to classify regions of tumors and	(31)

Table II. Continued.

Author(s), year	Title of study	Findings	(Refs.)
		stroma, using tumor cells exhibiting both Ki67 positivity and negativity, enhancing diagnostic accuracy.	
Campanella *et al*, 2019	Clinical-grade computational pathology using weakly supervised deep learning on whole slide images	Used machine learning methods based on convolutional neural networks and recurrent neural networks to evaluate PD-L1 expression in immunohistochemistry slides of late-stage non-small cell lung cancer specimens from needle biopsies, reducing manual annotation workload.	(32)

DR, diabetic retinopathy; DME, diabetic macular edemal CVD, cardiovascular disease; AI, artificial intelligence; ML, machine learning; DL, deep learning; PD-L1, programmed cell death ligand 1; IHC, immunohistochemistry; CNN, convolutional neural network; RNN, recurrent neural network.

death ligand-1 expression in immunohistochemistry slides of late-stage non-small cell lung cancer specimens from needle biopsies (32).

There are large volume of study and review on AI in healthcare highlighted the dominance of imaging-based specialties such as radiology, gastroenterology, and ophthalmology in AI research. A substantial portion of studies use deep learning (DL), with 75.2% of them focusing on image data. Large Language Models (LLMs) are gaining traction, particularly in general healthcare and surgery, suggesting a shift toward their broader application. The review suggests that future developments may involve multimodal models, enhancing both clinical and administrative aspects of healthcare through AI advancements. The above-mentioned studies are summarized in (Table II).

4. Challenges and opportunities of using AI for improving healthcare

Although the advantages of implementing AI in the healthcare industry are evident, there are noteworthy obstacles that require resolution. The following challenges are deemed to be of utmost significance: The ethical implications associated with the integration of AI technology, such as potential breaches of data privacy and confidentiality, informed consent and patient autonomy, must be addressed. In the realm of PM, AI, ML and BD analysis, establishing robust data protection regulations to effectively safeguard individual confidentiality, particularly for those receiving medical treatment, is crucial. Furthermore, the accurate analysis by AI algorithms heavily depends on the availability of large amounts of high-quality data. Healthcare data are often present in a fragmented manner, lacking interoperability and consistency, which leads to potential issues of completeness and accuracy. Ensuring the quality, accessibility and standardization of data poses significant obstacles.

The implementation of AI in healthcare decision-making processes raises a range of ethical questions. A conscientious examination of the transparency and accountability of AI algorithms, potential biases inherent in data and algorithms and the attribution of liability for AI-generated decisions is imperative. The dynamic nature of regulatory frameworks and guidelines aims to tackle these challenges. Furthermore, the process of integrating AI into pre-existing healthcare systems and workflows can be challenging. The successful implementation of AI technologies requires overcoming obstacles such as ensuring smooth integration and compatibility with legacy systems. Additional significant challenges to predict include healthcare system regulations that may limit the full potential of AI technology, as well as understanding the best practices for applying knowledge gained from AI in an ethical and optimal manner.

From a clinical perspective, a considerable issue for healthcare providers will be that they are no longer the sole authorities in medical treatment delivery. They must also respond to patients who, in certain cases, may have an understanding of their medical conditions comparable to that of the experts. Furthermore, healthcare providers may find themselves required to consider insights from an AI program that could be more knowledgeable in certain areas. Nonetheless, in both scenarios, it is the healthcare providers' responsibility to assess the information provided and administer the appropriate care, which may or may not align with the AI technology's recommendations.

5. Conclusion

AI has the potential to enhance healthcare service delivery in areas such as illness prevention, early diagnosis and treatment. The provision of health services is already undergoing a transformation. AI applications may be categorized based on the specific objectives they serve and the methods they employ to accomplish these goals. The integration of data from multiple sources, such as wearable devices, genetic information from genome sequencing, electronic health records, radiological imaging and even hospital rooms, has resulted in a surge of valuable data in healthcare.

For AI to directly impact and improve clinical care delivery, a corresponding evidence base is required to demonstrate improved outcomes and the absence of unintended consequences. For instance, validating the accuracy of AI-enabled imaging applications against current quality standards for conventional imaging may serve for clinical use. However, when AI applications extend to prediction, diagnosis and treatment, the evidence threshold should increase significantly, so that the wealth of information provides a fertile ground for AI systems to learn complex patterns, predict outcomes, and support decision-making processes that were previously beyond human capability.

Eventually, the integration of AI in healthcare poses potential benefits and challenges. Successful AI implementation requires addressing key issues such as data quality and accessibility, privacy and ethical considerations and seamless integration. Despite the challenges, the use of AI in healthcare can offer significant benefits, including improved diagnostic precision, personalized care, enhanced efficiency and accelerated medical research. As such, AI has become an invaluable asset in healthcare transformation and holds promise for improving patient outcomes. By adeptly navigating the challenges and leveraging the benefits, healthcare stakeholders can fully harness AI's capabilities to revolutionize healthcare services. Ethical considerations and human rights must be at the forefront of AI health technology design, development and deployment to benefit public health and medicine.

For AI to effectively integrate into healthcare systems, it is essential to eliminate existing biases encoded in the data used to train algorithms. Addressing the digital divide, or the unequal distribution of access the use of information and communication technologies is necessary. Global technology corporations are making substantial investments in data collection, big data algorithms and AI implementation. When used appropriately, AI has the potential to empower patients and communities to manage their healthcare and better understand their evolving needs. Of note, all of the revolutions seen today in AI are only the beginning.

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Authors' contributions

The author confirms sole responsibility for the following: Study conception and design, data collection and manuscript preparation. The author has read and approved the final manuscript. Data authentication is not applicable.

Ethics approval and consent to participate

Not applicable.

Patient consent for publication

Not applicable.

Competing interests

The author has no competing interests to declare.

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