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REVIEW PAPER

Innovating for tomorrow: industry 4.0's role in sustainable healthcare

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Abstract

Purpose It is essential for professionals to stay informed about the revolution we are witnessing and understand the related technical concepts in today's rapidly evolving society. In addition to exploring how Industry 4.0 technologies—such as artificial intelligence (AI), the Internet of Things (IoT), big data, and blockchain—are transforming the healthcare sector, this literature review aims to address a crucial question: *How can new technologies improve operational and environmental sustainability in healthcare while maintaining accessibility*, *safety*, *and equity?*

Methods A comprehensive literature study was conducted to analyze current research and discussions around the integration of Industry 4.0 technology in healthcare. This paper covers the various aspects of automation, data processing, system interconnection, ethical, financial, and infrastructure issues. Among the main topics discussed is data integration, which helps to enhance resource management, predictive analytics, and decision-making.

Results Through international case studies (Mayo Clinic, Cleveland Clinic, Manifal Hospital, University College London Hospitals, Charité Hospital, Mount Sinai Hospital, Centro Hospitalar e Universitário de Coimbra) this review shows how these technologies improve patient outcomes, healthcare efficiency, and the environment. Significant problems should be warned about, including ethical issues about patient data security and privacy, unequal access to technological developments, the necessity of guaranteeing health information system interoperability, and economic viability concerns, particularly in countries or regions with limited resources.

Conclusions Healthcare 4.0 has enormous potential for global justice and sustainability, but its ethical integrity, data security, and broad accessibility must be monitored. Although the healthcare sector will benefit much from the 4th industrial revolution, this analysis cautions about the related social and economic issues and inequalities. Encouraging ethical innovation will rely much on public policies to support this technological transition being implemented in a sustainable manner in the healthcare sector.

Keywords Industry 4.0 · Healthcare · Sustainability · Emerging technologies · Artificial intelligence

1 Introduction

The digital revolution of the 21st century, so-called Industry 4.0, defined by the convergence and integration of advanced technologies, is driving a profound transformation in healthcare, introducing the concept of "Healthcare 4.0" to establish efficient, personalized, and sustainable healthcare systems [1–3].

Industry 4.0 will have an impact on healthcare by improving operational effectiveness, care quality, and long-term sustainability. Aging population and rising rates of chronic diseases are stressing healthcare systems worldwide, so pursuing this objective is essential. To manage the rising expense of chronic diseases [4–6], innovative concepts for optimizing resources must be explored. By gathering and analyzing enormous amounts of data in real time

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to enhance diagnosis and treatment, digital transformation is also reshaping the healthcare industry [7, 8]. Real-time monitoring can be accomplished through online patient surveillance, which uses Internet of Things technology to collect physiological and biometric data, so it may be analyzed using artificial intelligence powered predictive analysis to enable early disease detection and patient-specific treatment [9]. Additionally, resource allocation and efficiency may be enhanced by these data-driven health strategies [3, 10]. Furthermore, applying AI to analyze population health data can help detect emerging public health patterns, anticipate illness waves, and lead the development of more efficient and long-term health policies [11]. The COVID-19 pandemic has speed up the healthcare sector's digital transformation, highlighting the urgent need for stronger and more adaptable healthcare systems [10–13]. It has been demonstrated that telemedicine, remote patient monitoring, resource and inventory logistics, and predictive analytics are essential tools for managing patient load and delivering care in unfavorable environments [3, 10]. This time frame demonstrated how Industry 4.0 technology could revolutionize healthcare during emergencies while contributing to the establishment of more sustainable and long-term healthcare systems.

1.1 Industry 4.0: key technologies involved

Industry 4.0 involves the integration of multiple foundational technologies that, when combined, allow industrial processes to be fully digitalized while simultaneously opening opportunities for efficiency and automation (Fig. 1).

Because it enables internet-based communication between machines, sensors, and systems, the **Internet of Things** (IoT) is essential to Industry 4.0. This makes possible to collect and share data in real time, which is required for the automation and optimization of industrial processes. IoT technology makes it possible to continuously monitor equipment, anticipate issues, and optimize processes while reducing costs [12–15]. Another technology used is called **Big Data**, which makes it easier to analyze large quantities of data. A key element of Industry 4.0 is big data analytics, which enables businesses to manage the enormous volumes of data produced by networked devices along with manufacturing procedures. This data is analyzed to detect trends, optimize processes, predict failures, and enhance product quality, resulting in smarter, more efficient operations [16, 17].

Artificial Intelligence (AI), in turn, enables Industry 4.0 systems to learn from data, make decisions on their own, and execute challenging tasks with exceptional accuracy. Predictive maintenance, supply chain management, and process automation are just a few of the many uses for AI. The ability of AI to evolve and adapt makes factories more resilient and efficient [17].

Concepts like **Machine Learning** (ML) and **Deep Learning** (DL) are commonly stated, and both refer to artificial intelligence. Artificial intelligence includes machine learning, which trains computers to find patterns in data and make predictions or decisions on their own without further programming; and those predictions and patterns can be found by machine learning models using statistical methods [18]. Deep learning is a subset of machine learning that uses multilayered neural networks to represent complex patterns in data. Insights from the structure and function of the human brain guide it [19, 20].

We cannot disregard **Advanced Robotics** since automation technology has advanced dramatically in Industry 4.0. Nowadays, automated machines can collaborate and learn new tasks quickly. This flexibility and mass customization allows producers to adapt swiftly to market needs [21].

Both **Cloud computing** and **Edge computing** provide the infrastructure needed to store and process large amounts of data. On the other hand, edge computing lets processing take place near the source of the data, therefore reducing latency and speeding up important processes. Operating efficiency and the need for real-time processing in Industry 4.0 depend on these technologies, which are therefore important [22].

As healthcare digitizes, protecting sensitive data becomes increasingly important. **Blockchain** has been incorporated into Industry 4.0 to provide transaction security and transparency in supply chains. In healthcare, it might securely store and exchange medical data, ensuring that only authorized users can access it [1, 2]. Healthcare data management could change with this technology, giving patients and professionals more confidence in digital system security. This technology also enables all parties involved in a transaction to verify and monitor the process in a safe and irreversible manner, enhancing confidence and lowering the risk of fraud [23].

2 Sustainable health services: concepts and importance

The concept of sustainable health combines public health promotion and environmental preservation, with the purpose of ensuring that current health practices are not compromising the resources and environment required for future generations' well-being. Sustainable health demands not only reducing but also preventing environmental effects as well as building an economically sustainable and socially fair healthcare system [24, 25]. The concept incorporates the idea that healthcare practices must respect the planet's ecological constraints, encouraging the effective use of natural resources and lowering the environmental impact of healthcare activities. Sustainable healthcare also aims to guarantee

Fig. 1 Main technologies of Industry 4.0

that all people have fair access to high-quality healthcare, regardless of their economic situation or geographic location, and in this regard, Industry 4.0 technologies will be rather significant.

3 Intersection between industry 4.0 and healthcare services

Industry 4.0 is transforming various economic areas, including healthcare. The convergence of The convergence of Industry 4.0 technologies and healthcare services is changing how care is provided, therefore making it more efficient, personalized/individualized, and sustainable.

3.1 Innovation in health services with industry 4.0

Significant advancements are being made in the healthcare sector as a result of the widespread use of Industry 4.0 technologies, such as IoT, AI, Big Data, advanced robotics, and Blockchain. The following sections will discuss each of these technologies, their pertinent applications in healthcare systems, and the benefits of their adoption.

3.1.1 IoT and smart sensors

IoT is playing an essential role in modernizing healthcare services, while enabling the integration of medical equipment and sensors, IoT has created a scenario in which patients' health data is collected and transmitted in real time. Wearable devices, such as heart rate monitors and glucose sensors, enable healthcare professionals to monitor patients both in the hospital and at home. Used together, both technologies offer faster and more individualized therapies, reduce hospitalization rates, and improve chronic disease management [12]. IoT also allows for the integration of data from several sources, therefore it might produce a complete and precise picture of a patient's health. This connectedness not only enhances clinical decision-making but also provides health care professionals with more thorough and up-to-date information, which leads to faster and more accurate diagnoses [15].

3.1.2 Big data and data analysis

Big data is another important Industry 4.0 technology changing the healthcare sector. Apart from spotting trends, big data analysis can predict illness outbreaks and improve treatments with customized medication for each individual patient. For instance, by analyzing genetic data and comparing medical records, it is possible to predict the likelihood of developing specific diseases and adopt preventative actions [16]. Since predictive analysis allows for better use of resources such as hospital beds, staff, and equipment, Big Data is also contributing significantly to hospital operational efficiency and leading to lower waste and increased efficiency [17, 26]. This optimization of resources not only improves the patient's experience but also lowers hospital running costs, ensuring the healthcare system's long-term viability.

3.1.3 Artificial intelligence (AI)

AI has become popular in healthcare, with applications ranging from diagnostics to hospital administration. AI-based technologies can analyze medical pictures, such as X-rays and MRIs (Magnetic Resonance Imaging), with far greater accuracy and speed than human radiologists, allowing for the early identification of illnesses like cancer [27, 28]. AI is also being employed to personalize therapies based on patient-specific data, which increases carer effectiveness while decreasing side effects [29, 30]. AI is also automating administrative tasks like appointment scheduling and electronic health record maintenance, allowing healthcare workers to focus on patient care and enhancing the healthcare system's efficiency [21].

While accumulating large volumes of unstructured data in their electronic health records, healthcare companies are now applying Machine learning (ML) for disease prediction, treatment, imaging, and drug development. By using natural language processing, machine learning reorganizes data into more organized collections, which permits healthcare professionals to quickly find useful information. Artificial intelligence and machine learning have also affected pharmaceutical company medicine research and development [31]. This approach has previously been used in clinical trials for the central nervous system, and drug companies are hopeful that machine learning will be able to predict how patients will react to treatments and who will benefit the most from the drug [32]. Moreover, telemedicine has taken advantage of the advantages of machine learning developments in healthcare; some machine learning companies are investigating how to capture data during virtual sessions to simplify processes and arrange patient information for healthcare professionals during telemedicine sessions. ML looks to be quite helpful for the healthcare industry. On the other hand, Deep Learning (DL) is widely used for the analysis of medical images, including MRIs and CT scans (Computed Tomography), facilitating the prompt and precise identification of health conditions [33]. Considering all these uses and benefits, Fig. 2 compiles a list of businesses applying machine learning in the healthcare sector.

Several healthcare organizations are using Machine Learning (ML) and Deep Learning (DL) technology to improve patient care (personalized treatment, fast data collection), operational efficiency (cost-efficient processes) and accelerated drug discovery and development. Notable examples include the Cleveland Clinic, Massachusetts General Hospital, Manipal Hospitals, and Children's Hospital Los Angeles (for more details read 6. Case studies). For instance, Massachusetts General Hospital enhances radiography and pathology diagnosis using NVIDIA's deep learning supercomputer and deep learning (DL). By educating neural networks on large volumes of medical image data [34], the hospital improves disease detection and treatment. Researchers at Children's Hospital of Los Angeles provide another interesting illustration; they are using DL models to improve treatment in pediatric intensive care units. Examining thorough health data helps the AI system to identify the optimal pharmacological treatments for critically unwell children, hence increasing patient outcomes [35]. These were only a handful of illustrations of how Machine learning and deep learning interact effectively with the Internet of Medical Things (IoMT), analyzing real-time data from linked devices to provide proactive healthcare.

3.1.4 Advanced robotics

Advanced robotics is transforming medical operations, while enabling more accurate and minimally invasive treatments. Surgical robots such as da Vinci give surgeons control and accuracy that exceed human limitations, resulting in fewer postoperative complications as well as shorter recovery periods [36, 37]. Hospitals are also using robotics to automate routine tasks like drug distribution and cleaning, therefore enhancing operational efficiency and reducing the risk of infection [38].

3.1.5 Blockchain

Blockchain technology is gaining importance within the healthcare sector, especially for the secure management of patient data, which is a main worry in the integration and interchange of personal information across several platforms and systems. This technology ensures that health records remain unchangeable and available only to authorized people, hence improving confidence in the healthcare system. Furthermore, Blockchain promotes interoperability among various healthcare systems, allowing for the safe and efficient flow of information between hospitals, clinics, and other healthcare entities [23]. Another significant application of Blockchain is medicine tracking, which aids fighting counterfeiting and ensures that patients receive genuine and safe products [39].

4 Benefits and challenges

While there are many advantages to integrating Industry 4.0 technologies in the healthcare sector, there are also challenges and obstacles that must be addressed to ensure that these integrations are successful.

4.1 Benefits

Improving healthcare quality is one of the key advantages of using Industry 4.0 technologies in healthcare. While IoT

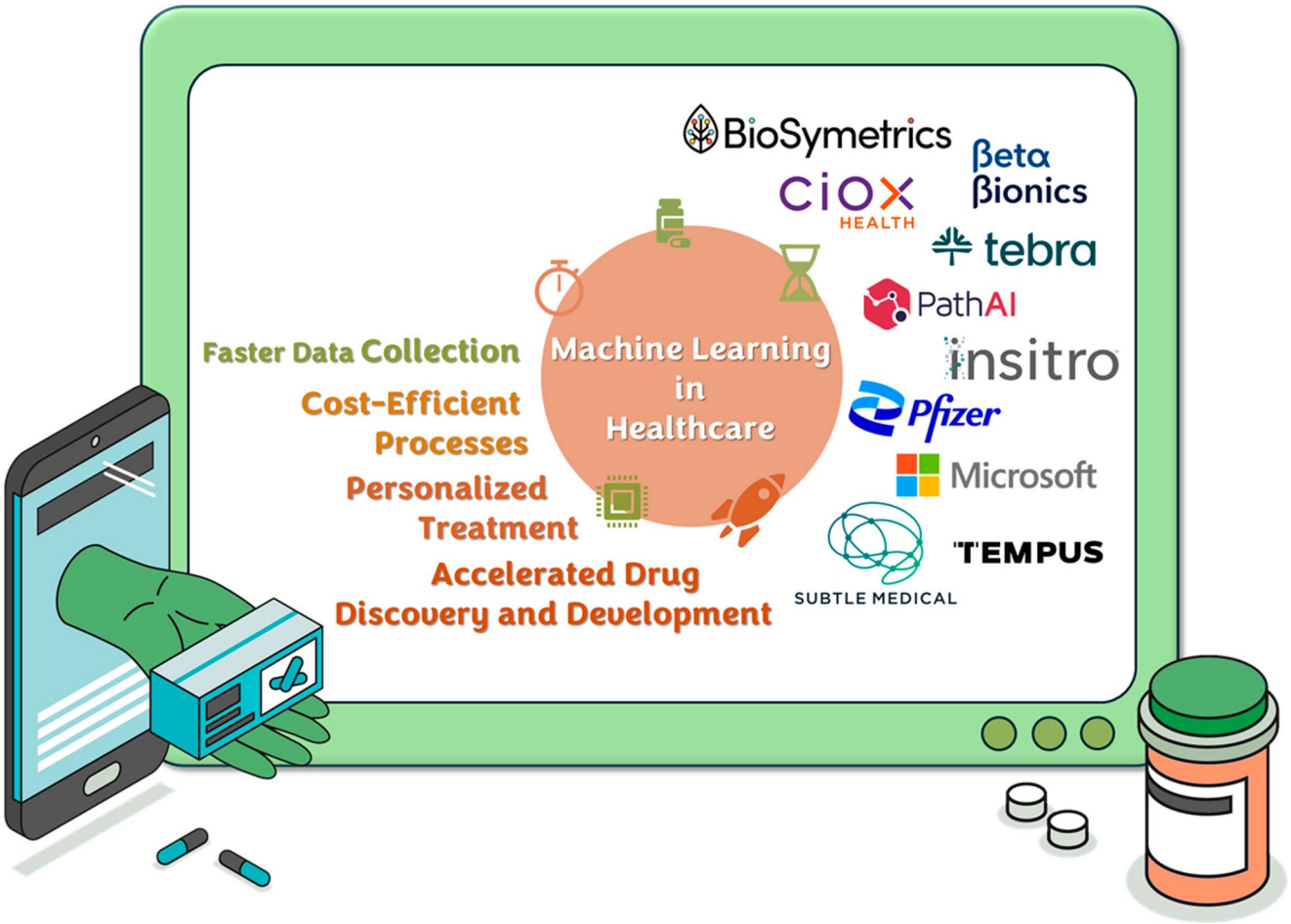

Fig. 2 Businesses applying machine learning in the healthcare sector

helps continuous patient monitoring, enabling faster and more personalized treatments, technologies like artificial intelligence offer accurate and faster diagnoses. Automating administrative and clinical tasks increases resource management and reduces the time set aside for manual procedures, hence greatly improving the operational efficiency of hospitals [21]. Improved resource use, including energy and materials, helps to sustain healthcare services by means of waste prevention as well. The sustainability of healthcare services is further enhanced through better resource utilization while minimizing waste. Big Data analytics may detect wasteful practices and facilitate the implementation of more sustainable solutions, enhancing a system's efficiency, cost-effectiveness, and environmental impact while providing high-quality patient care.

4.2 Challenges

Despite the numerous benefits that Industry 4.0 technologies offer to the healthcare sector, their integration presents significant challenges. The main obstacle is the substantial expense of their implementation. It costs a lot to protect and maintain technologies like AI, IoT, and complex advanced robots, and some hospitals and clinics may not be able to afford it, especially in areas with few resources [36, 40]. The expense of educating medical professionals on how to use this new technology is also a significant challenge. Another difficulty yet to overcome is the compatibility of systems. Industry 4.0 technologies require the integration of systems from several manufacturers and platforms and the absence of standardized protocols may restrict communication between devices and systems, compromising the effectiveness of existing solutions. Health systems must make investments in developing infrastructures that enable safe and efficient interoperability if they intend to maximize technology developments [23]. Patient data privacy must be given top priority given the growing digitization of health information and the application of technologies including IoT and blockchain, since data security and privacy are critically important issues. Cyberattacks on healthcare systems can result in severe repercussions, including disruptions in service and loss of patient confidence. Consequently, it

is essential for healthcare facilities to implement stringent cybersecurity protocols to safeguard sensitive information and maintain patient confidentiality [39]. Resistance to change constitutes another considerable challenge. Healthcare workers may be resistant to adopting new working techniques or may feel concerned that new technology could compromise their autonomy and participation in clinical decision-making. To overcome this reluctance, it is vital to engage in training and awareness initiatives that explain the benefits of new technology and include healthcare workers throughout the adoption process [41].

The ethical concerns associated with the use of AI and Big Data in healthcare are receiving more attention, since algorithm-based decision-making can generate issues about transparency, fairness, and responsibility. Students and teachers of health sciences are concerned about artificial intelligence safety, ethics, fraud, false information, and the necessity of professional oversight to deliver safe and correct healthcare. The appropriate integration of artificial intelligence technologies into healthcare education and practice may be questioned given students' and professors' inadequate expertise and training in artificial intelligence [42, 43]. Another example is the use of AI for patient triage may unintentionally propagate existing biases if the data on which it is based is not properly filtered and evaluated [27]. Therefore, it should develop and employ AI-based solutions with a significant focus on ethical issues and patient rights. Current solutions could become outdated if Industry 4.0 technology expands quickly. Healthcare companies must create long-term strategies to maintain their systems updated, and new technologies must be integrated continuously and efficiently [29, 44].

4.3 Impact on the quality and efficiency of health services

Industry 4.0 technologies have already significantly influenced and will continue to enhance the quality and efficiency of healthcare services. The use of AI for enhanced accuracy and individualized diagnoses is markedly diminishing medical mistakes and elevating clinical outcomes for patients. Furthermore, ongoing surveillance facilitated by IoT enhances the treatment of chronic diseases, thereby reducing the necessity for emergency interventions and extended hospital stays [12]. The automation of administrative and clinical procedures has enhanced the efficiency of healthcare services. Automation liberates healthcare workers to concentrate on direct patient care while enhancing resource management, including hospital bed occupancy and procedure scheduling, hence increasing operational efficiency and reducing costs [16]. On the other hand, the integration of Big Data and AI in hospital management has allowed a better allocation of resources by predicting demand and optimizing the use of materials and human resources. This approach has contributed to a significant reduction in waste and greater sustainability of the health system, both in economic and environmental terms [16]. It is also important to note that advanced robotics is improving the quality of healthcare services, especially in fields such as surgery, where robots enable greater precision, reduce the risk of complications and accelerate patient recovery [36, 38]. Additionally, through the use of robots for performing repetitive tasks, hospitals can improve patient and healthcare worker safety and hygiene while reducing the risk of hospital-acquired infections [37]. Blockchain improves the security of healthcare data by preventing unauthorized access to patient data and safeguarding the accuracy of health records. This technology not only promotes collaboration across various healthcare groups, but it additionally allows safer information exchange and better care coordination possible [23]. The convergence of Industry 4.0 and healthcare services is significantly changing how care is delivered, hence enhancing service quality and efficiency and helping the sector's sustainability. Still, if these technologies are to reach their full potential, challenges including costs of installation, data security, systems compatibility, change aversion, and ethical concerns must be solved. As hospitals and clinics keep adopting Industry 4.0 innovations, it will be crucial to ensure that the technologies are used ethically and responsibly, particularly in terms of improving patient care and long-term sustainability.

5 Relationship between industry 4.0, health and sustainability

The revolution called Healthcare 4.0 represents a potential to restructure and enhance healthcare services with an emphasis on sustainability (Fig. 3). Exploring these technologies can provide enhanced efficiency and efficacy in care delivery, as well as a more sustainable approach from both environmental and economic perspectives.

5.1 Industry 4.0 and operational efficiency in healthcare

The operational efficiency of healthcare services is significantly impacted by Industry 4.0. For instance, the Internet of Things allows medical equipment to interconnect within a digital network, thereby enabling real-time data collection and analysis. Remote monitoring helps to improve patient monitoring by means of remote monitoring, hence decreasing the necessity for frequent hospital visits. This interconnection using IoT, not only minimizes healthcare

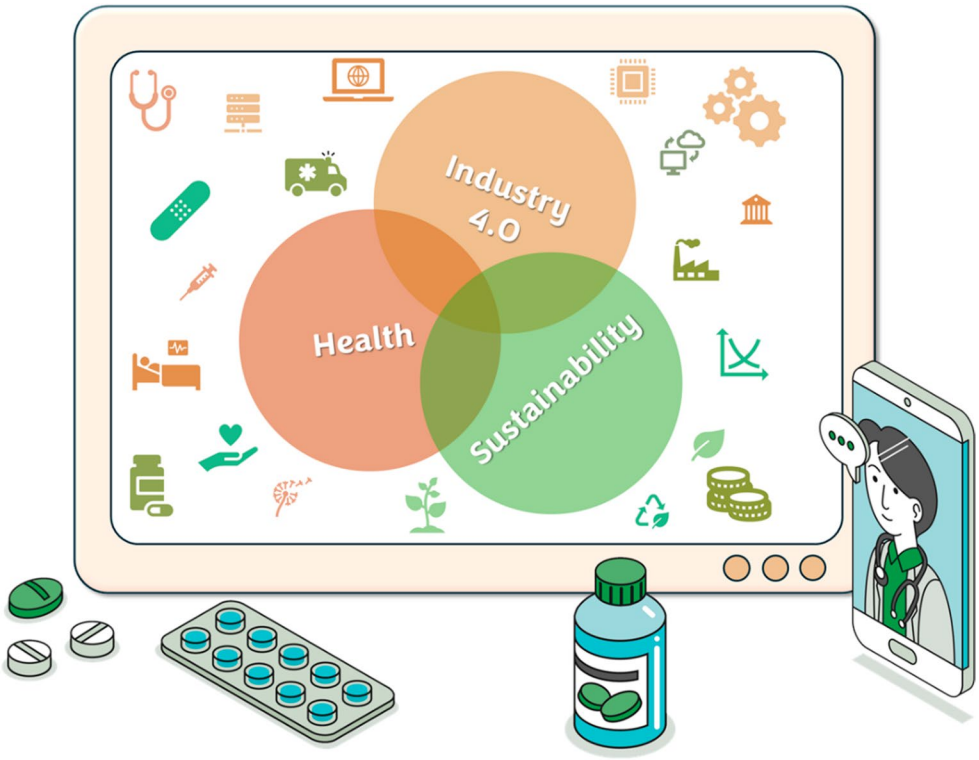

Fig. 3 Interconnection of Industry 4.0, Health, and Sustainability

consumable waste and drug waste but enables personalized treatment and resources optimization, and needless physical infrastructure usage as well [12, 26]. Otherwise, enhanced robots are changing medical procedures through artificial intelligence and automation, improving surgical accuracy and speeding up patient recovery. A clear example is surgical robots, which enhance precision and reduce the likelihood of postoperative complications. Shorter recovery durations reduce the demand for hospital beds and other resources, therefore supporting the operational and financial viability of health systems [38].

5.2 Environmental sustainability and healthcare 4.0

Environmental sustainability is another important issue in Healthcare 4.0 discussions. Technologies of Industry 4.0 can enable medical facilities to be more environmentally friendly. By enabling healthcare organizations to make data-driven decisions, Big Data helps to optimize the use of water and energy resources. By means of resource management optimization, these technologies allow reduce the energy consumption of healthcare infrastructure and hospital material waste [16].

Telemedicine and remote patient monitoring have been also making significant contributions to environmental sustainability [45]. These digital solutions help healthcare workers and patients to travel less, consequently lowering carbon footprints. Additionally, less people visiting hospitals and clinics relieve pressure on physical infrastructure, hence reducing the need for ongoing building of medical facilities [36, 38]. These technologies not only improve healthcare access but also encourage more environmentally friendly practices, hence aligning the sector with sustainable development objectives.

Still a major issue is the handling of hospital-generated waste. Regarding waste management, the use of blockchain technology allows for the tracking and appropriate disposal of hazardous substances and materials. Transparency ensures that hospitals engage with environmentally friendly procedures, lowers the likelihood of process failures, and ensures that hospital records can be traced [23].

5.3 Equity and accessibility

Social sustainability in the healthcare sector is guaranteeing equity and access for everyone. Telemedicine, which offers remote medical consultations, allows more people to receive treatments without traveling great distances, in isolated regions and among disadvantaged groups, and plays its role and has been crucial for enhancing access to healthcare and therefore lowering inequalities in healthcare access [45, 46]. By offering health information, promoting health, and enhancing service delivery, mobile connectivity helps to improve health outcomes in lower middle-income countries [46]. Affordable internet, reliable network coverage,

and mobile phone ownership might enhance health access and habits as well. Through an assistant mobile app, online, USSD (Unstructured Supplementary Service Data) and SMS (Short Message Service) to underprivileged and rural areas in Cameroon, GiftedMom provides pregnant women and nursing mothers health information recommendations and monitoring services; broad mobile ownership and inexpensive mobile internet make this possible [46].

Artificial Intelligence also plays an important role in fostering equity, because it can reliably identify diseases in the early stages in big populations. This enables faster and perhaps cheaper interventions, which is critical to guaranteeing the healthcare system's financial sustainability while still offering quality services to all segments of the population [29]. Furthermore, the personalized healthcare enabled by modern technologies allows each patient to get therapies tailored to their unique needs without significantly increasing operational costs. This is a major move toward guaranteeing that healthcare systems can offer sustainable high-quality treatments.

6 Case studies

Several healthcare institutions worldwide are using Industry 4.0 technology with outstanding quality, efficiency, and sustainability results. Next case studies briefly outlined how these technologies are being used and their benefits:

Mayo Clinic, EUA

The Mayo Clinic has been at the forefront of employing AI and Big Data technology to enhance diagnostic precision and tailor treatments [47–49]. Using AI to examine electrocardiograms (ECGs) is an example of this innovation, as it helps detect cardiac arrhythmias early with the same level of accuracy as specialists [48]. The implementation of these technologies enhances care quality while reducing the necessity for supplementary examinations and fostering a more efficient allocation of hospital resources. At the same time, cloud computing collaboration with Google makes it easier to manage clinical data, which also improves energy efficiency and lessens its impact on the environment [49].

Cleveland Clinic, EUA

The Machine Learning Arthroplasty Laboratory (MLAL) was established in 2018 at the Cleveland Clinic's Department of Orthopaedic Surgery. Its goal was to study important issues more deeply and see if machine learning could be used in musculoskeletal medicine to improve patient-specific, value-based care and human mobility [50]. In collaboration with Microsoft, Cleveland Clinic have been using machine learning algorithms to identify patients at high risk of cardiac arrest. The system can predict the need for treatments like vasopressors by means of patient vitals and laboratorial data, hence enhancing the health of patients [51–53]. The use of AI algorithms to predict the risk of readmission for heart failure patients has enabled more effective preventive interventions, resulting in better hospital resource management and fewer readmissions. This optimized process has resulted in more efficient use of hospital beds, lower energy consumption, and a more sustainable approach to healthcare [54, 55].

Manifal Hospital, India

In 2015, the Manifal Hospital introduced IBM's Watson for Oncology observed a significant difference in diagnoses between the clinical staff (multidisciplinary team) and Watson's judgment using datasets of 1000 cancer patients, including breast, colorectal, rectal, and lung cancer, collected over three years by two doctors. The agreement between Watson's treatment recommendations and physicians' recommendations varied by cancer type, matching in 85% of rectal cancer cases but only 17.8% of lung cancer cases [56]. IBM's Watson improves individualized care by comparing patient data to a huge repository of medical literature to suggest evidence-based therapies [29, 56, 57].

University College London Hospitals (UCLH), UK

Shorter hospital stays and less consumption of energy and water have resulted from UCLH's use of AI to enhance image diagnosis and customize treatments to each patient's needs [58]. Assisted robotics are being used in minimally invasive surgeries and have significantly reduced the use of disposable materials such as bottles and towels, promoting more sustainable and ecological practices in hospitals [58]. UCLH have also implemented an information retrieval and extraction platform. CogStack greatly improves the ability to collect and analyze unstructured data in electronic health records. For example, the CogStack platform handles unstructured healthcare data from electronic health records to help doctors make decisions, do research, and run their businesses more efficiently. At the same time, natural language processing gives doctors information about diagnoses, patient risks, and health trends [59]. Along with UCLH, DeepMind also collaborated to develop an algorithm to identify head and neck cancer using CT and MRI [60, 61]. Nikolov *et al*. have also demonstrated the generalizability of their model by evaluating it on patients from diverse geographies, demographics, and scanning techniques. A segmentation system that is as accurate as experts could speed

up, improve, and standardize the radiation process, which would lead to better patient outcomes [61].

Charité Hospital, Germany

Berlin's Charité Hospital, one of the largest university hospitals in Europe, has been pioneering technical innovations in the medical field. In cooperation with the European TEF-Health project, Charité has used AI and Big Data-based solutions to optimize hospital management, thereby increasing efficiency and reducing material waste. By using AI algorithms to forecast disease outbreaks, the hospital can minimize its energy and environmental impact while managing resources more effectively during medical emergencies [62, 63]. Charité's creative partnership with the BMW Group to research the intersection between automotive technology and healthcare is another interesting example. The automotive and healthcare industries can now work together more effectively thanks to AI, connected vehicles, and the digitization of healthcare [64].

Mount Sinai Hospital, EUA

Mount Sinai Hospital has used artificial intelligence to improve the efficiency of cardiovascular disease detection. Using computed tomography, Mount Sinai Hospital uses AI to more accurately identify arterial plaques, hence reducing diagnosis time and eliminating the need for follow-up tests. By reducing energy and material use, this efficiency helps the hospital's sustainability as well as the good use of resources. This efficient diagnostic method allows more sustainable and ecologically friendly hospital operations [65, 66]. Mount Sinai researchers were among the first in the United States to use artificial intelligence with imaging and clinical data to investigate COVID-19 patients. By analyzing the virus's expression in chest CT scans, an algorithm was created to quickly identify it, hence encouraging faster diagnosis and patient isolation during the epidemic [67, 68].

Centro Hospitalar e Universitário de Coimbra (CHUC), Portugal

In Portugal, CHUC adopted sustainable practices by integrating robotics and AI in minimally invasive procedures, leading to reduced reliance on throwaway materials and enhanced optimization of hospital resources. A research team from the Faculty of Medicine of the University of Coimbra (FMUC), in collaboration with CHUC and the University of Buffalo (USA), is creating an AI-driven algorithm to aid in the assessment of kidney biopsies from dead donors during organ retrieval. The goal is to reduce organ waste and increase the precision of donor kidney evaluations, thereby mitigating the organ shortage [69]. The hospital employs energy management systems with intelligent sensors to control electricity consumption in real time, thereby enhancing energy resource efficiency and significantly reducing the institution's ecological footprint [70]. Table 1 resumes how Industry 4.0 is being implemented in several examples of hospital institutions.

7 Conclusions, challenges and final considerations

Although there are still recognizable challenges to overcome, Industry 4.0 technologies represent a big step forward for health and sustainability. Among the most crucial questions and concerns is patient data privacy. More healthcare organizations embrace digital technologies, which increases the likelihood of data breaches and consequently decreases trust among consumers. Implementing these new technologies is challenging, and safeguarding client data is essential. Blockchain is considered a viable solution to this problem since it guarantees safe and transparent medical data management, despite ongoing technological and practical.

Interoperability among healthcare systems and technologies is another issue. Conflicting standards and IT systems make it difficult for healthcare institutions to adopt Industry 4.0. Fragmentation might decrease operating efficiency, therefore compromising these developments in healthcare quality and environmental advantages. Technology developers, medical professionals, and policymakers must collaborate to design and establish standard protocols that enable healthcare system integration and interoperability to get ahead of this challenge.

Another major challenge is the economic viability of implementing these technologies. In many circumstances, healthcare organizations face significant costs when implementing AI, IoT, or big data technologies, particularly in countries or regions with limited resources. However, the long-term benefits outweigh the early costs, so governments and health organizations must ensure that public policies supporting this technological transition are implemented sustainably.

In the healthcare sector, the integration of Industry 4.0 technological advances is more than simply a digital transformation of procedures; it also represents an important opportunity to improve environmental, social, and economic sustainability in this sector. The review of the literature revealed that technological developments such as Artificial Intelligence, Internet of Things, Big Data, Advanced Robotics, and Blockchain are redefining healthcare paradigms by not only enhancing healthcare quality but also optimizing efficiency and helping to lower the ecological footprint of health systems.

Table 1 Examples of Healthcare facilities using Industry 4.0 technologies and benefits

Healthcare facility (Country)	Example of Technology implemented	Benefits
Mayo Clinic (EUA)	• Remote Diagnostic and Management Platform • Home Hospital Platform • Computer-Aided Diagnosis (CAD) Technology • Mayo Clinic Cloud	• Improved accuracy and efficiency in clinical decision-making • Enhanced patient experience through remote care options • Accelerated medical research and innovation • Reduced costs through optimized resource allocation
Cleveland Clinic (EUA)	• Integration of f Microsoft's digital assistant Cortana • AI-Assisted System • Adoption of machine learning algorithms to detect patients at increased risk of cardiac arrest	• Improved accuracy and efficiency in clinical decision-making through predictive analytics • Enhanced patient experience through early intervention and personalized care • Increased operational efficiency through optimized resource allocation • Reduced costs through streamlined workflows and improved care coordination • Improved accuracy in diagnosis and treatment • Enhanced patient experience through personalized care and early intervention • Increased efficiency in clinical decision-making
Manifal Hospital (India)	• Clinical Decision Support System • Predictive Analytics • Image Analysis	• Improved Diagnostic Accuracy • Enhanced Patient Outcomes • Operational Efficiency
University College London Hospitals (UK)	• Image diagnosis • Natural Language Processing for clinical documentation, streamlining the process of recording patient information • Predictive Analytics	• Improved Diagnostic Accuracy • Enhanced Patient Flow • Increased Patient Satisfaction • Support personalized decision-making by healthcare professionals
Charité Hospital (Germany)	• Charité Lab for Artificial Intelligence in Medicine (CLAIM) • Machine and deep learning models across various medical fields • AI and robotics into healthcare (TEF-Health project)	• Support personalized decision-making by healthcare professionals • Ensure safety and efficacy • Improve diagnostics, treatment, and overall patient care • Increased Patient Safety and Reduced Errors • Accelerated Research and Innovation • Cost Savings and Healthcare Accessibility • Advancements in Robotics and Wearable Technology
Mount Sinai Hospital (EUA)	• AI in Emergency Room Admission Decisions • AI in COVID-19 Detection and to predict disease outbreaks • computerised tomography	• Enhanced diagnostics and early disease detection • Improved emergency care and decision support • Increased efficiency and reduced administrative burden • Enhanced patient experience through early intervention and personalized care • Enhanced patient flow • support mental health and emotional well-being • Cost savings and optimized resource allocation
Centro Hospitalar e Universitário de Coimbra (Portugal)	• Robotics and AI in minimally invasive procedures - Portuguese consortium of the TEF-Health Project • Intelligent sensors to control electricity consumption • AI-Based Clinical Decision Support Systems • AI-driven algorithms	• Improved diagnosis accuracy • Enhanced patient care: Increased efficiency. • Reduce organ waste • Increase the accuracy of donor kidney assessments • Enhanced data analysis • Enhanced energy resource efficiency • Reduced ecological footprint

Equally important is the economic efficiency these technologies generate. Especially in resource-limited regions, Industry 4.0 technologies minimize costs over time and make healthcare more sustainable and accessible by improving treatment accuracy and reducing consumption of resources.

In healthcare, using Industry 4.0 technologies offers a particular opportunity to increase operational efficiency, reduce environmental impact, promote equitable access to treatment, and minimize waste, hence making the industry more sustainable. Fair use of technology advancements and a balanced approach to ethical and economic issues help to fully fulfill all these possibilities. While firmly maintaining commitments to environmental, social, and economic sustainability, the success of this change depends on health systems' ability to adapt to an emerging technological reality. Through a purposeful and sustainable framework, Industry 4.0 possesses the capacity to enhance healthcare while fostering a more equitable and sustainable future for all.

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Code availability Not applicable.

Declarations

Ethical approval No ethics approval was required for this study.

Consent to publish All authors consent to the publishing of the manuscript.

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Conflict of interest The authors declare that they have no conflict of interest.

References

1. Kitsios F, Kapetaneas N. Digital transformation in healthcare 4.0: critical factors for business intelligence systems. Information. 2022;13:247. https://doi.org/10.3390/info13050247.
2. Nwobodo-Anyadiegwu E, Tambwe DB, Lumbwe AK. The integration of industry 4.0 in healthcare quality improvement. 2022 IEEE 28th Int Conf Eng Technol Innov (ICE/ITMC) 31st Int Association Manage Technol (IAMOT) Joint Conf. 2022;1–6. https://doi.org/10.1109/ice/itmc-iamot55089.2022.10033265.
3. Hines P, Tortorella GL, Antony J, Romero D. Lean industry 4.0: Past, present, and future. Qual Manage J. 2023;30:64–88. https://doi.org/10.1080/10686967.2022.2144786.
4. Husnain A, Hussain HK, Shahroz HM, Ali M, Hayat Y. A precision health initiative for chronic conditions: design and cohort study utilizing wearable Technology, machine learning, and deep learning. Int J Adv Eng Technol Innovations. 2024;1(2):118–39. https://ijaeti.com/index.php/Journal/article/view/183.
5. Nwosu NNT. Reducing operational costs in healthcare through advanced BI tools and data integration. World J Adv Res Reviews. 2024;22:1144–56. https://doi.org/10.30574/wjarr.2024.22.3.1774.
6. Omaghomi NTT, Elufioye NOA, Ogugua NJO, Daraojimba NAI, Akomolafe NO. Innovations in hospital management: a review. Int Med Sci Res J. 2024;4:224–34. https://doi.org/10.51594/imsrj.v4i2.820.
7. Ghosh K, Dohan MS, Veldandi H, Garfield M. Digital transformation in healthcare: insights on value creation. J Comput Inform Syst. 2022;63:449–59. https://doi.org/10.1080/08874417.2022.2070798.
8. Stoumpos AI, Kitsios F, Talias MA. Digital transformation in healthcare: technology acceptance and its applications. Int J Environ Res Public Health. 2023;20:3407. https://doi.org/10.3390/ijerph20043407.
9. Yaqub MZ, Alsabban A. Industry-4.0-Enabled digital transformation: Prospects, instruments, challenges, and implications for business strategies. Sustainability. 2023;15:8553. https://doi.org/10.3390/su15118553.
10. Chen C, Loh E-W, Kuo KN, Tam K-W. The Times they Are a-Changin' – Healthcare 4.0 Is Coming! J Med Syst. 2019. https://doi.org/10.1007/s10916-019-1513-0.
11. Osama M, Ateya AA, Sayed MS, Hammad M, Pławiak P, El-Latif AaA, et al. Internet of medical things and healthcare 4.0: trends, requirements, challenges, and research directions. Sensors. 2023;23:7435. https://doi.org/10.3390/s23177435.
12. Lew SQ, Ronco C. Use of eHealth and remote patient monitoring: a tool to support home dialysis patients, with an emphasis on peritoneal dialysis. Clin Kidney J. 2024;17:i53-61. https://doi.org/10.1093/ckj/sfae081.
13. Newcombe V, Coats T, Dark P, Gordon A, Harris S, McAuley DF, Menon DK, Price S, Puthucheary Z, Singer M. The future of acute and emergency care. Future Healthc J. 2021;8(2):e230–6. https://doi.org/10.7861/fhj.2021-0097.
14. Da Xu L, He W, Li S. Internet of things in industries: a survey. IEEE Trans Ind Inform. 2014;10:2233–43. https://doi.org/10.1109/tii.2014.2300753.

15. Li S, Da Xu L, Zhao S. 5G internet of things: a survey. J Ind Inf Integr. 2018;10:1–9. https://doi.org/10.1016/j.jii.2018.01.005.
16. Wang G, Gunasekaran A, Ngai EWT, Papadopoulos T. Big data analytics in logistics and supply chain management: certain investigations for research and applications. Int J Prod Econ. 2016;176:98–110. https://doi.org/10.1016/j.ijpe.2016.03.014.
17. Lee J, Kao H-A, Yang S. Service innovation and smart analytics for industry 4.0 and big data environment. Procedia CIRP. 2014;16:3–8. https://doi.org/10.1016/j.procir.2014.02.001.
18. Ahsan MM, Gupta KD, Islam MM, Sen S, Rahman ML, Hossain MS. COVID-19 symptoms detection based on NasNetMobile with explainable AI using various imaging modalities. Mach Learn Knowl Extr. 2020;2:490–504. https://doi.org/10.3390/make2040027.
19. Grapov D, Fahrmann J, Wanichthanarak K, Khoomrung S. Rise of deep learning for genomic, proteomic, and metabolomic data integration in precision medicine. OMICS a Journal of Integrative Biology. 2018;22:630–6. https://doi.org/10.1089/omi.2018.0097.
20. Hammad M, El-Latif AaA, Hussain A, El-Samie FEA, Gupta BB, Ugail H, et al. Deep learning models for arrhythmia detection in IoT healthcare applications. Computers & Electrical Engineering. 2022;100:108011. https://doi.org/10.1016/j.compeleceng.2022.108011.
21. Schuh G, Gartzen T, Rodenhauser T, Marks A. Promoting work-based learning through industry 4.0. Procedia CIRP. 2015;32:82–7. https://doi.org/10.1016/j.procir.2015.02.213.
22. Sadeghi AR, Wachsmann C, Waidner M. Security and privacy challenges in industrial internet of things. *Proceedings of the 52nd Annual Design Automation Conference (DAC'15)*, San Francisco, CA, USA, 7–11 June 2015; ACM: New York, NY, USA, (2015) 1–6. https://doi.org/10.1145/2744769.2747942
23. Nofer M, Gomber P, Hinz O, Schiereck D. Blockchain. Business & Information Systems Engineering. 2017;59:183–7. https://doi.org/10.1007/s12599-017-0467-3.
24. Bauer SE, Tsigaridis K, Faluvegi G, Kelley M, Lo KK, Miller RL, et al. Historical (1850–2014) aerosol evolution and role on climate forcing using the GISS ModelE2.1 contribution to CMIP6. J Adv Model Earth Syst. 2020. https://doi.org/10.1029/2019ms001978.
25. Afjal M, Trivedi J. Greening healthcare: exploring economic and ecological synergies in the pursuit of net-zero carbon futures. Sustain Futures. 2024;8:100381. https://doi.org/10.1016/j.sftr.2024.100381.
26. Kirişci M, Kuzu S, Kablan A. The handling of healthcare waste analysis with an interval-valued Fermatean fuzzy-based decision-making technique. Sustain Futures. 2025;100581. https://doi.org/10.1016/j.sftr.2025.100581.
27. Schmidt-Erfurth U, Sadeghipour A, Gerendas BS, Waldstein SM, Bogunović H. Artificial intelligence in retina. Prog Retin Eye Res. 2018;67:1–29. https://doi.org/10.1016/j.preteyeres.2018.07.004.
28. Wang C-P, Yeh Y-C, Chen J-C, Lee C-Y. Boosting predictive accuracy in tumor cellularity evaluation with AI-powered ensemble methods. Health Technol. 2025. https://doi.org/10.1007/s12553-025-00965-9.
29. Topol E. (2019). *Deep Medicine: How Artificial Intelligence Can Make Healthcare Human Again*. New York, NY: Basic Books. ISBN 9781541644632.
30. Davenport T, Kalakota R. The potential for artificial intelligence in healthcare. Future Healthc J. 2019;6(2):94–8. https://doi.org/10.7861/futurehosp.6-2-94.
31. Kumar Y, Koul A, Singla R, Ijaz MF. Artificial intelligence in disease diagnosis: a systematic literature review, synthesizing framework and future research agenda. Journal of Ambient Intelligence and Humanized Computing. 2022;14:8459–86. https://doi.org/10.1007/s12652-021-03612-z.
32. Vatansever S, Schlessinger A, Wacker D, Kaniskan HÜ, Jin J, Zhou M, et al. Artificial intelligence and machine learning-aided drug discovery in central nervous system diseases: state-of-the-arts and future directions. Med Res Rev. 2020;41:1427–73. https://doi.org/10.1002/med.21764.
33. Roy S, Meena T, Lim S-J. Demystifying supervised learning in Healthcare 4.0: a new reality of transforming diagnostic medicine. Diagnostics. 2022;12:2549. https://doi.org/10.3390/diagnostics12102549.
34. Peng Z, Fang X, Yan P, Shan H, Liu T, Pei X, et al. A method of rapid quantification of patient-specific organ doses for CT using deep-learning-based multi-organ segmentation and GPU-accelerated Monte Carlo dose computing. Med Phys. 2020;47:2526–36. https://doi.org/10.1002/mp.14131.
35. Winter MC, Ledbetter DR. Predicting time to death after withdrawal of life-sustaining treatment in children. Crit Care Explor. 2022;4:e0764. https://doi.org/10.1097/cce.0000000000000764.
36. Reddy K, Gharde P, Tayade H, Patil M, Reddy LS, Surya D. Advancements in robotic surgery: a comprehensive overview of current utilizations and upcoming frontiers. Cureus. 2023. https://doi.org/10.7759/cureus.50415.
37. Mohan A, Wara UU, Shaikh MTA, Rahman RM, Zaidi ZA. Telesurgery and robotics: an improved and efficient era. Cureus. 2021. https://doi.org/10.7759/cureus.14124.
38. Bogue R. Robots in healthcare. Industrial Robot: An International Journal. 2011;38:218–23. https://doi.org/10.1108/01439911111122699.
39. Kshetri N. Can blockchain strengthen the internet of things? IT Prof. 2017;19:68–72. https://doi.org/10.1109/mitp.2017.3051335.
40. Bajwa J, Munir U, Nori A, Williams B. Artificial intelligence in healthcare: transforming the practice of medicine. Future Healthc J. 2021;8:e188–94. https://doi.org/10.7861/fhj.2021-0095.
41. World Health Organization. A conceptual framework for action on the social determinants of health. World Health Organization. (Consulted on September 24th, 2024). 2010 https://iris.who.int/handle/10665/44489
42. Choukou M-A, Alkhamis MA, Syed-Abdul S, Alshawaf H, Alfadhli S. Perspectives on the use of artificial intelligence: an online survey of health sciences students and faculty members. Health Technol. 2024;15:53–65. https://doi.org/10.1007/s12553-024-00908-w.
43. Sibiya SE, Hurchund R, Omondi B, Owira P. Artificial intelligence for digital healthcare in the low and medium income countries. Health Technol. 2025;15:323–32. https://doi.org/10.1007/s12553-025-00950-2.
44. Carey S, Pang A, De Kamps M. Fairness in AI for healthcare. Future Healthc J. 2024;11(3):100177. https://doi.org/10.1016/j.fhj.2024.100177.
45. Sadrul S, Noushin N. Alternative mode of health service delivery. Sustainable Futures. 2021;3:100055. https://doi.org/10.1016/j.sftr.2021.100055.
46. Poulsen A, Hickie IB, Alam M, Wilson CE, LaMonica HM. Access to mobile health in lower middle-income countries: a review. Health Technol. 2025;15:333–43. https://doi.org/10.1007/s12553-025-00948-w.
47. Brereton TA, Malik MM, Rost LM, Ohde JW, Zheng L, Jose KA, et al. AIMedReport: a prototype tool to facilitate research reporting and translation of artificial intelligence technologies in health care. Mayo Clin Proc Digit Health. 2024;2:246–51. https://doi.org/10.1016/j.mcpdig.2024.03.008.
48. Suppah M, Roehl K, Lew K, Arsanjani R, Lester S, Ommen S, et al. Assessment of positive cardiac remodeling in hypertrophic obstructive cardiomyopathy using an Artificial Intelligence–based electrocardiographic platform in patients treated with Mavacamten. Mayo Clin Proc Digit Health. 2024;2:255–7. https://doi.org/10.1016/j.mcpdig.2024.04.002.
49. Abdelhameed A, Bhangu H, Feng J, Li F, Hu X, Patel P, et al. Deep learning–based prediction modeling of major adverse

cardiovascular events after liver transplantation. Mayo Clin Proc Digit Health. 2024;2:221–30. https://doi.org/10.1016/j.mcpdig.2024.03.005.
50. Ramkumar PN, Haeberle HS, Bloomfield MR, Schaffer JL, Kamath AF, Patterson BM, et al. Artificial intelligence and arthroplasty at a single institution: real-world applications of machine learning to big data, value-based care, mobile health, and remote patient monitoring. J Arthroplasty. 2019;34:2204–9. https://doi.org/10.1016/j.arth.2019.06.018.
51. Perumal R, Kaladevi AC. Early prediction of coronary heart disease from Cleveland dataset using machine learning techniques. Int J Adv Sci Technol. 2020;29(6):4225–34.
52. Shrestha D. Advanced machine learning techniques for predicting heart disease: a comparative analysis using the Cleveland heart disease dataset. Appl Med Inform. 2024;46(3):91–102. https://ami.info.umfcluj.ro/index.php/AMI/article/view/1060
53. Rahman A, Debnath T, Kundu D, Khan MSI, Aishi AA, Sazzad S, Sayduzzaman M, Band SS. Machine learning and deep learning-based approach in smart healthcare: recent advances, applications, challenges and opportunities. AIMS Public Health. 2024;11:58–109. https://doi.org/10.3934/publichealth.2024004.
54. Lee D, Yoon SN. Application of artificial intelligence-based technologies in the healthcare industry: opportunities and challenges. Int J Environ Res Public Health. 2021;18:271. https://doi.org/10.3390/ijerph18010271.
55. Helm JM, Swiergosz AM, Haeberle HS, Karnuta JM, Schaffer JL, Krebs VE, Spitzer AI, Ramkumar PN. Machine learning and artificial intelligence: definitions, applications, and future directions. Curr Rev Musculoskelet Med. 2020;13:69–76. https://doi.org/10.1007/s12178-020-09600-8.
56. Somasherkhar SP, Kumar R, Kumar A, Patil P, Rauthan A. 551PD validation study to assess performance of IBM cognitive computing system Watson for oncology with manipal multidisciplinary tumour board for 1000 consecutive cases: an Indian experience. Ann Oncol. 2016;27:1–2. https://doi.org/10.1093/annonc/mdw601.002.
57. Somashekhar SP, Sepúlveda M-J, Norden AD, Rauthan A, Arun K, Patil P, Ethadka RY, Kumar RC. Early experience with IBM Watson for oncology (WFO) cognitive computing system for lung and colorectal cancer treatment. J Clin Oncol. 2017;35:8527. https://doi.org/10.1200/jco.2017.35.15_suppl.8527.
58. Chand M, Ramachandran N, Stoyanov D, Lovat L. Robotics, artificial intelligence and distributed ledgers in surgery: data is key! Tech Coloproctol. 2018;22:645–8. https://doi.org/10.1007/s10151-018-1847-5.
59. Noor K, Roguski L, Bai X, Handy A, Klapaukh R, Folarin A, Romao L, Matteson J, Lea N, Zhu L, Asselbergs FW, Wong WK, Shah A, Dobson RJ. Deployment of a Free-Text analytics platform at a UK National health service research hospital: CogStack at university college London hospitals. JMIR Med Inf. 2022;10:e38122. https://doi.org/10.2196/38122.
60. Wong SH, Al-Hasani H, Alam Z, Alam A. Artificial intelligence in radiology: how will we be affected? Eur Radiol. 2018;29:141–3. https://doi.org/10.1007/s00330-018-5644-3.
61. Nikolov S, Blackwell S, Zverovitch A, Mendes R, Livne M, De Fauw J, Patel Y, Meyer C, Askham H, Romera-Paredes B, Kelly C, Karthikesalingam A, Chu C, Carnell D, Boon C, D'Souza D, Moinuddin SA, Garie B, McQuinlan Y, Ireland S, Hampton K, Fuller K, Montgomery H, Rees G, Suleyman M, Back T, Hughes CO, Ledsam JR, Ronneberger O. Clinically applicable segmentation of head and neck anatomy for radiotherapy: deep learning algorithm development and validation study. J Med Internet Res. 2021;23:e26151. https://doi.org/10.2196/26151.
62. Bürger VK, Amann J, Bui CKT, Fehr J, Madai VI. The unmet promise of trustworthy AI in healthcare: why we fail at clinical translation. Front Digit Health. 2024. https://doi.org/10.3389/fdgth.2024.1279629.
63. Amann J, Vayena E, Ormond KE, Frey D, Madai VI, Blasimme A. Expectations and attitudes towards medical artificial intelligence: A qualitative study in the field of stroke. PLoS ONE. 2023;18:e0279088. https://doi.org/10.1371/journal.pone.0279088.
64. Roy ERR, Wibawa ED, Sentosa GA, Riza IW. Success indicators of international corporate research cooperation: case study of collaboration between BMW Group and Toyota Motor Corporation 2011. Global Conference on Business and Social Sciences Proceeding. 2023;15(1):29. https://doi.org/10.35609/gcbssproceeding.2023.1(29).
65. Shameer K, Johnson KW, Yahi A, Miotto R, Li L, Ricks D, Jebakaran J, Kovatch P, Sengupta PP, Gelijns S, Moskovitz A, Darrow B, David DL, Kasarskis A, Tatonetti NP, Pinney S, Dudley JT. Predictive modeling of hospital readmission rates using electronic medical Record-wide machine learning: a Case-study using Mount Sinai heart failure cohort. Biocomputing. 2016. https://doi.org/10.1142/9789813207813_0027.
66. Levin MA, Kia A, Timsina P, Cheng F-Y, Nguyen K-A-N, Kohli-Seth R, Lin H-M, Ouyang Y, Freeman R, Reich DL. Real-Time machine learning alerts to prevent escalation of care: a nonrandomized clustered pragmatic clinical trial*. Crit Care Med. 2024;52:1007–20. https://doi.org/10.1097/ccm.0000000000006243.
67. Robert P, Hirten I, Ensari YS, Kim M, Danieletto M, Zweig K, Landell LJ, Shaw ZA, Fayad. An AI Doctor on your wrist: wearable devices to monitor health and disease, frontiers of medical research: artificial intelligence. Washington, DC: in TBA (Science/AAAS; 2023. pp. 17–8. https://www.science.org/do/10.1126/resource.adm6778/full/icahn_booklet_2023_11_10-1718906666370.pdf.
68. Mei X, Lee H-C, Diao K-Y, Huang M, Lin B, Liu C, Xie Z, Ma Y, Robson PM, Chung M, Bernheim A, Mani V, Calcagno C, Li K, Li S, Shan H, Lv J, Zhao T, Xia J, Long Q, Steinberger S, Jacobi A, Deyer T, Luksza M, Liu F, Little BP, Fayad ZA, Yang Y. Artificial intelligence–enabled rapid diagnosis of patients with COVID-19. Nat Med. 2020;26:1224–8. https://doi.org/10.1038/s41591-020-0931-3.
69. Rodrigues L, Sarder P, Jen K-Y, Ginley B, Pratas J, Sousa V, Figueiredo A, Alves R. The rediscovery of nephropathology with artificial intelligence. Portuguese J Nephrol Hypertens. 2021;34. https://doi.org/10.32932/pjnh.2021.01.096.
70. Amaral MJ, Amaral M, Freitas J, Oliveira RC, Serôdio M, Cipriano MA, Tralhão JG, Tumor stroma area and other prognostic factors in pancreatic ductal adenocarcinoma patients submitted to surgery,. (2023) 655. https://doi.org/10.3390/diagnostics13040655.