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REVIEW

Advances in Nano-BioElectronics, Robotic Surgery, and Technologies for Medical and Healthcare

Ali Soltani Sharif Abadi [*], ***Agata Koguciuk***, ***Mateusz Jangas***, ***Patryk Korycki***, ***Katarzyna Tylicka***, ***Piotr Targos***

Institute of Electronic Systems, Faculty of Electronics and Information Technology, Warsaw University of Technology, Warsaw 00-661, Poland

ABSTRACT

The convergence of electronics and digital technologies with healthcare has revolutionized medical services, enhancing patient care, streamlining operations, and expanding access to critical resources. Over the years, groundbreaking innovations in medical devices, diagnostic tools, remote health monitoring, telemedicine, and electronic health records (EHRs) have significantly improved healthcare efficiency and patient outcomes. These advancements have not only optimized clinical workflows but also facilitated the widespread dissemination of medical knowledge, making healthcare more accessible and data-driven. A thorough exploration of electronic applications in medicine is essential to understanding their transformative impact and future potential. This review provides an in-depth analysis of recent progress in medical electronics and digital health technologies, examining key developments, current applications, and emerging trends. The discussion encompasses vital topics such as wearable health technologies, smart sensors, robotic-assisted surgery, the role of digital tools during the COVID-19 pandemic, the Medical Internet of Things (M-IoT), electronic health record systems, the influence of social media and digital platforms, and the rise of mobile health applications. The review paper presents recent electronic technologies in the medical and healthcare fields and compares them across various aspects. Each section offers a comparative evaluation or detailed assessment of various innovations, highlighting their functionalities, advantages, and challenges in modern healthcare.

Keywords: Robotic Surgery; Bioelectronics; M-IoT; Wearable Technologies; COVID-19

*CORRESPONDING AUTHOR:

Ali Soltani Sharif Abadi, Institute of Electronic Systems, Faculty of Electronics and Information Technology, Warsaw University of Technology, Warsaw 00-661, Poland; Email: ali.abadi@pw.edu.pl

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1. Introduction

The intersection of electronics, digital technologies, and medicine has ushered in a transformative era in healthcare, enabling a shift from reactive to proactive care, enhancing diagnostics, and promoting personalized medicine. Over the last decades, advances in computing power, sensor technology, wireless communication, and artificial intelligence (AI) have converged to revolutionize medical practices and improve patient outcomes. These technologies have been instrumental in bridging gaps in healthcare accessibility, optimizing treatment protocols, and supporting clinical decision-making processes [1–3]. Their integration has not only streamlined hospital operations but also introduced new paradigms of remote and real-time patient monitoring, which are vital in managing chronic diseases and aging populations.

Among the most notable developments is the proliferation of wearable devices and smart sensors, which facilitate continuous monitoring of physiological parameters such as heart rate, blood oxygen saturation, and glucose levels. These devices empower patients with real-time feedback, promoting preventive health behaviors while allowing clinicians to intervene earlier in disease progression [4,5]. Simultaneously, robotic-assisted surgical systems and AI-driven diagnostic tools have enhanced precision, reduced procedural risks, and contributed to shorter recovery times [6]. These innovations exemplify the integration of mechanical, electronic, and computational elements in delivering safer and more efficient medical interventions.

Another critical advancement lies in the widespread adoption of electronic health records (EHRs), which has reshaped how patient data is stored, accessed, and shared across healthcare systems. EHRs have improved care coordination, reduced medical errors, and enabled data-driven policy and research initiatives. Likewise, telemedicine has emerged as a viable alternative to in-person consultations, particularly in underserved or rural areas, offering convenience and lowering healthcare costs. These tools gained unprecedented relevance during the COVID-19 pandemic, when rapid, digital responses were essential in maintaining care delivery amid global disruptions [7–9].

The concept of the Medical Internet of Things (M-IoT) has further extended the digital transformation in healthcare. M-IoT involves interconnected devices and systems that collect, analyze, and transmit health-related data, contributing to predictive analytics and remote care models. This interconnectedness, combined with mobile health (mHealth) applications and the growing role of social media in health promotion, has led to a more engaged and informed patient population. These tools also facilitate large-scale epidemiological studies and provide real-time health trend data, enabling a more agile public health response [10–12].

Given the breadth and depth of innovations in medical electronics and digital health technologies, it is imperative to conduct a comprehensive review of their current landscape, practical applications, and potential challenges. This paper aims to provide a critical analysis of key digital health trends, from wearable technologies and robotic-assisted surgery to the M-IoT and mobile health platforms. By evaluating their operational mechanisms, clinical implications, and societal impact, this review seeks to highlight how these technologies are shaping the future of healthcare delivery and research.

2. Nano-BioElectronics

In the electronic drug delivery systems section, nanobioelectronics was already mentioned as a futuristic way of treating epilepsy. This is only one of the various applications of this quickly expanding and developing field. For clarity and simplicity of the topic, we can define bioelectronics as a combination of biological system signals converted into electronic impulses, which a program can interpret. Those signals are sent, for example, by neurons and cardiomyocytes as ionic currents. The “nano” prefix refers to the microscopic scale of materials used during measurements (and plenty of other operations), such as nanoparticles, nanotubes, nanowires, and nanosheets. Structures described in this article are characterized by various dimensions. Zero-dimensional structures have no dimensions, resembling points without width, length, or height. One-dimensional structures primarily extend along a single dimension, appearing as lines or wires. Two-dimensional structures, on the other hand, primarily expand across two dimensions.

2.1. Nanowires and Nanoparticles – Description and Application

Nanowires are one-dimensional structures with diameters from 3 to 500nm, and they are particularly interesting as electronics based on them allow cell electrophysiology to be monitored [13]. It is crucial in understanding neurons and cardiomyocyte activity. Generally, nanowires can be created using various techniques and divided into bottom-up and top-down. The top-down approach focuses on the accurate control of nanowires through a series of fabrication processes developed in the semiconductor industry, including lithographic patterning, reactive ion etching, and ion implantation. The bottom-up approach to nanowires is not as limited as the top-down approach. Thanks to its simultaneous control of geometric shapes and atomic composition, it can lead to new device ideas [14]. On the other hand, nanoparticles are zero-dimensional spherical polymeric particles composed of natural or artificial polymers with a similar size to nanowires [15]. They were previously mentioned as the “material” used in epilepsy treatment. In this case, their application has been reduced to acting as a very delicate sensor. Phenytoin drug molecules were loaded into polymer nanoparticles during polymerization through noncovalent interactions with polypyrrole and polydopamine. After linking those two polymers, hybrid nanoparticles have become very sensitive to electrical impulses, rapidly releasing antiepileptic drugs in response to epileptic discharges [16].

2.2. Silicon Nanowire Field Effect Transistors in Biotechnology

Semiconductors are, so far, one of the most essential products in electronics. One of the most commonly known ways of controlling the current flow in semiconductors is using a field effect transistor (FET). The reason behind this is that with a tiny size, it can control the current flow by applying voltage on the gate, which alters the conductivity between the drain and the source. For years, 16 nm and 10nm fin field effect transistors (FinFETs) were mass-produced and used in everyday electronics. However, FinFETs struggled to control complementary metal-oxide-semiconductor (CMOS) technology due to compatibility with the design principles of CMOS circuits. That was one of the reasons why, in some cases, there was a requirement to exchange them for silicon nanowire field effect transistors (SiNWFETs) [17]. The gate-all-around (GAA) NW FET design aims for meticulous regulation of electron flow within its silicon core, mitigating leakage current at remarkably brief gate lengths yet ensuring ample drive current via stacked NWs. SiNWs have been commonly used as ion transducers in biosensors for medical applications since 2001, when they were reported by Lieber’s group [18]. Their massive use in nucleic acid and protein detection could also be noticed, which is essential for diagnosing diseases, screening drugs, and studying proteomics. As research advances, SiNW-based biosensors have the potential to transform medical diagnostics and personalized healthcare, catalyzing additional innovation within the field.

2.3. Nanocarbon as a Futuristic Approach to Bioelectronics

Nanocarbon is a term used to refer to the connection between carbon and nanotubes. It has been a fascinating material for many scientists due to its superior mechanical, electrical, chemical, and thermal properties [19,20]. Carbon nanotubes, with impressive properties like high thermal conductivity and surface area, find applications in electronics, electrodes, and drug delivery. However, to maintain their unique qualities at scale, it’s crucial to organize Nanocarbon structures effectively, which could be achieved through aligned films, yarn, fibers, and three-dimensional microarchitectures [21]. They find various applications in bioelectronics, such as recording and stimulating neuronal activity. These materials encourage the growth of neurons, conduct electricity, and shape into capacitive electrochemical electrodes with exceptionally high specific surface areas [22]. With all the properties mentioned above, they are ideally suited for neuronal interfacing. This is possible due to the concept of multi-electrode arrays, a significant development in carbon nanotube technology. Devices based on them consist of an array of electrically conducting microelectrodes (typically 20–200 μm in diameter) connected to an external circuitry to allow recording or stimulation of neural electrical activity [22]. The most crucial disadvantage of carbon nanotubes and the reason for their relatively slow development are nanotoxicity mechanisms, which could lead to serious health issues. There have been plenty of in vivo and in vitro studies of carbon nanotubes [23], which are still discovering the potential dangers of this technology.

2.4. Comparison Between Different Nano-Biotechnologies

Every approach to bioengineering uses nanotechnology differently. Some are often used together in more significant projects to archive everything each technology offers. The comparison of their most significant differences is shown in T**able 1**.

Table 1. Nano Structures Comparison.

	Dimensions of structures	Materials	Most important properties	Application
Nanoparticles	Zero-dimensional	Metals, semiconductors, oxides	High surface area-to-volume ratio	Mostly drug delivery and cancer therapy
Nanowires	One-dimensional	Metals, metal oxides, polymers	Can be synthesized with precise control over dimensions	Silicon FET transistors, disease diagnosis, screening drugs, studying proteomics
Nanotubes	Two-dimensional	Carbon	High aspect ratios, high tensile strength, and excellent electrical conductivity	Biosensors, which are recording and stimulating neuronal activity and drug delivery

3. Robotic Surgery Systems

Robotic surgery is among the most advanced forms of Minimally Invasive Surgery. The integration of robotic technology into surgical practices began almost 40 years ago. In the late 1980s [24], Imperial College in London developed a robotic system called PROBOT to assist with transurethral prostatectomies. This system employs a computer-generated 3D model of the prostate, enabling the surgeon to specify the areas for resection. PROBOT then calculates the excision paths and autonomously executes the procedure. Its key benefits include a compact design, high cutting precision, and the reduction of surgeon fatigue during operations.

Various robotic surgery systems are available, such as the da Vinci Surgical System, which is used for prostatectomies and is increasingly employed for cardiac valve repairs as well as renal and gynecologic procedures. Robotic surgeries are not only on those parts of the human body, they can also be used for eye surgeries. Robotic eye surgery, especially for delicate procedures involving the anterior segment and vitreoretinal areas, uses advanced systems to boost precision, minimize tremors, and automate tasks [25,26]. This technology not only improves surgical outcomes but also makes remote operations possible.

The Da Vinci Surgical System and other surgical robots will be discussed in greater detail, highlighting their different applications. A standard robotic surgery system includes three main parts: the surgical cart, the vision cart, and the surgeon's console [27]. Surgical manipulators are divided into master manipulators (located on the surgeon's side) and slave manipulators (located on the patient's side). At the control console, the surgeon views images from an endoscopic camera and uses master manipulators to guide surgical instruments and the endoscopic manipulator inside the patient's body, with the patient-side manipulators mirroring the surgeon's movements. In each case, the surgical cart and robotic arms are positioned on the same side of the surgical site. The operator, assistants, and nurses are also on this side, while the surgical cart and vision cart are on the opposite side, allowing the operator to see the same 2-dimensional monitor as the other staff members to enhance teamwork [27]. A suitable, robust, and fast control algorithm is very important in the surgical systems [28–31].

3.1. Da Vinci Surgical System

With more than 10,000 peer-reviewed publications in several surgical specialties, the safety and association of Da Vinci Surgical Systems with favorable patient outcomes have been proven repeatedly [32]. It is, without a doubt, the leader in the robotic surgical field. The remarkable success of this robotic platform can be attributed to its three-dimensional (3D) visualization, seven degrees of motion, motion scaling, and tremor filtration. These advanced features collectively enable highly precise performance of increasingly complex surgeries. However, the platform does have some drawbacks, including the absence of haptic feedback, a limited variety of instruments, and, most notably, its high cost. Those costs are the biggest downside of robotic surgeries. Studies show that considering maintenance, disposable instruments, the initial investment in a robotic system, and the length of stay in the hospital, robotic surgery systems are more expensive than standard surgeries, up to 1600$ per procedure [33]. In this article, those costs relate to the Da Vinci Surgical System and every other robotic surgery system. Despite the high initial costs, robotic surgery should not be viewed negatively. Costs are decreasing yearly while the precision and effectiveness of operations are continually improving. This is particularly visible in recent Da Vinci Single-Port Robotic Surgery advancements for gynecologic tumors. Single-port surgery, a minimally invasive technique using a single entry point, typically provides better cosmetic outcomes and improved patient satisfaction. Although it presents technical challenges such as limited instrument movement, collisions, and poor visualization, it has significantly reduced the time of various gynecological surgeries and minimized average blood loss and changes in hemoglobin levels [34]. Da Vinci Surgical System has also proven to be very useful and an excellent improvement for hospitals in fields other than gynecology, like urology or cardiology.

3.2. Versius

This robotic surgery system is a new futuristic approach with a modular design and dual-console capability, allowing two surgeons to operate in different anatomical fields simultaneously and independently [32]. The Versius system's modular design allows for various port placements, providing adequate surgical access and reach and enhancing its usability in a range of minimally invasive surgeries [35]. It is proven very effective in procedures like cholecystectomies, radical nephrectomies, and trans-anal total mesorectal excision. The system's flexibility and portability allow adequate surgical access to critical areas within the retroperitoneum and pelvis [36]. Unlike the Da Vinci system, which has limitations such as the need for redocking and the inability to complete specific procedures synchronously, the Versius system allows for fully synchronous dual-field robotic surgeries.

3.3. Senhance

Senhance is a relatively new robotic surgery system with outstanding results in gynecological and abdominal surgery with 3 mm instruments [37]. Its independent arms, which can reposition and install instruments easily sterilized again, set it apart from other robotic surgery systems. Examining 223 patients undergoing colectomy and proctectomy with the Senhance robot [38], the study assessed primary outcomes such as intraoperative efficacy, conversion rates, and estimated blood loss. Secondary outcomes were centered on postoperative morbidity and length of hospital stay. The research revealed a decline in operative times with increasing experience, suggesting a learning curve for the surgical team. These instruments work with 5-mm trocars and can be set up like in traditional laparoscopy, making the transition smooth and familiar for surgical teams. Despite its advantages, the Senhance system requires an initial learning curve and presents challenges such as limited space for the assistant surgeon and high costs [39].

3.4. Comparison Between Various Robotic Surgery Systems

As shown above, Da Vinci is undoubtedly the leader in robotic surgical systems, with plenty of benefits and few disadvantages. Versius and Senhence surgical systems have a promising future according to how new those systems are and how promising their current results are. A comparison between all of the discussed surgical systems is shown in **Table 2**.

Table 2. Robotic Surgery Systems Differences.

	Da Vinci	Versius	Senhence
Advantages	3D visualization, seven degrees of motion, motion scaling, tremor filtration, proven safety, and favorable outcomes in multiple surgical specialties	Modular design, dual-console capability, flexible port placements, enhanced usability in various surgeries, effective in synchronous dual-field surgeries	3 mm instruments, independent arms, instruments easily sterilized, smooth transition from traditional laparoscopy
Disadvantages	Absence of haptic feedback, limited variety of instruments	Potential for high costs, still relatively new, requiring further validation in diverse procedures	Initial learning curve, limited space for assistant surgeon, high cost
Operations Performed	Gynecologic surgeries, urologic surgeries, cardiologic surgeries, general surgeries with increasing complexity	Cholecystectomies, radical nephrectomies, trans-anal total mesorectal excision, and other minimally invasive surgeries	Gynecological surgeries, abdominal surgeries, colectomy, proctectomy
Technological Differences	Three-dimensional (3D) visualization, seven degrees of motion, single-port surgery advancements	Modular design allowing various port placements, dual-console capability for simultaneous operations in different anatomical fields	Independent arms for instrument repositioning, use of 5-mm trocars similar to traditional laparoscopy

4. Smartphones Applications

Smartphones are the most commonly used mobile computers in our current civilization. Such an environment encourages the usage of smartphones in every aspect of today's world. With such a mobile device, access to the internet also allows one to improve knowledge, stay updated with news, and keep in touch with other people. The medical field benefits from this technology thanks to the internet and many mobile applications that help doctors, technicians, patients, nurses, and even everyday people. The usage of smartphone applications in medicine can be divided into three groups according to their purpose: education, diagnosis, and assistance. Each group can be divided further into the receiving group, which consists of lay users and professionals.

4.1. Smartphone Applications in Education

The first group is applications that help students and trainees learn. For example, many quiz apps that check knowledge in anatomy, pharmacology, etc. Another is "Medical Encyclopedia," a comprehensive medical reference from the University of Maryland Medical Center. Apps such as "Pubmed" contain thousands of articles with citations and abstracts that keep up with the growing number of scientific publications [40]. Despite their popularity, there is no unambiguous evidence of their effectiveness in improving student academic performance [41]. The studies showed that the group accessing smartphone applications had increased scores, but the statistical significance was not reached [41]. It shows that even though smartphone applications are popular, their usage might improve the overall knowledge of lay users and not necessarily professionals.

4.2. Smartphone Applications in Diagnosis

The second group of smartphone applications aids in diagnosing and treating diseases. "Medscape" is one such application that describes symptoms, their cause, and suggested treatment. Most of the applications from this category are directed to lay users. Their goal is to save people time and money, soothe anxiety, educate, and make people aware of what is happening to them and what they should do [42]. It is important to seek that information from trusted sources and not to search your symptoms online and base your diagnosis solely on the information found there. The studies show that roughly 42% of Google symptoms give an incorrect diagnosis [43].

4.3. Smartphone Applications in Assistance

The last group can be further divided into two categories: lay users and professionals. Assistance applications for lay users help in daily life. "Samsung Health," for example, helps keep track of your sleeping schedule, number of steps taken that day, calories eaten, and water drunk. All this can help maintain a healthy lifestyle and be taken even further by connecting the app with a smartwatch that can track many more things like heartbeat, blood pressure, or stress levels. Wearable devices are a massive step towards digitalizing your physical health. On the other hand, many applications are meant to assist with your mental health. Unfortunately, this field is far more complex. Many mental disorders and traumas are very individual, and it is quite a challenge to create a universal application that would suit a large number of people. A few applications try to improve users' mental self-care, though their ratings are often very extreme [44]. The field of mobile mental health still has a long way to go, but shortly, we might see more of them on the market [44].

On the professional side, there is a concern about the common usage of smartphone applications [45]. There is a discussion about ethics. Awareness about the risks should be widely spread as unsafe usage of those applications can lead to infractions of the code of health professional ethics. Studies conducted in Saudi Arabia published in 2019 show that only 42.3% of healthcare workers utilize smartphones in healthcare practice [46]. Only 6.1% of all healthcare providers use mobile applications frequently, and 26.2% use them sometimes. These studies show that the most common reason for professionals to use these apps is to check drug information (69.8%), diagnose (56.4%), and access medical websites (42.5%).

4.4. Deep Learning

Some applications use Deep Learning for more complex problems. Thanks to its learning ability, it can be used to interpret photos. One of the possibilities is plant recognition. There are thousands of plants; some have medical properties, and some are poisonous. That's why it is essential to know which is which. An application called "MedicPlant" uses deep learning to recognize seventy medicinal plants [47]. It has an educational value and can also help people who hike and need help recognizing plants they discover. Professionals commonly use Deep learning structures to interpret and detect malaria parasites or skin cancer based on pictures alone [48,49]. However, it is mainly used on a more complex computer than a smartphone and can achieve a 94.74% accuracy [49].

4.5. A Review of Medical Smartphone Applications

As stated in previous paragraphs, many applications are meant strictly for professionals and medical personnel. That is why only some of the applications discussed earlier are available to everyone. **Table 3** provides a summary and short description of applications available to every user.

Table 3. A Review of Available Applications for Everyone.

Application	Description
Medical Encyclopedia	A medical reference from the University of Maryland Medical Center
Pubmed	A collection of thousands of articles with citations and abstracts
Medscape	A wellness app that helps diagnose, treat, and suggest healthy habits
Samsung Health	An everyday assistance app that keeps track of your activities and habits
PsyberGuide	Mental health app that helps with maintaining your stress and provides several exercises like meditation
MedicPlant	DL app that recognizes medical plants based on pictures of them
MedCalc	A calculator with a wide array of medical formulas and scores
Quick LabRef	An app that allows to look up information on the most commonly used clinical laboratory values
WomanLogCalendar	An app for women that helps keep track of a menstrual and fertility calendar
My pregnancy today	An app that contains a guide on pregnancy and offers advice and answers that pregnant women need

5. Virtual Reality (VR)

Researchers in the field of medicine have been using simulations for years [50,51]. For decades, those simulations were nothing more than an experienced surgeon performing and explaining the procedure. It massively limited the number of viewers and depended on the older doctors' presence and skill [52]. Furthermore, as the technical side of the surgeries developed, simulations became even more exclusive due to the higher costs, ethical concerns, and decreasing resident work hours [52]. It has become a real problem as simulations were commonly used to teach students and prepare doctors before complicated procedures. Virtual reality is one step towards more realistic simulation, leading to better performance. Head Mounted Display (HMD) allows a multisensory environment where the user can fully immerse and interact with everything around him. It provides a unique opportunity to perceive 3D stereoscopic images [53]. It connects the advantages of a digital photo and a 3D model. The first one allows us to magnify the picture and take a very close look at the image. The second one will familiarize you with the shape of a tissue and allow you to "feel" it. Various input devices such as joysticks, wands, and gloves allow one to interact with such images and freely move and look around the Virtual environment. Such training does not require supervision as the simulation can verify the procedure. Attendance of a patient is also unnecessary because of an entirely virtual environment. That allows the training of many doctors simultaneously without resetting the procedure after every attempt and for every trainee.

5.1. VR in Surgery Training

Different sets of devices are used depending on the purpose of using virtual reality systems. For example, in surgery training, the main focus is for the trainees to get familiar with the structures of different tissues [53]. Many high-resolution images of skin, bones, muscles, veins, etc., are used for that [54]. Furthermore, such training is aided by entire robotic systems that help simulate the instruments with which the surgeon will operate in the future. The trainee uses the same robotic tools during the actual procedures, but everything the trainee sees is simulated. Those simulations can also help explain the procedure and the risks involved to the patient. The doctor can easily show a recording of a procedure simulation so that patients know what to expect.

5.2. VR in Robotic-Assisted Surgeries

Another common usage of VR in medicine is joining it with robotic systems in Robotic-Assisted Surgery (RAS) [55]. For years, operating those robots was done by watching through stereoscopic visualization. It is a system with two cameras and two lenses that allow it to be perceived multi-dimensionally. Researchers wanted to test whether the HMD would better visualize 3D structures with which robotic arms interact. The tests proved that using VR as a visualization tool is more ergonomic for doctors. The testers gave a 3.9 satisfaction rating on a 5-point scale. Considering that there was no noticeable difference in the performance, VR systems will likely be a common addition to robotic-assisted surgeries. The most used robot in operation rooms is a DaVinci robot. It is a system of arms with different instruments and cameras that allow us to conduct various operations in many medical fields such as urology, gynecology, colorectal surgery, laryngology, cardiac surgery. While it uses cameras and screens rather than a VR system there are studies that show that VR training can improve performance on DaVinci robot. It can also result in an early plateau in the learning curve for robotic practice [56].

5.3. Remote Surgeries

Time is one of the most critical factors for successful surgeries. Because of that, it is sometimes impossible for the surgeon to arrive at a hospital that can be thousands of miles away. Thanks to the current state of VR [57], it is no longer necessary. In 2001, there was a successful cholecystectomy (surgical removal of the gallbladder) that was performed over a distance of 6230 km [57–59]. Despite being a huge success in remote surgeries, it is worth noting that the connection was explicitly set for this operation. The secure communication is a key challenge in remote surgery [60].

Another use of remote surgeries is more common but less spectacular. Thanks to robotic-assisted surgeries, it is possible to perform an operation with minimal interference to the human body. The surgeons can insert tools and cameras through a tiny cut. The whole operation is done inside the body of a patient, and later, there are no visible scars.

One more obstacle must be overcome for remote surgeries to be more common. During operation, precision is crucial. That is why the feedback of the VR must be as accurate as possible so that the surgeon can operate at his full potential. Surgeons must have full control over the strength of the robot's grip and clearly understand the boundaries of its working space.

5.4. Advantages and Disadvantages of VR in Medicine

Studies show that VR can improve doctors' accuracy and learning [61]. The list of advantages mainly contains a psychological aspect of learning. Trainees say that VR training has a positive mental effect, improves self-confidence, and allows for more frequent and accurate training. The disadvantages, on the other hand, are mostly connected with VR being an expensive solution. From a technological point of view, there are a lot of different aspects, such as suitable hardware, well-written software, and stable and fast internet connection, that need to work for VR to be efficient [62]. **Table 4** compares and lists the most important advantages and disadvantages.

Table 4. Comparison of the Advantages and Disadvantages of Usage of the VR Systems in Medicine.

Advantages	Disadvantages
It allows for the creation of an entire alternate environment for the student	reported "simulation sickness" — motion sickness and disorientation caused by extensive use of VR
The variety of possible environments and scenarios	High cost of simulators
Positive psychological impact on trainees	Its implementation requires the identification of the influential factors and conditions of that society.
Reduction in errors during surgeries	The course of studies is minimal; therefore, further studies and more accurate evaluations are necessary.
Increased self-confidence in trainees	
Valuable approach for Standard and unified education of medical groups	
Better understanding of the exterior and interior space relationships between the organs	
Overall performance improvement	

6. Medical Sensors

Medical sensors are one of the fundamental elements of modern medical devices. They provide data that can be interpreted by the device and given to the doctor so they can diagnose a patient. They became popular in the mid-seventies and constantly evolved into what we use today [63]. The first procedure that used sensors was plethysmography (a procedure that measures changes in volume in different parts of the human body) [63]. This procedure is still one of the most frequently used methods to measure peripheral blood flow. Medical sensors can be divided into two main groups: professional equipment and wearable devices.

6.1. Wearable Devices

When considered in the context of the sensors, wearable devices are not the most reliable sources of information about our bodies. A smartwatch —the most common wearable device with sensors— is often used to track pulse, blood pressure, or stress levels [64]. But because of its focus on wearing comfort and convenience, they are limited to a measurement in one place, usually a wrist, and they are not correctly adjacent to the body (again, because of the wearer's comfort). That is why making medical decisions based on measurements from wearable devices is unreliable. That being said, wearable devices are a great way to warn about some abnormalities in measured data. This could be a sign to get checked by a professional. Studies show that wearable devices and their ability to measure bio-signals are straightforward to understand for most users, and their implementation is very beneficial [65].

6.2. Professional Equipment

Professional equipment is devices used in a controlled environment such as hospitals. The most common sensor procedures are electrocardiography (ECG), ultrasonography (USG), electroencephalography (EEG), blood pressure, and pulse oximetry. On top of that, sensors are commonly used in imaging procedures such as RTG or MRI.

ECG uses electrodes attached to the human body and interprets electrical currents detected by the electrodes [66]. There are three different types of ECG measurement: 3-lead, 5-lead, and 12-lead. The larger the number of leads, the more detailed the measurement. The downside of using the 12-lead method is the time needed to place all the electrodes. 3-lead measurement is more efficient and can be used to find some pathologies in cardiac work. If the pathologies are detected, the patient can be directed to further imaging using a 12-lead method.

USG is a procedure that uses the fact that the speed of sound depends on the material's acoustical impedance. Different tissues have different acoustical impedances. Thanks to that, it is possible to differentiate between different tissues during the procedure. A large emitting head (**Figure 1**) is used to acquire the image [67]. Most often in medical usage, the head also acts as a receiving sensor, which obtains an echo of sent ultrasounds. The sensor is an ultrasonic transducer that converts the electric signal to ultrasonic waves and vice-versa [68].

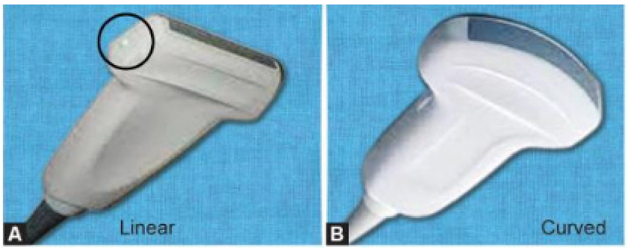

Figure 1. USG Head with a Piezoelectric Transducer [67].

EEG, similar to ECG, measures electrical currents detected by electrodes. EEG, however, is used to detect the work of a human brain. Because of that, signal quality requirements for EEG are much higher than ECG and, for many years, were limited by noise and usability usage. Standard measurements of EEG are done on the scalp using a conductive gel to ensure a good electrical connection. However, modern technology allows EEG to be more patient-friendly. There was research on building dry, through-hair, non-contact sensors [69]. The test showed that these devices are as reliable as the previous ones.

Blood pressure measurement can be performed using an invasive or non-invasive method. The invasive procedure uses a catheter tip in a transducer as a pressure sensor. The transducer uses a microelectromechanical system to convert pressure waves to electrical signals. Other invasive methods are based on nonvascular implantable miniaturized sensors compatible with body tissues. Most widely used non-invasive methods use sensors based on stroke volume methods (**Figure 2**) [70,71] . The performance of this method is highly dependent on the design and fabrication of electrodes and the continuous contact with the skin.

Pulse oximetry is a simple procedure measuring hemoglobin saturation in blood. A light sensor is used to measure that. At given wavelengths, the molecular absorption of light is constant. We can calculate the hemoglobin saturation by measuring light absorption [72]. Conventional pulse oximetry uses optoelectronic devices as sensors, but modern researchers test using organic materials to measure hemoglobin saturation in blood [73]. Those tests use organic light-emitting diodes (OLED) and organic photodiodes (OPD). This organic sensor measures blood's pulse rate and oxidation with 1% and 2% errors, respectively [73].

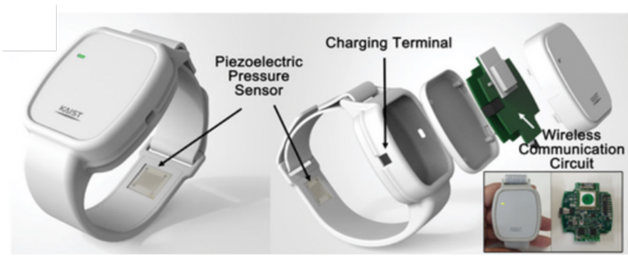

Figure 2. Exemplary Application of a Pressure Sensor on a Smartwatch [71].

RTG uses X-ray radiation to make non-invasive images of tissues inside the human body. Different tissues absorb different amounts of X-ray radiation. That is why a set of sensors behind a patient can detect the quantity left of radiation and make an X-ray image. New research in the context of RTG is an amorphous Silicon (a-Si) x-ray imaging detector designed for medical imaging applications [74].

Magnetic resonance imaging (MRI) is a non-invasive procedure that maps the internal structure of human tissues. It uses nonionizing electromagnetic radiation. The patient is put inside a giant magnet, which induces a strong magnetic field. This field causes the nuclei of atoms in the body (mostly Hydrogen) to align with the magnetic field. Then, thanks to built-in coils (**Figure 3**) the computer detects and uses the energy released from the body to construct the MR image [75,76]. Current research is focused on testing single-sided, handheld MRI sensors [77]. The biggest challenge to overcome in those devices is the low signal-to-noise ratio.

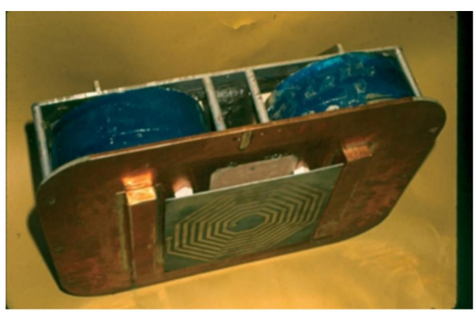

Figure 3. A Magnet and a Coil Used in MRI Procedures [76].

6.3. Review of Different Procedures and Signals Detected

Table 5 shows a review of different procedures and lists the sensors used.

Table 5. Review of Medical Sensors Explained in This Chapter.

Procedure	Data detected	Sensor
ECG	Electrical currents	Conductive material that allows the flow of electrical current to a microcontroller that evaluates them
USG	Sound echo	Piezoelectric transducer
EEG	Electrical currents	Conductive material that allows the flow of electrical current to a microcontroller that evaluates them
Blood pressure	Pressure waves	A pressure sensor in a transducer
Pulse oximetry	Light	Photodiode
RTG	X-ray radiation	Silicon detectors
MRI	magnetic resonance	Coils

7. Blockchain Technologies

Blockchain technology is a technology of distributed ledgers of digital transactions [78]. Thanks to the fact that it is decentralised, it allows for a thrustless exchange of data. It means that no authority manages the transaction. All exchange participants create a network where every party holds and maintains data. Every block in the blockchain includes a cryptographic signature about other records in the chain, along with the exact information about when the block was created. New records can only be added with the consent of other network maintainers. Adding it will automatically change its signature, so there is no chance that any undetectable break will be created in the chain. Because of this technology's immutability and transparent nature, each blockchain stakeholder can be sure that the data that they possess is an unmodified copy of the blockchain's data stream [79].

This technology was created as a peer-to-peer electronic cash system. An anonymous author, Satoshi Nakamoto, described it for the first time in 2008. In their article, they acknowledge the great need to adopt an electronic payment system so it would be cheaper, more trustworthy and resistant to fraud. They present blockchain technology as an answer to all these needs, describing it as "an electronic payment system based on cryptographic proof instead of trust, allowing any two willing parties to transact directly with each other without the need for a trusted third party" [80].

7.1. Blockchain Technology in the Healthcare System

After the great success that blockchain has achieved in the economic and financial area, it became clear that this technology has the potential to reconfigure all aspects of society [81]. With its immutability, openness and security of architectural approaches, it could find a use in any system that consists of data transactions, including healthcare system [82]. In his article, Marco Piccininni notes that contemporary medical records serve more institutions than patients or caretakers [83]. There is no easy access to medical data, and, what is more, every transaction occurs through a hospital, which represents a central authority [84]. With the use of blockchain technology, the healthcare system can be changed into a modern, individualised, patient-centred system where medical information is available to patients so they can take an active part in their care [85]. Using blockchains will also increase the privacy and security of health information and ensure its completeness. McKiney & Company, in their study, also shows that if the medical data is used effectively, more than $300 billion could be recovered per year from national healthcare expenditure [86].

7.2. Examples of Usage of Blockchain Technology in Healthcare System

Although blockchain technology seems promising, only a few healthcare systems use it daily. Most of them were conducted under laboratory conditions with the closed-source dataset, so there is still no assurance that they will work efficiently in a real-world environment. However, with the development of research, we can suspect that it is only a matter of time before they are brought to the real market.

Most blockchain applications that are being tested focus on data sharing, access control and health records [87]. Their purpose is to create a patient-centred system for managing health records that will ensure data security and, at the same time, allow data sharing between patients and healthcare professionals. One of the most cited examples is a blockchain-based platform distributed by Guardtime company. It is used in Estonia and secures over 1 million patients' records [87]. Similar to other systems developed by, for example, Gem Health Network, it allows healthcare experts to access the same healthcare data. This real-time medical data access minimises the risk of medical omission due to misinformation caused by outdated medical records. On the other hand, the system needs to face the problem of identity management for the patient and securing shared records from abuse [88]. The OmniPHR model developed by Roehrs solves those problems by giving patients the power to authorise access to their records for anyone else. The model guarantees scalability, elasticity and decreased latency thanks to its cloud-related features [89]. However, it is firmly based on the conviction that the patient will responsibly manage access to his medical records, which can be a problem in the real world. Another system, MedRec, solves this problem using smart contracts implemented through the Ethereum blockchain. They log the provider-patient relationship, connecting concrete records with data retrieval instructions and viewing permission [90].

The change of record is accompanied by a notification that allows data providers to accept or reject the proposed change. A similar system is used by the MeDShare system designed by Xia, SIfah, Asamoah, Gao, Du and Guizani. It uses smart contracts and an access control mechanism to track the data and deny access to any violation in the system [91]. This approach increases data security but creates a problem with adding latency when many requests for records are to be added or changed. It also, as many blockchain systems like OmniPHR, a system created by Gem Health Network, Pervasive social network (psn) system or Healthcare Data Gateway, do not address the problem with key management and recovery. Many more healthcare systems are based on blockchain technology and have different aims, advantages, and disadvantages. Some of them are shown in **Table 6** [19,20,88,91–95].

Table 6. Main Aim, Advantages and Disadvantages of Selected Medical Data Management Systems Using Blockchain Technology.

Name of system	The main aim of the system	Advantages	Disadvantages
System by GemHealthwork [88]	To use Ethereum Blockchain Technology to create a shared network framework	decentralisation (all users have access to the same data), real-time access to data	lack of key management to protect data from abuse and tampering, lack of recovery of a key in case of its loose or leakage
Guardtime System [92,93]	to create an infrastructure for validating patient identities that link different government institutions with the healthcare sector	decentralisation, increased safety compared to other systems that maintain decentralised ledgers	all data is available to the government, which distorts the concept of decentralisation of the system
OmniPHR [20]	to create a patient-centered system based on PHR that will be interoperable for both healthcare providers and patients	scalability, capacity of elasticity, latency is not impacted when the number of backbone routers and routing overlays increases if the number of nodes stays the same, real-time access to data	data must be located in the model-enabled paths and follow the standards supported by the OmniPHR model, the system needs to be able to determine the creator of each data, patient always need to authorise access to their data for health organisations, limited security and privacy protection
MedRec [19]	to create a patient-centred system that improves data quantity and quality for medical research and prioritises patient agency	decentralisation, use of smart contracts, using data as a mining incentive, real-time access to data, ease of modification by adding contract encryption	lack of the security assurance of individual databases, no solution to the problem of Digital Rights Management
MeDShare [88,91]	to create a system that ensures data provenance and auditing by using smart contracts with self-retrieving keys and enables trust-less data exchange	use of smart contracts with self-retrieving keys, use of cloud technology, use of access control mechanism	a considerable increase in latency when more users are using the network, lack of solution to the problem of key management and recovery

Table 6. *Cont.*

Name of system	The main aim of the system	Advantages	Disadvantages
Pervasive social network (PSN) system [88,94]	to create a network-based healthcare system comprising wireless sensing and mobile computing that enables the sharing of data between patient and physician	data involved in the blockchain is addressed rather than health data (ensuring data security), reduction of computational burden on measuring sensors used by patients, data is stored on mobile devices and measurement sensors to protect against data leakage	the network system is more of a facilitator of sharing data rather than a stand-alone solution to managing healthcare information problems, lack a solution to the problem of key management in case of key leakage
Healthcare Data Gateway (HGD) [95]	to create a patient-centred system that enables a patient to share, own and control their data	decentralisation, data is immutable once uploaded, which increases data security, the patient fully manages data, support of smartphone applications	lack a solution to the problem of granting temporary access to user information in case of emergencies, lack of a solution to the problem of key loss management

The blockchain technology has the potential to change the healthcare system irreversibly. However, it's more than possible that this won't happen anytime soon. Scientists and researchers working on it still need to find a consensus on data security, seamless data sharing, and real-time access to records. It will take a lot of time and money to bring blockchain systems to the healthcare market, but when they are brought, they will change the healthcare system as we know it.

8. Electronic/Digital Healthcare During COVID-19

The Pandemic of COVID-19 and related restrictions force healthcare systems to revise approaches related to contact with a patient and accelerate the development of improvements in the healthcare system. An example of stimuli forcing medical staff to organizational change could be the situation of hospitals in New York during the first wave of pandemics in March 2020, where in 11 hospitals, the number of beds with intensive care unit capabilities grew three times in 6 weeks [96]. High demand for health care services stimulated reorganizing staff work, prioritizing patients based on their medical needs, and attempting to maintain medical services regardless of emergency room occupancy [97].

Similar to the New York case, situations were an impulse to create solutions and platforms that fulfil patients' needs. The main difficulty during that time was the increased demand for specialistic healthcare services and limitations present during pandemics (like lockdowns and quarantines [98]). This caused a more significant focus on developing healthcare systems improvement based on new technologies, remote communication, and contactless data exchange. In general, such solutions are called Digital healthcare platforms, a set of technologies and applications used to aid the traditional healthcare system [99].

8.1. Digital Health Solution That Made Life Easier During COVID-19

Movement restrictions, social distancing, healthcare systems overload, and the demand for medical appointments of patients with less severe symptoms / with more stable health states created a niche to manage. Research conducted in the first year of pandemics proposed a new solution for lowering the transmission rate coefficient by reducing the number of physical contacts during a medical investigation by introducing telemedicine as an available communication channel for medical professionals [7, 100]. The idea was caught in the first outbreak of the disease in December 2019 in mainland China by launching commercial telemedicine services like Ali Health, WeDoctor, or JDHealth [100]. Another country, like the USA, followed the path of raising companies like AmWell or Teladoc in the USA or introducing WhatsApp-based solutions like in South Africa [100,101]. An overview of available solutions in the telemedicine market shows 5a few primary forms of telemedicine services shown in **Table 7**. Each is characterized by opportunities for patients and convenience for physicians, but also disadvantages listed with telemedicine forms.

Table 7. Examples of IoT-Based Solutions Introduced Purely in the COVID-19 Context [104–107].

Role	Function	References
Storage and processing data of COVID-19 patient	**Storing patients' locations for a safe-road navigation system recommends the road omitting the town's high-risk areas.**	**Misra et al. [104]**
Early warning systems	Early warning systems of patient zero cases in the form of IoT solutions mounted in public places where illness could be transmitted between parts of the world (e.g., airports)	N.V. et al. [105]
Alert about the COVID-19 disease	Alert systems connected with tracking database informing about possible hazardous contact	Munzert et al. [106]
Health monitoring systems for early COVID-19 symptoms detection	The Data acquisition device collects data from various sensors (e.g., blood oxygenation, bodily temperature, heart rate) and processes it on an external server. The solution provides contact with professionals in case of detecting suspicious symptoms.	Sabukunze et al. [107]

8.2. Digital Health Solutions Developed During Pandemics–Progress in Existing Fields

As a complex sensor and data acquisition system, IoT is crucial in medicine, providing diagnostic data and collecting and processing them. The range of monitored measures covers heart rate, oxygenation, sugar level, blood pressure, and environmental conditions [102,103]. Technology also played an essential role during the COVID-19 pandemic as a part of a more extensive medical infrastructure. Pandemics gave a new opportunity to develop Internet-of-Things-based systems, providing additional aid for medical systems and helping people take preventive action to stop the spread of disease. **Table 7** presents a few essential steps that have been taken in the IoT area to improve healthcare services or contribute to broadly understood digital healthcare [104–107].

8.3. Deep Learning Techniques

Deep learning has undergone significant advancement and widespread adoption in healthcare, particularly during the COVID-19 pandemic. Core branches of artificial intelligence—such as convolutional neural networks (CNNs), recurrent neural networks (RNNs), transformer-based large language models (LLMs), and hybrid architectures—were leveraged across various digital health applications. Notably, LLMs played a critical role in combating medical misinformation during the pandemic. These models, often based on transformer architectures like BERT and GPT, were fine-tuned on domain-specific corpora including social media posts, health-related news, and scientific publications to detect misleading or harmful narratives. Fine-tuning involved supervised learning with annotated misinformation datasets and domain adaptation techniques to enhance model relevance in the healthcare context [108].

In diagnostic imaging, deep learning-based analysis of radiological data such as CT scans and chest X-rays emerged as a powerful tool for COVID-19 detection and classification. Prior to the pandemic, CNNs had already demonstrated robust performance in identifying features in medical images. During COVID-19, pre-trained architectures such as InceptionV3, ResNet-50, DenseNet-121, and VGG-16 were widely employed using transfer learning strategies. These models were fine-tuned on relatively small datasets of annotated COVID-19 images, with augmentation techniques applied to address data scarcity and class imbalance [109,110]. In particular, ResNet and DenseNet architectures were favored due to their deep-layer feature extraction capabilities and residual connections that mitigate the vanishing gradient problem, improving convergence and diagnostic accuracy. However, COVID-19 and its influence on world healthcare systems have also impacted this field. Research of available papers shows a handful of solutions in detection, classification, and diagnosis areas differentiating COVID-19 characteristic x-ray images from another type of pneumonia. A significant number of proposed solutions rely on some predesigned architectures of a model like Inception-V3, Resnet-50, or Densenet 121. Proposed solutions taken to put in the review bring a new opportunity to aid physicians in illness detection and differentiation

Many of the proposed models employed supervised learning approaches, using annotated datasets like the COVIDx dataset, which includes labeled X-ray images for normal, non-COVID pneumonia, and COVID-19 cases. In some studies, ensemble models combining outputs from multiple CNNs were used to improve classification performance. Additionally, attention mechanisms and Grad-CAM visualizations were integrated into diagnostic pipelines to provide explainable AI outputs, allowing clinicians to interpret which regions of the image were most influential in model decision-making. This increased the transparency and trustworthiness of AI-assisted diagnostics.

Beyond image-based diagnostics, deep learning was also applied in time-series analysis for patient monitoring, forecasting COVID-19 outbreaks, and modeling patient risk trajectories. Long Short-Term Memory (LSTM) networks and gated recurrent units (GRUs) were used to model temporal dependencies in clinical data such as vital signs, lab results, and electronic health records. In some hybrid frameworks, CNNs were combined with LSTMs to first extract spatial features (e.g., from image sequences) and then model their evolution over time for prognostic predictions.

The pandemic accelerated the integration of deep learning into clinical workflows, yet challenges remain. Issues such as model generalizability across demographics, lack of standardized datasets, and the need for real-time, edge-deployable solutions continue to limit widespread implementation. Future research should focus on the development of more robust architectures tailored for low-resource settings, federated learning approaches for privacy-preserving model training, and multi-modal systems that can integrate image, text, and sensor data for comprehensive clinical decision support [111].

8.4. Technologies Developed for Monitoring the Epidemiological Situation

The COVID-19 pandemic required rapid improvements and widespread adoption of digital technologies to monitor and manage the epidemiological situation in different countries. Several states have adopted systems of personal contact tracking and quarantine monitoring for screening the transmission of disease and estimating the area of a virus spread. South Korea and Singapore were the first countries to introduce digital contact tracing (DCT) as a smartphone app and prevention system tool. The solution's effectiveness resulted at the end of 2020, the idea was caught up by over 40 other countries [106].

During the first pandemic outbreak, researchers focused on analysing the social tracing model in the context of the spread of disease. The proposed system was based on a mobile app that monitored Bluetooth activity coming from nearby mobile devices. In case of the first symptoms of influenza-like disease, confirmation with a test and information about risky contact is sent to the central hub, informing exposed users about the event and requesting them to self-isolate and perform a test. Researchers claimed that the transmission rate could be reduced based on the assumed mathematical model of disease transmission between individuals. However, the reduction was somewhat limited, considering the high infectiousness from presymptomatic and asymptomatic cases. Regardless of the limited reduction of a transmission rate from two to one or slightly below, it was recommended as one of the countermeasures in prevention [112].

9. Conclusions and Research Gaps

This paper provided a comprehensive review of recent advancements in electronic and digital applications within the medical and healthcare sectors. It explored key areas including wearable electronics, the M-IoT, electronic health record systems, smartphone applications, VR, AI, flexible hybrid electronics, and digital healthcare innovations during the COVID-19 pandemic. The review also examined the impact of medical sensors, social media, Blockchain technologies, electronic drug delivery systems, Nano-BioElectronics, and robotic surgery systems on modern healthcare. Comparative analyses were conducted to highlight the advantages, limitations, and distinctions across these technologies, such as VR-based therapeutic interventions, robotic-assisted surgery, social media's role in healthcare communication, and blockchain-enabled medical data management.

While the progress in these domains is substantial, several critical research gaps remain that warrant further exploration. For instance, optimizing the biocompatibility and functional stability of nanoparticles used in Nano-BioElectronics is essential for safe and long-term integration in human physiology. Similarly, improvements in VR haptic feedback mechanisms are needed to enhance the realism and efficacy of medical simulations and rehabilitation tools. Current wearable technologies still face challenges in achieving accurate, continuous monitoring while maintaining user comfort and battery life, suggesting a need for advances in flexible and energy-efficient materials.

Moreover, the scalability and interoperability of blockchain systems for secure medical data exchange require robust frameworks to ensure widespread adoption in diverse healthcare environments. In robotic surgery, the refinement of AI-assisted decision-making and adaptive control systems presents a promising avenue for reducing intraoperative risks and improving surgical outcomes. The integration of social media platforms with real-time public health surveillance also remains underdeveloped, indicating opportunities for enhancing health communication strategies and behavioral health interventions.

Future research should also focus on developing standardized protocols and ethical guidelines for deploying these technologies on a scale, ensuring equity, privacy, and accessibility. By addressing these gaps, the next generation of medical electronic and digital innovations can be more effectively tailored to meet the evolving needs of both patients and providers, thereby maximizing their impact on global health systems.

Author Contributions

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