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How 5G Wireless (and Concomitant Technologies) Will Revolutionize Healthcare?

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Abstract: The need to have equitable access to quality healthcare is enshrined in the United Nations (UN) Sustainable Development Goals (SDGs), which defines the developmental agenda of the UN for the next 15 years. In particular, the third SDG focuses on the need to "ensure healthy lives and promote well-being for all at all ages". In this paper, we build the case that 5G wireless technology, along with concomitant emerging technologies (such as IoT, big data, artificial intelligence and machine learning), will transform global healthcare systems in the near future. Our optimism around 5G-enabled healthcare stems from a confluence of significant technical pushes that are already at play: apart from the availability of high-throughput low-latency wireless connectivity, other significant factors include the democratization of computing through cloud computing; the democratization of Artificial Intelligence (AI) and cognitive computing (e.g., IBM Watson); and the commoditization of data through crowdsourcing and digital exhaust. These technologies together can finally crack a dysfunctional healthcare system that has largely been impervious to technological innovations. We highlight the persistent deficiencies of the current healthcare system and then demonstrate how the 5G-enabled healthcare revolution can fix these deficiencies. We also highlight open technical research challenges, and potential pitfalls, that may hinder the development of such a 5G-enabled health revolution.

Keywords: healthcare; 5G; Internet of Things; big data analytics; artificial intelligence and machine learning

1. Introduction

Good health has a constructive effect on all aspects of human life and social well-being including personal happiness, workforce productivity and economic growth. Recognizing the importance of healthcare, facilitating affordable universal access to healthcare is already enshrined as an important goal of the United Nations' new Sustainable Development Goals (SDG). This defines the UN's development agenda for the next 15 years. In the words of the Nobel Laureate Amartya Sen, "Health is a critically significant constituent of human capabilities which we have reason to value". It has been shown in the literature that investment in healthcare pays huge dividends. In the Economists' Declaration, originally launched in 2015 with 267 high-profile economist signatories, world-leading economists called on global policy-makers to plead for a pro-poor pathway to universal health coverage as an essential pillar of sustainable development [1]. A case was made that healthcare investments make perfect economic sense since according to the Global Health 2035 report by the Lancet Commission on Investing in Health, every dollar invested in the healthcare of poor countries has a nine-fold or higher return.

Despite the core role of human health in human development and progress, today's healthcare system is largely dysfunctional and in the need of a major overhaul. Broadly speaking, the ills of the healthcare system can be categorized into four major deficiencies, which we discuss next.

Firstly, the current healthcare system is *not convenient for patients since it is not patient-centric.* As an example, the patient has to go, or be taken, to a doctor's office or a hospital for any non-trivial illness, which is inconvenient for the patient (who would likely prefer to rest). This is equitably unsuitable for the patient's caregivers (e.g., the patient's guardian or family member) who must take the patient to the clinic. Further, the patients also need to slot their health-related appointments into their busy schedule. Sometimes, this leads to carelessness in giving due attention to regular and required health-checks with doctors.

Secondly, the current healthcare system is *not personalized* according to the individual patient. Doctors prescribe medications based on population averages rather than the individual characteristics. As of today, it is very difficult and costly to adopt tailored treatments based on individuals' medical history and genetic profile.

Thirdly, the current healthcare system is *not equitably accessible*. Similar kinds of healthcare facilities are not equally accessible to patients. These facilities are utilized by only a certain groups of people, based on their ethnicity, socioeconomic status, geographic residence, etc. Similarly, lack or limited access to basic healthcare services is putting patients (especially disabled people) at much higher risk and causing adverse health outcomes.

Fourthly, the current healthcare system is *not holistic/data-driven*. The Institute of Medicine, a division of the National Academy of Sciences, representing our most prestigious scientists and physicians, published the report "*To Err Is Human*", which proclaimed that "at least 44,000 people, and perhaps as many as 98,000 people, die in hospitals each year as a result of medical errors that could have been prevented", but which arose because "faulty systems, processes, and condition" led people either to make mistakes or to fail to prevent them. Beyond the human toll, these errors cost between $17 billion and $29 billion.

Although modern medicine is ripe with numerous success stories (such as the eradication of diseases such as smallpox, the invention of antibiotics and anaesthesia, the development of modern surgery and therapy techniques), the overall healthcare industry has been largely impervious to a technological revolution. This has been the case due to many reasons such as its highly regulated and policy-driven nature, as well as the unique nature of its value chain unlike other markets. In the healthcare system, someone makes choices (e.g., a doctor); someone else is a consumer and user (e.g., patient); and someone else altogether pays (e.g., the insurer or the government via taxpayers). The Institute of Medicine (IoM), a division of the U.S. National Academy of Sciences (NAS), summarized the ills of the US healthcare system as follows:

> *If banking were like health care, automated teller machine (ATM) transactions would take not seconds but perhaps days or longer as a result of unavailable or misplaced records. If home building were like health care, carpenters, electricians, and plumbers each would work with different blueprints, with very little coordination. If shopping were like health care, product prices would not be posted, and the price charged would vary widely within the same store, depending on the source of payment. If automobile manufacturing were like health care, warranties for cars that require manufacturers to pay for defects would not exist. As a result, few factories would seek to monitor and improve production line performance and product quality. If airline travel were like health care, each pilot would be free to design his or her own preflight safety check, or not to perform one at all* [2].

While the point of the charge sheet above is certainly not that healthcare should function precisely in the way that other industries do, indeed each industry is different from others, however, the point is that the banking, construction, retailing, automobile manufacturing, flight safety, public utilities and personal services have developed certain best practices in terms of quality assurance, accountability and transparency that the healthcare industry should also incorporate.

More than anything else, the healthcare industry needs to be reoriented so that the patient becomes the core concern of the system. In such patient-centric healthcare, the individuals will be empowered with information, and preferences for the convenience of patients will automatically be incorporated. Furthermore, payment incentives should be redesigned so that outcomes and values are rewarded with a less volume of procedures. Finally, with this transparent system, errors will be promptly identified and corrected. In this way, a data-driven approach will become routine allowing for continuous improvement through reflections on past and evidence-based healthcare decisions.

In this paper, we show how 5G (and other concomitant technologies such as IoT, big data analytics, Artificial Intelligence (AI) and Machine Learning (ML)) has the potential to revamp a healthcare system struggling to cope with the burden of modern diseases and the challenge of scaling up to ever-increasing populations. In the future, ML algorithms will estimate appropriate micro-dosages of drugs (e.g., it may be used to administer insulin dosage through an implanted pump) and detect anomalies that might be forwarded to human experts who can manage the medical problems. Telemedicine or e-Health will allow scaling up of healthcare systems to meet a rising population, especially in remote, rural and low-income areas, by employing technologies such as remote consultation and surgery. Surgeons using telemedicine will have access to haptic feedback, which will allow for the feeling of touch to be transmitted. Patients will be able to measure their own vitals at a fraction of the cost and with great convenience. We believe that the 5G network will address not only personal communications, but also create a fully-digital society in which sensors may be embedded in tissue (pacemaker), ingested (using ingestible smart pills), printed on skin (using epidermal sensors such as smart skin or digital tattoo) and worn (using wearable technology such as smart clothing, smart jewellery or smartwatch).

To the best of our knowledge, this is the first paper that discusses how 5G-enabled healthcare systems, armed with other technologies such as AI, ML, big data, IoT, will enable a future healthcare revolution. Our paper is timely both because of the rising need of scalable global healthcare solutions (particularly for the developing world) and the promise of substantial technical support from 5G to facilitate a health revolution. Apart from highlighting the promise of 5G-enabled healthcare, this paper also discusses various technological challenges and potential pitfalls that will accompany the efforts of developing 5G-enabled healthcare solutions.

The paper is organized as follows. In Section 2, we discuss the various challenges posed by the current healthcare system. In Section 3, we highlight how technology can fix these issues. The promise of 5G-enabled healthcare and its associated opportunities are introduced in Section 4. To make matters more concrete, we present a case study in Section 5 in which the economic benefits of using 5G-enabled healthcare are described. A discussion of various technological challenges and potential pitfalls related to 5G-enabled healthcare is provided in Section 6. Finally, we conclude this paper in Section 7.

2. Challenges Posed by the Current Healthcare System

The current healthcare system is stressed by a number of challenges including an ageing population; the rising burden of lifestyle-related chronic diseases; the absence of patient-centred scalable clinical operating models; the lack of healthcare facilities and human resources (or limited access thereto); and the high costs associated with the provision of high-quality care [3]. Some of these and other major global healthcare challenges are discussed in more detail next.

2.1. Challenges with EHRs

The Electronic Health Record (EHR) is a repository containing patients' digital data that are exchangeable securely with multiple authorized users. It stores retrospective, prospective and concurrent health information with the purpose to support efficient, continuing and quality service in integrated health [4]. In contrast to the virtues and success of EHRs, there are various challenges and limitations. The lack of interoperability is a major problem because hospitals and physicians are mostly not connected. This causes the patients' health information to be constrained within hospitals and laboratories.

2.2. Lack of Universal Access

Universal access to healthcare entails that everyone can have equitable access to health services without any discrimination especially on the capacity to pay [5]. Coverage of healthcare services is limited when a country lacks trained healthcare professionals, services and equipment; available resources are not located in proximity; and individuals are unable to afford services due to their high cost [6]. Universal healthcare services are particularly challenging for developing and underdeveloped countries, where health resources and practitioners are in short supply, particularly in rural areas [7]. Universal access to healthcare can be achieved by progressively eliminating the above-mentioned challenges that prevent people from having fair and comprehensive health facilities determined at the national or international level.

2.3. The Long-Term Chronic Care Burden

Chronic diseases are increasing globally and have become the most dominant and serious threat to the world. They are affecting people of all ages in both developed and developing countries and responsible for 60% of 56.5 million total deaths in 2001, approximately contributing 46% of the global burden of disease. This number is projected to grow to 57% by 2020 [8].

The current global healthcare system is particularly troubling for people with chronic illness [9]. Because people suffering from chronic diseases rely more heavily on the healthcare system: they utilize the system more often, consume extra resources, visit multiple doctors and have long-term relationships with them. Therefore, when the healthcare system fails, patients with chronic disease are more affected.

2.4. Challenges for Ageing Populations

The world's population is rapidly growing older, leading us to a higher number of elderly people in our society. The number of people aged 65 or older is projected to increase from 8% (524 million) of the world's population in 2010 to 16% (1.5 billion) in 2050 [10]. The rise of elderly people around the world is depicted in Figure 1. The increasing share of the elderly population with increased life expectancy is changing the cause of death from parasitic and infectious diseases to chronic non-communicable illnesses. These demographic shifts are posing enormous challenges to healthcare systems. In the near future, the current healthcare systems will fail to provide long-term care to older people with multiple chronic illnesses. Changes are required to make strategies for older adults to live independently by providing high-quality care.

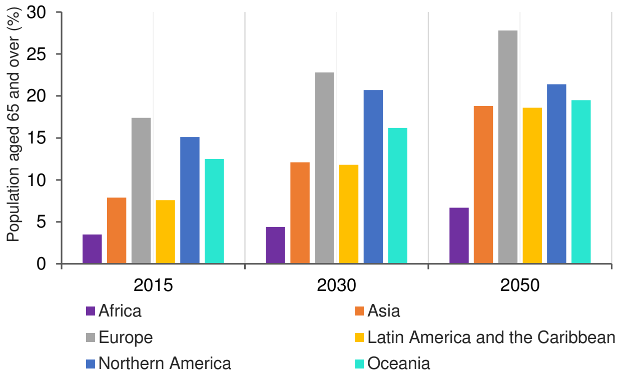

Figure 1. Population aged 65 and over by region. Adapted from: [11].

2.5. Resource Constraints

Despite the great success in creating an impressive outlook of the healthcare system, the overall healthcare services are still insufficient. Patients have to travel from distant places to visit their doctors. Travelling barriers cause rescheduling or missing of appointments and delay in medications. There are 57 countries with a critical shortage of healthcare workers; for instance, Africa has 2.3 health workers per 1000 population as compared to the Americas, which have 24.8 health workers per 1000 population [12]. Similarly, in Pakistan, there is one doctor for 1038 inhabitants [7]. The problem is now becoming more acute, and the world will have an anticipated shortage of 12.9 million healthcare workers by 2035 [13]. Therefore, we need some serious developments in healthcare to increase the productivity of health professionals by using telemedicine and e-Heath-like services.

2.6. Problems with Healthcare Information Systems

The advancements in information communications technology have potential to bring a significant transformation in the healthcare system by connecting medical devices, automating financial transactions and preventing errors to enhance consumer confidence in the health system. However, the healthcare systems are very complex, as they include communication and processing of heterogeneous health information, optimal allocation of available resources and their administrative management simultaneously. Existing wireless technologies (3G, 4G and WiMAX) exploit macro-cells to provide a wider range suitable for lower data rates. These technologies are mainly suitable for smart health monitoring devices, social interactions and wellness monitoring applications [14]. For healthcare systems, we require a heterogeneous wireless technology with multiple frequencies ranges that can provide a guaranteed high data rate and very low latency for medical services like remote surgery.

2.7. Lack of a Data-Driven Culture

In the current healthcare paradigm, patients are assessed on population averages and data-poor practices, and it is practically not possible to conduct standard parallel group Randomized Controlled Trials (RCTs). Moreover, clinical evidence generated by non-standard RCTs has poor generalizability, therefore, having limited applicability to patients, and even is also restricted in comparing the effectiveness of drugs and medical devices [15]. In such a data-poor system, the medication doses are often over-or under-estimated, which can result in adverse drug reactions. This represents a crucial missed opportunity to embrace the development of intelligent and evidence-based healthcare solutions. These solutions can provide and apply the best evidence-based care to each patient; discover the natural outgrowth of patient care; and also ensure innovation, safety, quality and added value to the healthcare system.

2.8. Healthcare Disparities

Currently, healthcare systems are mostly income-based instead of need-based. People who need healthcare services crucially are getting less access than the people who need it least. For example, on average, in United State, the rich are the biggest buyers of healthcare services despite being healthier than the poor [16]. In another study, it is found that people in the lower incomes quartile have poorer health [17]. This dramatic shift in healthcare is creating disparities in health outcomes across income groups.

3. How Technologies Can Fix the Current Healthcare System

In this section, we will discuss how technologies such as the Internet of Things (IoT), big data for healthcare (wireless connectivity) and other disruptive health innovations can fix the current broken healthcare system.

3.1. Various Health Advances with IoT

The Internet of Things (IoT) is an abstraction of infinite, smart, physical and virtual objects that have unique identities connected to create an ultimate cyber-physical pervasive framework. These devices capture, monitor and transmit data to a public or private cloud to facilitate a new level of convenient and efficient automation. IoT-based solutions are very effective in terms of energy consumption, CPU and memory usage [18].

We are witnessing the rise of the cellular Internet of Things (IoT), and it is expected that there will be 20 billion devices or things connected to the Internet by 2020 [19]. The IoT trend is a next-generation technology that can change the whole business spectrum with a variety of applications such as smart cities, industrial control, retails, waste management, emergency services, security and logistics. Most importantly, IoT is considered as an enchanting technology that can revolutionize the current healthcare system with a variety of cutting-edge and highly individualized solutions. These solutions include remote health monitoring, remote diagnostics, tele-auscultation, chronic diseases management, independent care for elderly and much more [20]. Patients compliance with medication and treatment by healthcare providers is another prominent potential application of IoT. In addition, IoT can also be used to authenticate medicine, monitor drug supplies and provide efficient scheduling of available resources to ensure their best use for more patients.

In medical IoT, various medical sensors, devices, smartphones, imaging devices, personal digital assistant (PDAs) and EHRs act as core parts of the system. These devices monitor important health information, like physiological vital signs, changes in mood and behaviours and blood glucose, which can be effectively utilized by healthcare providers to improve the quality of care and health outcomes. Furthermore, IoT-based solutions have potential to reduce the required time for remote health provision and increase the quality of care by reducing costs with enriched user experience.

3.2. Big Data for Healthcare

In the last few years, we are increasingly living in a digital world where devices like smartphones, EHRs, biomedical and wearable sensors produce a large volume of health data. Such data can be referred to as “big data” due to its high-velocity and wide variety; this holds great promise for evidence-based human developmental efforts [21]. The digitization of human beings allows the remote and continuous monitoring of each heartbeat, moment-to-moment blood pressure, oxygen concentration in blood, body temperature, glucose, human activities and emotions. This big health data and behaviour information can be used for analytics to gain deep insights into the various aspects of human life. For example, when the information about human activities, their geographical location, shopping habits, travel patterns and social circle is combined with health information (such as health records and genetic information), latent personalized and population-based health patterns can be discovered. Big data provide the necessary support for developing a patient-centric personalized healthcare system in which the right health intervention for a given person and the health problem can be identified in an evidence-based manner. While big data have a disruptive potential to herald the much-awaited dawn of personalized medicine, there are substantial technical, legal and socio-economic challenges that remain to be addressed.

Rapid strides of big data analytics have been taken to disrupt almost every other sector in the global economy, but the healthcare industry has been relatively slow in its adoption of big data analytics [22]. This is largely due to the fact that the problems of the healthcare industry are complex and interconnected and have to be addressed by a myriad of stakeholders in academia, industry, public organizations, healthcare industry and government [23]. Perhaps the most pressing challenge is the lack of patients’ trusts to share their personal data, as patients are wary of the abuse of their personal data when they are not in control of their health information. To overcome this barrier, patients must be put in control over their personal information by providing them full visibility and control in a big data ecosystem (see Figure 2). The new strategies must be formed to stimulate active, legal and performance-based models. This will encourage open information sharing and a vast variety of opportunities for the healthcare system.

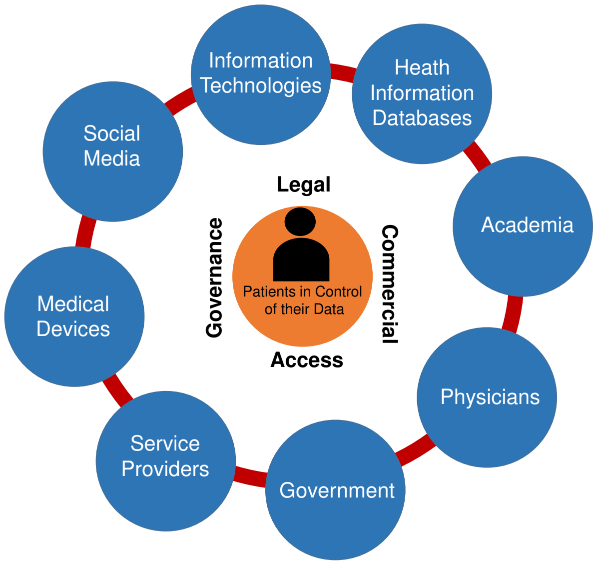

Figure 2. Patient-centric big data-enabled healthcare ecosystem.

3.3. (Wireless) Connectivity

Wireless technologies due to the untethered nature and inexpensive deployment cost are ideally suited to provide the necessary connectivity that is needed between the various stakeholders of the healthcare system. The use of wireless technology for healthcare has been explored in various studies [24,25]. The advancements in wearable computing, bio-engineering and mobile devices have enabled a dramatic increase in the exploitation of ubiquitous and pervasive wireless technologies in the healthcare system. This trend will likely continue and further be strengthened by the development of 5G wireless technology, which will provide much better performance in terms of throughput and latency compared to pre-5G technologies (as is illustrated in Figure 3).

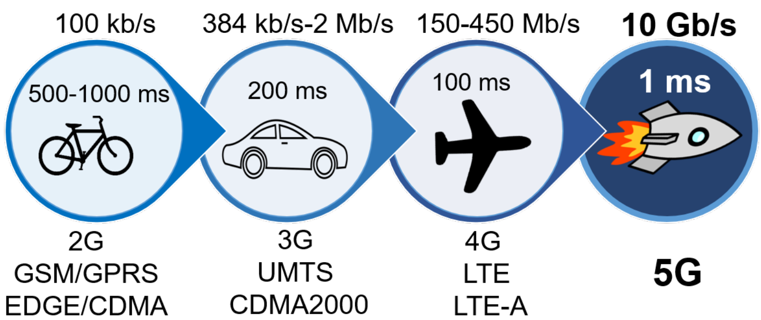

Figure 3. The performance trends (throughput and latency) of 2G, 3G, 4G and 5G wireless standards.

One of the most prominent e-Health application that wireless technology can enable is telemedicine, or the provision of expert-based medical care from a distance (see Figure 4). In particular, wireless technologies can be used to facilitate an electronic exchange of data, voice, text, images and other health-rated files. Ng et al. [26] present how wireless technologies and medical services can be integrated to provide flexible, convenient and economical telemedicine. Nowadays, the rapid growth of wireless sensor networks, wireless communications, wearable sensors and especially smartphones has paved the path to new e-Health systems, which are superior to traditional telemedicine systems. Future technology like Ultra-Reliable Low Latency Communications (URLLC) enabled by 5G will make health communications more resilient and will open many new healthcare opportunities like remote surgery and remote diagnosis with haptic feedback. Moreover, Simultaneous Wireless Information and Power Transfer (SWIPT) can result in a significant gain in the performance of medical implants.

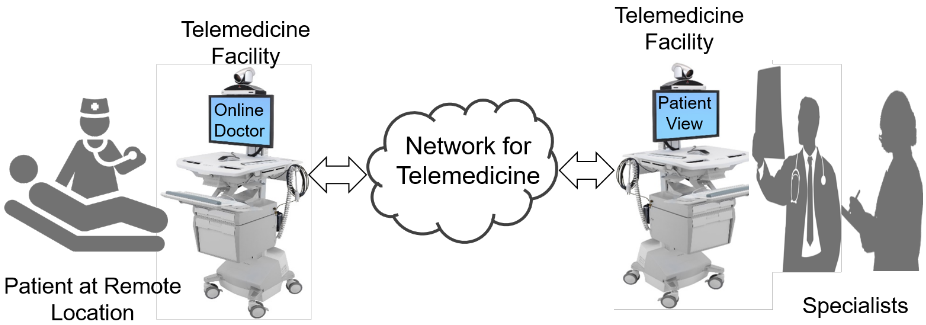

Figure 4. A general architecture of telemedicine with two locations.

Another promising application of 5G is bio-connectivity, which will decentralize hospital services and enable the provisioning of medical care on the move (i.e., for emergency response in ambulances) [27]. This will open a new era of advantages from enhancing performance in hospitals to new ways of monitoring the patients' health, disease progression and individualized pharmaceutical analysis. We will discuss more details of 5G-related healthcare and applications in Section 4.

3.4. Artificial Intelligence and Machine Learning

Traditional healthcare systems often give suboptimal health outcomes despite the best efforts of the clinicians and physicians. The incomplete knowledge of patients' health and the personal biases of clinicians account for most of these suboptimal health outcomes. Optimal results require such systems that are driven by scientifically- and statistically-validated data to provide benefit choices to the population. In the near future, it is inevitable that the majority of classical or traditional physicians' practices, prescription methods and monitoring system techniques will be replaced by intelligent devices, software toolboxes and testing procedures. Healthcare will mature into being more consistent and more scientific in terms of delivering a better quality of care at the expense of AI and data-gathering techniques. This will provide continual monitoring, more rigorous, personalized, precise, as well as logical care. This evolution from an exclusively human-based system to the intelligent and automated expert systems will provide a bionic assist to doctors by substantially complementing or enhancing their expertise. This will make even the average nurse or physician perform at the level of the best specialists [28].

As an example of the advances in ML and AI, we point out the significant advancements the ML technique of deep learning has made, particularly in image processing and recognition. There is now growing hope that deep learning and other ML models will help improve diagnostic procedures by recognizing patterns that may be too subtle for the human eye [29]. Deep learning is already being used to detect skin cancer in images with almost the same number of errors as made by professional dermatologists [30]. Recently, a multidisciplinary research team of pathologists, geneticists, biomedical engineers and computer scientists at Stanford's School of Medicine succeeded in developing a deep learning algorithm that can detect lung cancer more accurately than human pathologists [31]. Healthcare systems based on AI, machine learning and probabilistic models have potential to provide therapeutic recommendations, prognosis learning, personalized real-time risk scoring, etc. There is now growing interest among doctors and entrepreneurs to largely deploy deep learning techniques.

3.5. Disruptive Health Innovations

Technological innovations (e.g., implantable devices, Point-Of-Care (POC) testing, robotic surgery and 3D printing are changing the landscape of current healthcare systems in terms of diagnostics, treatments and delivery of quality care. Advances in big data, ubiquitous computing, semiconductors and nanotechnology are creating profound opportunities for disaster recovery coordination, epidemics' prediction, evaluation of new medicine and large-scale DNA sequencing to detect human genetic variations. Some of these important technologies are discussed next.

3.5.1. Ingestible Sensors

The ingestible sensors allow physicians to monitor patient's ingestion and adherence to medicines in real time. These sensors are activated after the ingestion and transmit information about the drug's ingestion and its relation with patients' behaviours such as physical activity and physiological responses (blood pressure, heart rate and sleep quality). They are being used to monitor medication adherence [32], like adherence to tuberculosis therapy [33] and highly reliable monitoring of the timing and intake of drugs for clinical management of kidney transplant patients.

3.5.2. Wearable Sensors to Wireless Charging Implants

Recent advancements in sensing technologies have made great progress in monitoring patients' health in an unobtrusive manner. The wearable devices are widely being used to measure various physiological signs and physical activities. Recent advances in microelectronics and nanofabrication have shifted the trend from wearable sensors to implants, which transmit health-related information from inside the body. These implantable sensors have enhanced capabilities to capture vital health-related signs along with critically accelerated detection of failing implants, thereby minimizing healthcare hazard [34]. SWIPT has the potential to ease sterilization and reduce procedure and maintenance time by increasing reliability for these implants. Now, it is not too distant in the future when a patient having severe memory loss due to injury or Alzheimer's stroke will be able to create long-term memories with the help from an electronic implant [35].

3.5.3. Robot-Assisted Therapy and Surgery

Medical robots and computer-aided surgery have great potentials to fundamentally change the nature of medicine and surgery. They work as the patient-specific information-driven surgical tools that empower the surgeons to treat the patients with great safety, reduced morbidity and improved efficiency. The most striking efforts by robot-assisted surgery can be seen in stereotactic brain surgery, surgery in gynaecology, microsurgery, endoscopic surgery and orthopaedics surgery, as well as for providing assistance to nurses in labour-intensive tasks [36–38]. Robotic prosthetics are also revolutionizing healthcare by creating neurally-controlled artificial organs (i.e., limb) that can restore near-natural motor and sensory capabilities of amputee patients.

3.5.4. Open Source EHR/EMR Systems

The open source EHR or Electronic Medical record (EMR) is very crucial to improve the efficiency of present resource-constrained healthcare systems. Open source software is gaining attention for is adoption in the healthcare industry, which is helping to overcome several barriers (i.e., excessive cost, lack of interoperability and the transience of vendors). The fully-integrated and secure EMRs have various interesting features like practice management, electronic billing, scheduling, internationalization, patient demographics, medical reports and patient access portal. These features enable people to adopt EMRs that results in cost reduction and capacity and quality enhancement, and they especially lessen the disparities between wealthy and poor. Therefore, various open source task forces, scientists, organizations and research groups are offering open source platforms for the compilation of EMRs. Examples include OpenEMR, OpenMRS , FreeMED, OSCAREMR, OSCARMcMasterand VistA.

3.5.5. Point-Of-Care Testing

POC testing or bedside testing refers to medical diagnostic testing near the patient in the clinic or in the patient's home instead of a central laboratory. It can be advantageous in emergency situations to avoid delays in sending patients away from the point-of-care. POC testing devices communicate (uni- or bi-directionally) with the POC testing data management system, where the information is used for the decision-making process. There is a myriad of truly portable devices that are being used for POC testing by healthcare practitioner, as well as by patients. For example, dipsticks are being used for the semi-quantitative estimate of a range of clinically useful analytes in urine and whole blood [39]. Similarly, another new entrant for POC teasing called PIMA® is being used for the measurement of T-helper cells (also known as CD4 counts). Measurement of these cells is very crucial for antiretroviral HIV therapy and monitoring of immunosuppression [40]. A descriptive list of various existing POC testing devices can be found in [41].

4. 5G and Healthcare Opportunities

5G is not just the new generation of 3G and 4G technologies, but it will create a new era of agile and turbo-charged connectivity with great performance and applications tailored precisely according to the different needs of users and the economy. Some prominent use cases along with related examples of 5G are shown in Figure 5.

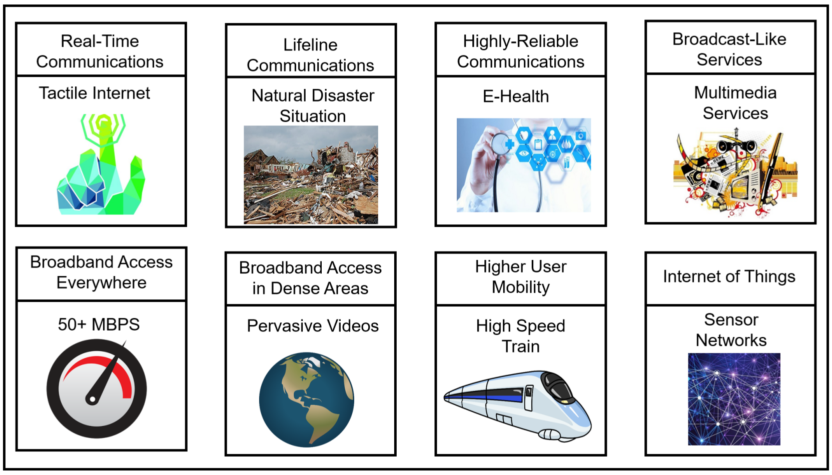

Figure 5. 5G use cases and related examples. Adapted from: [42].

It is anticipated that 5G will achieve one thousand-times improvement in throughput with close to zero latency as compared to previous generations. The goals envisioned for 5G are shown in Figure 6. The latency of 5G is expected to be just a single millisecond, that is 50-times faster than 4G. The new paradigm of 5G will also bring various innovative health services with URLLC. As a result, patient care will be improved with low physician workloads and reduced costs. The "Tactile Internet" [43] will enhance current transmission capabilities of touch and skills. This ultra-responsive network will enable remote physical experiences for the surgeon to provide an accurate medical diagnosis and surgery. The extended transmission of multi-sensorial data including robotic touch (i.e., haptic feedback) will improve the overall experience of real-time remote interaction and consultation. Further, virtual and augmented reality will provide an immersive user experience and can be used for virtual reality exposure therapy. These distinctive features of 5G are the driving force in the future of medicine. This will change the trends in healthcare from reactive care to proactive care by providing the following missing pieces in the previous mobile communication network.

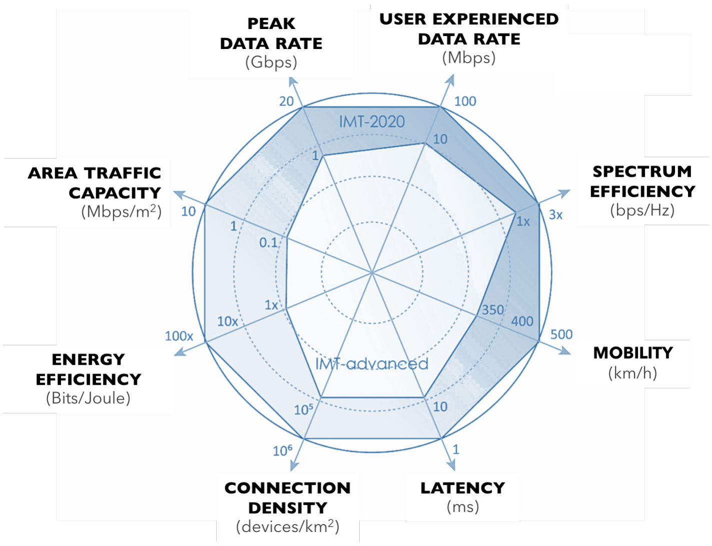

Figure 6. Some major goals articulated for 5G. Adapted from resources made available by the European Telecommunications Standards Institute (ETSI).

5G will integrate various technologies in addition to those already employed by Long-Term Evolution (LTE) and will also utilize higher frequency bands to provide enhanced mobile broadband to address human-centric use cases. Some novel applications that will be enabled by 5G include ultra-reliable-low latency communications and massive machine-type communications for a huge number of connected devices [44]. In 5G architecture, new features—such as OFDMA (Orthogonal Frequency Division Multiple Access), MIMO (Multiple Input-Multiple Output), carrier aggregation, Filtered OFDM (F-OFDM), Multi-User Multiple-Input Multiple Output (MU MIMO) and Sparse Code Multiple Access (SCMA)—will allow one to utilize the existing spectrum more effectively and increase user throughput rates and coverage. Self-Organizing Networks (SON) [45] will likely play a key role in the radio access portion. The 5G architecture will also incorporate Network Function Virtualization (NFV), network slicing and Software-Defined Networking (SDN) to create intelligence automation that will enable quick network scalability.

5G will deliver sufficient rates to the end consumer and pave the way for a fully-connected and mobile society with various promising healthcare applications (as already being conceived by various industry players [46] and the standardization organization 5GPP [47]). In what follows, we highlight some open research issues and future research directions for 5G-enabled healthcare.

4.1. Mobile Devices and Tablets can Help Leverage AI, Big Data and Connectivity

The proliferation of mobile communication devices and associated wireless technologies has stimulated various innovative health interventions for personalized care. The advanced connectivity of mobile devices (like mobile phones, tablets, laptops, EHRs, sensors, PDAs, etc.) and applications provide enough health-related information that can be excellently utilized by big data and AI to provide smart healthcare solutions [7]. In addition, smartphone and tablets can also serve as IoT controllers to monitor health data in real time that can make necessary changes to physical sensors or components in the medical IoT network. When 5G becomes available with improved connectivity and cloud-based storage, a much wider mesh of devices, even the smallest sensors, will be able to communicate. Powerful cloud-based computations will bring up a mobile IoT that will provide a wide variety of opportunities, especially in healthcare.

The world's persisting problems like the uneven distribution of healthcare resources, healthcare disparities, the growing number of patients with chronic diseases and increasing medical expenses will be greatly mitigated with the blend of technologies like 5G, IoT, big data and cellular technology.

4.2. 5G and Universal Coverage

Currently, 5G is in a formative stage and is anticipated to materialize by 2020. 5G will be the first technology to be developed in an age when the vision of global Internet connectivity is close to reality (as almost 60% of the world's population is already covered by a mobile 2G/3G/4G signal). 5G should materialize on this legacy and aim to provide universal coverage to digitize societies. By 2020, it is expected that 5G will provide connectivity to 50 billion devices, 212 billion sensors and enable access to 44 zettabytes of data [48]. Similarly, the 5G cloud is likely to cover one-third of world's population with 1.1 billion connections by 2025 [49]. In a report by the Global mobile Suppliers Association (GSA) [50], it is estimated that the commercial deployment of 5G will begin after the completion of standardization process in 2020. They also projected that over 270 operators will have deployed the commercial services of 5G over the globe. In the context of universal access, 5G is exploring the integration of various technologies such as Device-to-Device (D2D) communications, IoT, Massive Multiple Input-Multiple-Output (MIMO), millimetre wave communications and full-duplex transmissions to increase coverage in all urban and rural areas, as well as on roads and on railway tracks. Additionally, Unmanned Aerial Vehicles (UAV) and drone communications will also be utilized to provide coverage in rural areas.

Despite its great potential for universal access, we have noted in our previous work [51] that many 5G technologies—including the big three 5G technologies [44] of ultra-densification, millimetre Wave (mmWave) and massive MIMO—are primed towards increased performance rather than coverage. In fact, technologies such as ultra-densification and mmWave will make universal coverage even more challenging; even though massive MIMO can be used for coverage gains and energy reduction if the associated computational cost of massive MIMO can be overcome. The problem of universal reliable coverage for 5G will be an important concern for healthcare applications due to the criticality of its subject domain that directly affects human lives. In particular, research on extending coverage, and providing reliability guarantees is key for enabling the various e-health applications. In terms of technologies, energy optimization (e.g., via advanced MIMO and beamforming) will become important and will require further innovations.

4.3. In-Home Health Monitoring

Wearable sensors and implantable medical devices (to monitor and transmit health recorded data) will feature prominently in the future of wireless healthcare systems. There are already many examples of wearable/implantable medical devices (e.g., cochlear implants, cardiac defibrillators/pacemakers, insulin pumps) that are having a large impact on patients and bringing them much ease. In the future, interfacing these wireless sensing devices with 5G will present unprecedented opportunities, as well as formidable challenges.

Currently, there are several technological constraints (i.e., low data rates, limited connectivity, security concerns, etc.) that prevent the large-scale adoption of in-home health monitoring services. The future 5G infrastructure will open up a new set of possibilities to tackle these constraints by providing extended security along with higher bandwidth, transmission reliability and ubiquitous access. This will provide always-available communication services for health monitoring, with a great increase in transmitting capability between health service providers and patients.

Already, there have been exciting advances in terms of the ability to conveniently perform in-home health monitoring. For example, patients can now measure their vitals (e.g., AliveCor ECG application at home using mobile devices at a reduced cost with more convenience, compared to previous options that typically entailed a visit to the local hospital. The advances in 5G can spur a decentralization trend in which healthcare facilities can be delivered locally in homes, nursing centres, surgery centres, clinics, rehabilitation places, remote areas and even in ambulances (e.g., when shifting critical patients to central healthcare facilities). 5G will also open up new opportunities for radar technologies to monitor the health of elderly people (i.e., fall detection and quantitative gait measurement) in a non-invasive manner both in a home and the clinical environments.

4.4. Virtual Reality + Haptic/Tactile Internet

The Tactile Internet is an ultra-responsive and ultra-reliable network connectivity that is envisioned to transmit touch and actuation in real time. It will revolutionize almost every segment of society with unprecedented applications and also truly shift the paradigm from content-delivery to control communications (skill-set or labour-delivery) also called haptic communications. It will create an Internet of an entirely new dimension to machine-machine and human-machine interaction by providing low latency and high reliability, secure with a supper coverage network; which are the daunting requirements for real-time interactive systems [43]. Tactile Internet underpinned by the zero-delay network will provide virtual reality-based headsets, which can facilitate doctors in performing operations through telepresence.

4.5. Internet of Medical Skills

The exhilarating breakthrough in technology focuses on connecting societies and professionals with a great responsiveness and reach. This will create an Internet of medical skills to transfer or share your experience and expertise over a long distance using robotics and haptic feedback. 5G will not only spread connectivity, but it will also enhance the opportunity for remote training with visual and tactile communication. Doctors will become teachers, and students in remote areas can follow and experience surgical procedures. Robots will be controlled by the use of haptic glove, and they will transfer tactile data back to operating doctor over a distance. This exciting glimpse of the future is only possible with the ultra-low latency of under ten milliseconds.

5. Case Study: Economic Benefits of 5G-Enabled Healthcare Solutions

Healthcare spending takes a big chunk out of the national budgets of various countries globally (e.g., healthcare spending accounts for roughly 18% of North America's and 10% of the global economy's gross domestic product (GDP) [52]). A study by the Economist Intelligence Unit on 60 countries shows the growth of healthcare expenditure in different regions (see Figure 7). It is expected that the percentage of GDP spent will rise globally mainly due to population ageing and the rise of chronic disease.

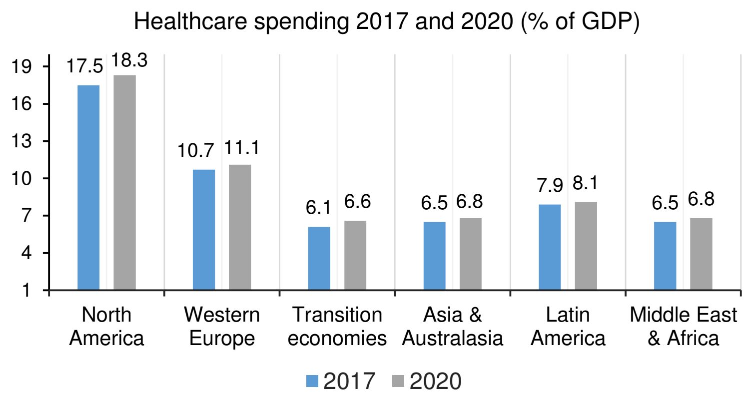

Figure 7. Region-wise comparison of healthcare spending (as a percentage of of GDP) in 2017 and projected expenditure in 2020. (Adapted from: [52,53]).

In a report by Deloitte, it is estimated that 50% of global healthcare expenditures (about $4 trillion) will be spent on three leading non-communicable diseases (i.e., cardiovascular diseases, cancer and respiratory diseases) by 2020 [52]. They also projected that healthcare spending as a percentage of GDP will rise more quickly in low-income countries due to the rise in cardiovascular disease and limited government reimbursements for respiratory conditions. An analysis performed by the World Health Organization in 23 low-and middle-income countries reported the economic losses from three non-communicable diseases (stroke, heart disease and diabetes) from 2006–2016 [10]. The National Diabetes Inpatient Audit reported that at any time, around 15% of hospital beds are taken up by people with diabetes in the U.K. [54]. A major cause for the rise of these diseases is a dramatic increase in average life expectancy. Countries with the lowest relative need have the highest proportion of healthcare workers. Figure 8 presents the distribution of healthcare workforce, where the horizontal axis represents the number of health workers, the vertical axis shows the burden of disease and the size of the dots is the total health expenditure. Figure 8 clearly shows that the region of the Americas has only 10% of the global burden of disease, but almost 37% of the world's healthcare workers reside in this region; and their health expenditure is over 50% of the world's financial resources. In contrast, Africa suffers more than 24% of the global burden of disease, but has access to only 3% of health workers with less than 1% of the world's financial resources.

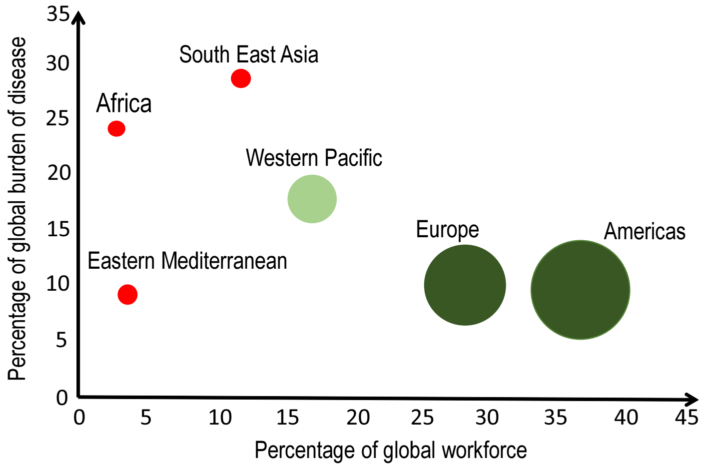

Figure 8. Distribution of health workers by level of health expenditure and burden of disease, by WHO region (adopted from: [55]).

Technology-enabled healthcare systems can deliver care outside the traditional setting by keeping patients at remote locations, promoting adherence to medications, lowering readmission rates and reducing cost. They not only boost healthy lifestyle, but also benefit regional and global economic growth in various ways. They offer huge commercial chances and opportunities. These opportunities are not only limited to hospitals, healthcare providers, health insurers and the pharmaceutical industry, but will become very crucial for network operators, telecommunication providers and software developers. Some of the economic benefits of technology-enabled healthcare are discussed below.

5.1. Cost Saving with Mobile Health and Telemedicine

Technology-enabled virtual care is the right solution to the rising burden of healthcare expenditure by tackling healthcare issues and reducing cost. The integrated healthcare systems by utilizing 4G LTE for e-Health and mHealth applications have sound economic benefits fuelled by the continuously increasing amount of smartphones and expeditiously improving connectivity. For example, the mobile-based health solution enables remote treatment and monitoring of chronic conditions and equips physicians to make better clinical decisions. In this way, mHealth can reduce the healthcare cost substantially. In a report on the European Union (EU), it is noted that mHealth solutions could save €99 billion in total annual healthcare spending and would add €93 billion to EU GDP in 2017 if mHealth is encouraged [54]. These savings equate to the treatment of an additional 24.5 million patients with the same number of doctors and facilities. Each year, mobile health-based remote monitoring of the elderly at home saves €2.4 billion in Sweden, €1.25 billion in Denmark and €1.5 billion in Norway [56].

Telehealth serves as a low-cost clinic, extends clinical staff to other locations and provides a convenient, private and integrated diagnostic and treatment. The global telehealth market is growing rapidly; it accounted for revenue of $17,878.7 million in 2015, and is expected to grow at a compound annual growth rate (CAGR) of 18.7% during 2016–2022 due to increasing acceptance of the 4G and 5G spectrum [57]. GSMA Intelligence provides an overview of the market value of global digital health including telemedicine, mHealth, EHRs, etc. (see Figure 9).

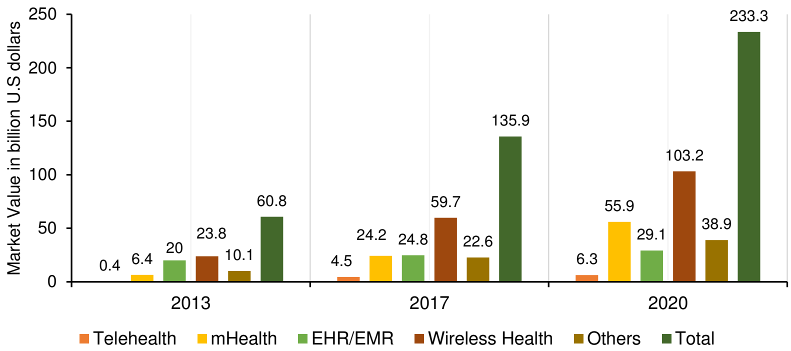

Figure 9. Global digital health market from 2013–2020, by segment (in billion U.S. dollars) (source: GSMA Intelligence).

It can be seen from Figure 9 that the total market value is expected to grow from $60.8 billion in 2013 to $233.3 billion in 2020 [58]. According to the report by Deloitte on connected health, the telehealth hub across 210 homes can reduce 35% of hospital admissions, 53% use of accident and emergency department visits and 59% of hospital bed days [59]. Further, telehealth can save $100 a visit by reducing medical costs (81% of the reduction in medical costs) [60].

Despite the tremendous increase in the mobile phone coverage and Internet access, 46.4% of the global population still lacks Internet access, and there are twice as many mobile-broadband subscriptions per 100 inhabitants in the developed world as in developing nations [61]. The 5G network has potential to significantly fill this gap by ensuring a consistent user experience ranging from dense areas to villages or even remote areas. In this way, the emerging healthcare applications (i.e., mHealth and e-Health) will be available in a much wider spread than today. This paves the path of telehealth and mHealth to be available nearly everywhere. Hence, health services will be available to people of remote areas like Sub-Saharan Africa where the average distance between a person and the nearest medical facility is five miles. It is projected that mobile health could save over one million lives in Sub-Saharan Africa over the next five years [46].

5.2. Economic Benefits of IoT

5G use-cases like the Internet of Things (IoT) will enhance productivity and boost economic activities across the globe. IoT can enable data-driven patient management that will provide improved healthcare effectiveness and efficiencies with minimum cost. IoT will create $14.4 trillion net profit from 2013–2022 by increasing revenues and lowering costs [62]. The following are five factors that fuel IoT value that are at stake:

- Better asset utilization results in a $2.5 trillion cost reduction
- Greater employees' productivity causes a benefit of $2.5 trillion
- Improved supply chain management eliminates waste of $2.7 trillion
- Improved customer experience adding more customers equivalent to $3.7 trillion
- Reduced time to market of $3.0 trillion

According to the report compiled by McKinsey & Company, IoT will have a total economic impact of $3.9 trillion–$11.1 trillion per year in 2025. In healthcare, it could have an economic impact of 170 billion USD–1.6 trillion per year by 2025. The societal benefits in terms of reduced cost, chronic disease management and improved health of users could be worth more than 500 billion USD per year. These potential annual economic impacts will be 62% in developed economies and the remaining 38% in developing economies. In the past, 3.3 million activity trackers and fitness bands were sold in one year (between April 2013 and March 2014) in the U.S., and these numbers continue to grow [63]. According to Aruba Networks, globally, 60% of healthcare organizations have introduced IoT devices into their facilities, and it is expected that IoT is heading for mass adoption by 2019 with better business results [64]. The productivity gains and cost savings through smart monitoring and adaptive systems are estimated to create $1.1 trillion–$2.5 trillion in the healthcare sector [65]. IoT-based remote patient monitoring will drive the global market at a CAGR of 24.55% by 2020, where the smart pill technologies alone are expected to reach $6.93 billion by 2020 with a CAGR of 23.62% [66].

5.3. Economic Benefits with Big Data Analytics

In the 5G orchestration, IoT will be the key part where billions of sensors pass or process a huge amount of data (including videos). The opportunity here is to use these big data to improve the quality of applications that will emerge in 5G. Artificial intelligence, big data analytics and self-managing systems will be used to incorporate these ideas in the 5G architecture. Big data analytics is playing important roles in every sector of the global economy. The global market for big data-related software, hardware and professional services like networking, data-centre computing, storage and information management is projected to reach €43.7 billion Euros by 2019 (10-times more than in 2010) [67]. Big data have been considered as an effective tool to reduce the required healthcare costs by reducing readmissions, eliminating adverse events and unnecessary tests [68]. Big data also proved a cost-effective solution for high-cost patients, triage and decompensation situations by optimizing treatments [69]. Following are some possibilities of economic benefits for which big data can effectively be used.

- Tracking high-cost patients, reducing adverse events, lowering readmissions and treatment optimization [69]
- Reduction of healthcare expenditure by predictive modelling [70]
- Better earlier detection of medical conditions [71]
- Reduce the development costs for pharmaceutical companies [72]
- Lower costs through better patient interventions [68]
- Big data analytics could reduce the time required for research study by predicting the patients that would most likely comply with the studies [71]

There are strong pieces of evidence that big data can significantly benefit national economies and their citizens. For example, the University of Michigan Health System has increased $200,000 in monthly savings in providing blood transfusions using big data analytics [73]. A report by IBM on data-driven healthcare described that the Rizzoli Orthopaedic Institute in Bologna, Italy, is improving care with reduced cost by using advanced analytics for hereditary bone diseases. They attained more efficient and cost-effective care with 30% reductions in annual hospitalizations and over a 60% decrease in the number of imaging tests [74]. Similarly, a U.S. healthcare alliance has a network of more than 2700 member health systems and hospitals, 400,000 physicians and 90,000 non-acute care facilities. The Premier alliance has compiled a database of the information on one in four discharged hospital patients in the United States. The database provides the detailed information about the comparative clinical outcome measures, resource utilization and transaction-level cost data. Through Premier, the healthcare processes of more than 330 hospitals have been improved, more than 29,000 lives have been rescued and healthcare expenditures have been reduced by approximately $7 billion. Another report compiled by McKinsey & Company (New York, NY, USA) [75] found that the government administration of Europe can save $149 billion in operational efficiency improvements alone by using big data. They also estimated that the potential of data in the U.S. health sector could be $300 billion each year if the U.S could exploit big data effectively and creatively.

5.4. Economic Impacts of AI

It is expected that in the future, AI will have a big impact on the healthcare industry with the AI health market growth expected to reach $6.6 billion by 2021 [76]. The interest in AI-based healthcare systems can be gauged from the fact that Babylon Health (London, UK) raised close to $60 million in April 2017 for its platform that uses AI and smartphone-based chatbots [77]. A research work conducted by Accenture projected that the use of AI in healthcare could significantly enhance (nearly double) the annual economic growth of the twelve developed economies studied by 2035 [78]. According to the report by Accenture, 10 key AI-based healthcare applications can potentially create $150 billion in annual savings for the U.S. economy by 2026. The Accenture report also estimated that the shortage of physicians will likely double over the next nine years. AI and 5G communication have the power to alleviate this burden on clinicians by providing remote care settings directly to the patients. In another study conducted by Frost & Sullivan, it was projected that AI has the potential of improving health outcomes by 30–40% while reducing the costs of treatment by 50% [79]. The estimated impact of AI applications on the health sector and the national economies is shown in Figure 10).

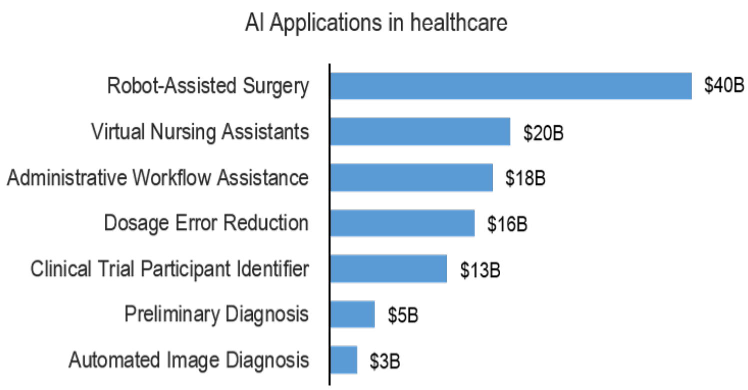

Figure 10. AI healthcare applications with the greatest impact on the economy (Adapted from: [79]).

6. Technology for Healthcare: Challenges/Pitfalls

Currently, healthcare industries are mainly concerned with the increased burden of chronic disease and life expectancy, shortages of resources, regulatory requirements problems, rising patient expectations and required costs. In the upcoming years, IoT-automation, big data analytics, cloud computing and robotics will result in a great transformation of healthcare worldwide. Many challenges will arise from these advancements such as patients' privacy, cybersecurity and data governance issues. Similarly, a 5G-enabled integrated, intelligent and massive healthcare system in every city, town and community of the world will require enormous amounts of money, time and human capital. It is critical to adopt intelligent, informed and pre-planned strategies to avoid the waste of money, time and labour.

6.1. Will Computers Replace Doctors?

Today's diagnoses and treatments are partially performed by patients' medical histories and symptoms. A study [80] found that each year, 40,500 deaths are caused by misdiagnosis in the USA. Similarly, the system-related factors, e.g., poor processes, lack of teamwork and inadequate communications, incorporated 65% of diagnostic error [81]. These kinds of diagnostic errors are adding to the rise in healthcare expenditures [82]. Most of the physicians perform check-ups and testing to suggest prescription and behaviour modification that can be done better by data-driven analytics. Computers can perform better in much of the diagnosis and treatments by utilizing more complex physiological and sensor data than a practitioner could comprehend. It has even been argued that computers will replace 80% of what doctors do in the future while providing quicker, more accurate and fact-based clinical performances [83].

Notwithstanding the hype, it is safe to assume that computers will play a much larger complementary role in clinical settings in the future through the automation of the various routine matters that doctors must do, thereby creating more space for doctors to engage in non-routine health decisions that humans can manage better than algorithms. Human doctors will likely warm up to the use of information technology in the long run due to the benefits it affords. Human doctors can use their intuition that is trained over years of experience to oversee the working of algorithms and AI. Furthermore, human doctors are better equipped to manage personalized care than a machine.

The transition to automation in health will not be easy due to the sensitive nature of the domain and the high cost associated with any kinds of errors. Furthermore, there are numerous technical challenges associated with the collection and processing of enormous amounts of data to comprehend the patients' problems and thereafter perform diagnostics through sophisticated AI and ML algorithms.

6.2. Technological Revolution Needed or Behavioural Revolution?

Increasingly, the most critical challenges in healthcare are not related to information, but behavioural challenges. For example, in the U.S., more than 36.5% of adults have obesity. People have knowledge (eat less, exercise more) about losing weight [84]. However, behavioural changes, include changing ingrained lifestyle habits such as to overcoming cravings and finding time and motivation to exercise, are difficult to adopt. To change the traditional healthcare trends and practices, a behavioural revolution is also very crucial to encourage patients. Personal behaviour has deep influences on one's health. For example, many people can make their health better by managing their chronic disease. They adopt specific health behaviours, i.e., by managing their diet plans or by regularly engaging themselves in health-promoting activities [85]. Significant progress has already been made in understanding and changing health behaviour [86,87], but additional technological models based on human psychology and innovative behavioural economics theories are needed; which can effectively utilize advanced technologies to meet the goals for behavioural changes among individuals and society.

6.3. Bias in Humans and Data: The Perennial Bugbear

Every field of science experiences human biases, but in medicine, human bias is more acute and causes diagnostic inaccuracies and medical errors. Doctors mostly encounter common diseases, and occasionally some distinct diseases. In many cases, different patients having the same disease react differently to medicine, and physicians' attempts to make sense and perform diagnosis from such uncertain and imprecise information may lead to wrong therapeutic decisions. Similarly, physicians apply new medical products or treatments to their patients since most of the evidence regarding such innovative medical treatments has been generated from highly controlled research environments [88]. These new medical products and interventions can influence patients' health differently because of various disparities such as quality of life, sex, income, geographic location, education and disability status. The same biases are experienced by any predictive model or algorithm that works on data and used statistical processes to identify patterns. For example, machine-learning models learn from initial training data by analysing their patterns and make predictions about the new (test) data by finding similar patterns. If these models learn the wrong signals from training data, the subsequent results will lead to the wrong prediction. In [89], Mukherjee notes insightfully that the emergence of innovative medical technologies will not reduce the bias from medicine, but they will amplify it. Furthermore, big data are not the solution of this bias; they comprise a source of more subtle biases. Therefore, to facilitate this biased learning, we required algorithms that ensure the actual effect of an intervention by comparing the groups of similar patients rather than the propensity score methods, which include attributes of many patients. In this way, confounding biases can be reduced in healthcare databases.

6.4. Cost Barriers for 5G

Many proposals or solutions have been proposed in order to attain the proposed goals of 5G architecture. These solutions include spectrum allocation approaches, massive MIMO, heterogeneous cell architecture, content caching, NFV, etc. Each solution is able to achieve several goals to overcome multiple challenges. However, many of these proposals will require additional changes or modifications in the telecommunication infrastructure to work [90]. The changes such as additional small cell deployments, fibre installation to replace copper and upgrades in the core network require enormous costs. In the GSA survey, it is also reported that the cost is the highest ranked issue to meet the 5G goals [50].

6.5. How to Incentivize 5G Healthcare?

The objective of a digital healthcare system, empowered by 5G across the globe, is the benefit of consumers (patients and doctors), businesses and inclusive of the economy. 5G will pave the new ways for the provision of specialized healthcare services, in particular services by IoT (telecare and telehealth). Currently, healthcare providers hardly receive reimbursement for telemedicine and at-home health therapies over video conferencing or mobile phone [48], which discourages the use of such services. This calls for new policies that would promote appropriate incentives and reward (investment) for telemedicine like services and 5G orchestration platforms. These investments and incentives should be enough to operate 5G-based health monitoring services and should remain productive enough to finance continuous upgradations for speed and capacity. In addition, for 5G-based digital healthcare system, value-based reimbursement, rather than fee-for-service, should be adopted to reward physicians by linking health outcomes with the treatment results and diagnosis records suggested by physicians. In this way, both service providers and patients will be able to observe the results of treatments that can directly be correlated with the worth of expenditure.

6.6. Security and Privacy for 5G-Enabled Healthcare

The 5G network will link almost every aspect of human life to the Internet by using billions of devices and sensors. This will probably result in various threats to the security and privacy of consumer data. 5G security threats are more serious to healthcare systems as cyber attacks on them can be detrimental at a society level. In particular, IoT devices will be more exposed to vulnerabilities as most of the small sensors and tiny devices with low computational power are unable to handle complex encryption algorithms. Consequently, the data in transit will have to be sent without any encryption. Therefore, strong mechanisms are required to secure or encrypt such bare communications. Similarly, cloud-based IoT platforms used for outsourced storage and computation, due to the resource constraints of IoT sensors and devices, will also bring a series of privacy and security issues [91]. 5G networks must deal with the cybersecurity risks and privacy concerns of users, governments and organizations. The vision of 5G will not become a reality without robust security measures that can preserve the ethical and privacy concerns. Therefore, the level of end-to-end integrated security and confidentiality for 5G networks should be more comprehensive than previous generations of mobile networks.

7. Conclusions

> *"In the next ten years, data sciences and software will do more for medicine than all of the biological sciences together."*—Vinod Khosla [28]

It remains to be seen if the optimistic prediction of Vinod Khosla (a prominent Silicon Valley technologist and healthcare investor) will come to fruition. However. it is safe to assume that with 5G along with the confluence of other emerging technologies—such as the Internet of Things (IoT), big data, Artificial Intelligence (AI) and Machine Learning (ML)—the healthcare industry will change drastically as these technologies are used to augment human capacity and enhance the effectiveness of human potential. In the near future, 5G technology, when it is finalized, will enable novel healthcare applications while facilitating an ad hoc orchestration of healthcare services by integrating patients, medical practitioners, and social workers through its enhanced Mobile Broadband (eMBB), URLLC and ubiquitous access services. 5G will enable resource pooling of expert human resources through high-performance and reliable telemedicine, including enhanced telemedicine using the tactile Internet with haptic feedback. Personalized healthcare will become possible through advancements in big data, sensor technologies and AI/ML. Furthermore, routine activities of humans including diagnoses of most cases will be managed by AI and ML algorithms. In this way, the overall healthcare systems will be improved, thereby benefiting the global economy.

The purpose of this paper was to present for the first time a big-picture overview of this impending 5G-enabled healthcare revolution that will be driven by 5G wireless technology and fully supported by other associated technologies. We provide a description of each of the various involved technologies and their potential for healthcare, while providing pointers to existing literature and advances. We also presented a case study on the economic benefits that will be offered by 5G technology-enabled healthcare. Further, we have highlighted the exciting research and implementation opportunities in building this future of 5G-enabled healthcare while also pinpointing the substantial challenges involved and the potential pitfalls.

Author Contributions: All authors contributed equally to this work. Junaid Qadir suggested the skeleton of the paper and also provided the supplementary material for paper write up. Siddique Latif wrote the main paper with the guidance of all other authors. Shahzad Farooq and Muhammad Ali Imran provided the technical guidance for 5G and related applications with proofreading the paper. All authors provided comments on the manuscript at all stages.

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