ABSTRACT

Technological advancements have led to significant improvements in healthcare for prevention, diagnosis, treatments, and care. While resourceful regions can capitalize on state-of-the-art healthcare technologies, there might be barriers and delays in technology-enabled healthcare availability for a low-resource region. Unique innovations guided by the constraints of low-resource regions are required to truly make healthcare technologies ubiquitous and achieve the goal of "healthcare for all". In this review, we identified several research and development works that have investigated technology-based healthcare innovations targeted at low-resource regions. We found three main pillars of work towards this end: low-cost hardware for the affordability of medical devices, use of information and communication technology (ICT) tools for scalability and operational efficiencies in healthcare services, and mobile health solutions. Several emerging technologies are also promising for healthcare in low-resource regions, such as artificial intelligence, the Internet of Things (IoT), and blockchain technology. We discuss these emerging technologies too in this review.

Keywords Healthcare technology · Low-resource · Developing Countries · Low-Cost Healthcare · Health Technology

1 Introduction

The healthcare burden has been rising globally with increased incidences of sickness and poor health [1]. We have observed the situation get further dire in the past years due to the global pandemic of COVID-19. While the healthcare needs have only been increasing, the skilled human resources required to meet the associated increasing needs have not been growing proportionally [2]. Technological advancements could help to reduce the burden in the healthcare system, for example by automating diagnosis and improving operational efficiencies. The need to improve diagnosis, treat new diseases and provide care for more people has meant that the state-of-the-art healthcare infrastructure is getting more complex. This increasing complexity has also meant rising costs. The standard healthcare infrastructure of today could be cost-prohibitive in many low-resource regions. Since many people still live in areas that can be categorized as being low-resource regions [3], efforts toward making healthcare accessible and affordable in low-resource regions should also be a priority. This will help to fully realize the global goals of healthcare for all such as the sustainable development goals of good health and well-being [4].

Low-resource regions, also referred broadly to as low and middle-income countries (LMICs), are the geographical regions with a smaller economy and poor access to basic infrastructures [5]. While healthcare has several general challenges such as identifying treatments for new diseases, there are some challenges specific to the low-resource settings. Standard healthcare infrastructures being highly cost-prohibitive in low-resource settings is one of such challenges. Even in terms of human resources, the low-resource regions tend to have a smaller health professional to patient ratio [6]. Skilled healthcare professionals often chose to live in resourceful regions for better facilities and remuneration [7]. Hence, it is not uncommon in low-resource regions that personnel without appropriate training for a healthcare role still fill in that role due to the lack of available trained professionals. An example is the non-physician
clinicians commonly seen in low-resource regions [8]. This unavailability of adequate skilled health professionals has implications on the quality of healthcare. Besides healthcare professionals, the patients themselves are also a factor in the quality of healthcare delivery. Generally speaking, people living in the low-resource regions might have had lesser access to quality education [9]. Thus, they might have less awareness about health, good practices, and seeking care which has implications for the effectiveness of the healthcare that they receive. Similarly, there might be impediments due to cultural and religious barriers which impact health services and delivery in low-resource regions [10].

Technology can play a vital role in addressing some of the healthcare challenges in low-resource regions. New devices for diagnosis and treatment could be helpful to streamline healthcare where adequate healthcare professionals are not available. For example, a device for automated respiration rate monitoring could relieve nurses from having to manually estimate respiration rate [11] and enable them to triage more patients in a given time. New technological designs and manufacturing improvements geared for cost reduction can make healthcare devices affordable for low-resource regions. However, there are also open questions regarding the impact of cost reduction on the quality and reliability of the devices (solutions). Information Technology (IT) and automation can also help make healthcare solutions cheaper by scaling existing healthcare solutions and simplifying workflows in healthcare delivery. Similarly, automated clinical decision-making to aid healthcare professionals can increase the efficiency of health processes and reduce associated costs. An important platform for pervasive and affordable healthcare solutions could be the currently ubiquitous smartphones and mobile networks which are getting more accessible in low-resource regions [12]. Some of the upcoming technologies will also likely contribute to improving healthcare in low-resource regions. For example, advanced machine learning and artificial intelligence have already shown promises for improving and democratizing healthcare [13]. Other emerging technologies like the Internet of (Medical) Things (IoT/IoMT) and blockchain are also poised to revolutionize healthcare [14] and likely lead to the advancement of healthcare in low-resource regions [15].

In this paper, we review some representative works on healthcare technologies for low-resource regions. In Section 2, we present works on low-cost medical devices. Then the use of IT solutions to scale and democratize healthcare resources is presented in Section 3. Smartphone applications geared towards healthcare that could be relevant for healthcare in low-resource regions are presented in Section 4. In Section 5, we present some of the emerging technologies that could improve healthcare in low-resource regions. Based upon the reviewed works, we discuss the current state and outlook of healthcare technologies for low-resource regions in Section 6.

2 Low Cost Medical Devices and Equipment

Medical devices are an important component in the healthcare delivery chain used across diagnosis, treatment, and care. For example, diagnostic devices like vital sign sensors and patient monitors, life-critical support devices like ventilators and pacemakers, among others, are required in general and specialized healthcare services. Effective healthcare delivery requires supporting medical devices. However, the cost of medical devices in a particular care setting can be high. The costs are alarmingly high in higher acuity care settings like ICU (Intensive Care Unit) or OR (operating room) and still relatively high in lower acuity care settings like GW (General Ward). These high costs, both the capital expenditure and operating costs, can in themselves be a big impediment to the wider reach of quality healthcare services in low-resource regions [16].

Cost reduction of the medical devices can be achieved by several means such as:

- Re-design the existing devices to reduce components or use low-cost component alternatives
- Use alternate modalities to achieve similar functionalities as the standard medical devices
- Innovative operating model to maximize the utilization of costly devices

In this section, we review some works on low-cost medical device development. The works are categorized based on the approach toward lowering the costs.

2.1 Low-cost medical devices with reducing component costs

The overall cost of electronic components goes down every year [17]. The bill of materials for standard medical devices would thus lower too and possibly result in devices being affordable for use in low-resource regions. This, for example, has been presented to be a case by [18] for home-based glucose monitoring devices. Glucose monitoring is essential for monitoring chronic conditions like diabetes, a disease of growing worldwide concern and of increasing concern in low-resource regions too [19, 20, 21]. According to the authors in [18], the glucose monitoring devices for home use are getting affordable due to the general trend of lowering prices for semiconductor technologies. Standard electronic components such as microcontrollers, real-time clocks, flash memories, etc. have increased functionality while getting
cheaper. This proliferation of semiconductor technologies will further help reduce the overall costs of medical devices and thus barriers to entry of medical devices in low-resource regions.

2.2 Add-ons to smartphone

Another approach to reducing the cost of medical devices is to use the ubiquitously available smartphone as an add-on or replacement for some components of the medical devices. The authors in [22] proposed a low-cost blood pressure measurement device for low-resource settings. The authors suggested the use of smartphones for interfacing with a simple sensory front-end comprising a pressure sensor. With all the signal processing and visualization done in the smartphone, with the power supply too coming from the smartphone itself, the cost of the blood pressure measurement device could be significantly lower than a standard measurement device. Further, the smartphone as an interface helps to provide customized measurement guidance based on a person’s medical training, preferred language, etc. Similarly, the authors in [23] presented an approach to using a low-cost device add-on, acoustically coupled to a standard smartphone, for realizing a digital stethoscope. This approach reduced the cost by 150 to 400 times in mass production. The digital stethoscope can be used for various care conditions like the remote assessment of heart sounds from a cardiac patient or elderly patient monitoring at home. A digital stethoscope in the context of the COVID-19 pandemic to diagnose lung pathologies in the low-resource setting has been proposed by the authors in [24]. The applicability of digital stethoscopes in various application areas is still being actively investigated in several other works too [25, 26, 27, 28].

2.3 Alternate modalities of measurement

The price of standard medical devices can also be reduced by developing alternate modalities for diagnosis and treatment, which are comparatively cheaper. The authors in [29] developed an intermittent fetal heart rate monitoring device using Doppler ultrasound. It provided a comparative diagnostic value to that of a standard reference device such as the Cardiotocograph, at a much lower cost. The proposed device could operate with alternate power sources such as wind and solar power which made it further suitable for low-resource regions. The authors in [30] proposed the use of wood-lamp technology, a technology for UV light generation, to detect various skin infections. Early detection of skin infections could be crucial in the diagnosis of medical conditions like HIV/AIDS. The authors outlined various challenges related to technology, business model, etc. for the use of the proposed device. Nonetheless, the proposed diagnosis tool could provide a low-cost (pre-) diagnosis solution, suitable for use in low-resource settings when properly designed for easy use. The authors in [31] reviewed various technologies for cancer diagnosis, treatment, and care in low-resource settings. The authors found, for example, low-cost and portable commercial ultrasound solutions to be suitable in low-resource settings as a powerful diagnostic imaging tool.

Low-cost solutions for advanced state-of-the-art technologies have been discussed in several previous works. The authors in [32] presented a gyroscope-based gait monitoring system that can be employed for use in a non-clinical setting also. Gait monitoring has applications in the detection of the onset of neurodegenerative diseases, among others. IMU (Inertial Measurement Unit) like gyroscopes and accelerometers provide a cheaper alternative to standard references like optical marker-based motion capture technology or force plate sensors. The authors in [32] indeed found that cheaper alternative methods like gyroscope-based monitoring provided comparable accuracy to other standard reference methods. Similarly, the authors in [33] found inertial sensors to be a suitable tool to monitor physical functioning tasks in low-resource settings.

A smartphone could also provide an alternative to diagnostic devices for certain medical conditions. The authors in [34] presented a smartphone-based tool for mental health assessment that could be deployed in low resource settings. The developed application uses contextual data like actigraphy and light, along with the available vital sign measurements from third-party devices and validated clinical questionnaires, to assess and track an individual’s mental health. As the proposed solution does not require the use of any other diagnostic devices and can be deployed in a scalable way, it is well suited as a pre-diagnostic alternative for use in low-resource settings. Smartphone-based mobile sensing data have been shown to be promising in other mental health applications like schizophrenia [35], depression [36], bipolar disorder [37], etc.

2.4 Commodity hardware and software to improve efficiency

Technological solutions could also improve workflow and reduce clinicians’ burden where the patient to clinician ratio is commonly high. The authors in [38] discussed the Humanitarian Technology Challenge (HTC) on using technology to solve the challenges of healthcare service delivery in low-resource settings. RFID technology is proposed to identify and link different healthcare service interactions, e.g., at a clinic or from a mobile health worker, with a central database of a healthcare resource center. Robust identification of healthcare service interactions and linking to electronic health records is aimed at reducing errors in medical decision-making and enabling proper care planning.
The authors in [39] proposed machine learning techniques for the automatic identification of clinical conditions like pneumonia using heart rate, respiration rate, and other clinical information. Such automatic (pre-)diagnosis will lead to significant workflow improvements and medical error reduction. These will then reduce the costs in healthcare delivery. With the commodification of health devices (e.g., smartwatches consisting of several health sensors), the availability of trained personnel for data interpretation and diagnosis can still be an impediment to effective healthcare services in low-resource settings. Automatic data analysis and (pre-)diagnosis, such as those proposed by [39], can improve the usefulness of available health data in low-resource settings. Other works such as [40] also discussed the use of smartphone applications to support patient diagnosis in low-resource settings, especially where workflow can be burdened by the low-doctor-patient ratio. The authors also proposed a machine learning-based tool for automated diagnosis of disease. In a similar approach, the authors in [41] presented a mobile telecardiology system suitable for a low-resource setting. In the proposed solution, the ECG strip recorded by an ECG technician is captured as images using a mobile camera and sent to a remote server where it is automatically processed to extract key ECG features. Recommendations, and further referral to a trained doctor if required, are provided based on the ECG parameters and associated automatic assessments of cardiovascular conditions.

In the overall landscape of medical devices, the cost associated with infrastructure maintenance cannot be overlooked. In [42], the authors discussed the costs associated with healthcare infrastructure maintenance in a low-resource setting. The infrastructure in this context encompassed not only the medical devices but also the related support structures like the buildings, energy management, waste management support, etc. High costs were found to be mostly associated with the operating costs. The capital expenditure could be less in principle, thanks to the various international aid and support provided to low-resource regions. The authors suggested that the design and planning of infrastructure should be done according to the local circumstances of deployment areas. For example, the availability of components for repair, the possibility of training maintenance personnel, the availability of energy sources like solar plants, and the available monitoring unit for proper aid deployment should be taken into consideration. The authors in [43] discussed some challenges in maintaining computer-based infrastructure in low-resource settings. The authors also note that the cost of required trained professionals to sustain and maintain such infrastructure is the most significant. The authors proposed a centralized technological support model for cost-effectiveness that could be relevant for healthcare infrastructure deployments in low-resource regions.

2.5 Considerations for low-cost devices

Multiple issues need to be taken care of in the effort toward affordable medical devices for low-resource settings. Proper considerations of the underlying technology (suitability/reliability), business and cost models (sustainability/affordability), associated quality and usage factors, etc. need to be made. The authors in [44] advocated the need to approach medical device development for low-resource settings differently from a mere technology transfer process. A sustainable approach to the introduction of new technology is suggested by considering different factors such as customer needs in low-resource regions, the context of device/application usage, viable business models, etc. The authors in [45] raised various issues that could arise in low-cost medical device development. The authors suggested that many of the proposed low-cost devices could be bogus and lack adequate safety designs. Therefore, proper scrutiny of propositions to ensure patient safety and quality care is recommended. The authors also remarked that actual device development costs might not be properly accounted for in many low-cost medical device propositions. Many low-cost medical device development initiatives are undertaken in the academic research setting, usually supported by an external grant. Thus, the research expenditure for a new low-cost device might not always be transparent and fully accounted for. This has implications when new device development projects in low-resource regions are planned.

2.6 Section summary

To summarize, several works have investigated low-cost medical device/solution development for low-resource regions. Some works have relied on the decreasing cost of semiconductor technology to argue that medical devices are getting affordable for use in low-resource regions. This is true for many consumer-facing healthcare technologies (e.g., smartwatches and home-based health monitoring devices). However, much complex medical equipment is still very costly [46], and it might be a while before the prices for standard medical devices required in a health care center become affordable in most low-resource regions. Other works have relied on a smartphone as an add-on for medical devices, overcoming the need to procure standard devices (e.g., a smartphone-based digital stethoscope in place of a standard stethoscope). Though this approach is a viable alternative, e.g., using a smartphone display as a medical device display, the functionality of the proposed solutions must be rigorously validated. For example, it should be ensured that the functionality of the proposed solution/device works across different smartphone types, network quality, etc. Some works have investigated alternate modalities for affordable diagnostic and therapeutic solutions in low-resource settings. These research works should continue as low-cost measurement modalities might replace costlier alternatives. Other advances we are making in data science and analytics for robust measurements could be helpful. For example, thanks to the
Table 1: Summary of works on low-cost medical devices for applications in low-resource settings. Various approaches have been proposed in the literature for reducing the costs, ranging from using alternative sensing technology to the usage of a smartphone as an add-on for medical devices.

| Approach for low cost medical devices and healthcare solutions | Example Clinical Applications and Example Works |
|---------------------------------------------------------------|------------------------------------------------|
| Reliance on reducing the price of the semiconductor technologies for Glucose monitoring at home for Diabetes care. e.g., [18]. | |
| Smartphones as an add-on for medical devices Blood pressure monitoring, Remote cardiac monitoring, and Elderly patient monitoring. e.g., [22], [23]. | |
| Low cost alternative for diagnosis and therapy e.g. using alternate signal for diagnosis Fetal Heart rate monitoring, Skin infection diagnosis, Cancer diagnosis, Gait monitoring, Mental health assessment. e.g., [29], [30], [31], [32], [34] | |
| Improvement of workflow to bring cost reductions and reduce burden on clinicians Automated Electronic health record, Automated Diagnosis, Mobile telecardiography. e.g., [38], [39], [40], [41] | |

Advances in data science, photoplethysmography (PPG) from consumer devices can potentially be used for arrhythmia detection [47, 48] and consumer cameras can be used as a vital sign monitoring device [49, 50]. Technological solutions have also been proposed to improve healthcare workflows and improve efficiency. This reduces the overall healthcare costs and thus needs further exploration of their applicability in low-resource settings. Finally, a holistic view of the cost of medical device deployment considers the cost of infrastructure in low-resource settings. This has been discussed in some previous works and must be a part of any proposed general healthcare solution targeted at low-resource regions. Overall, no matter what approach (or a combination thereof) is used towards low-cost medical devices, one must ensure that the quality and patient safety aspects are kept as the priority.

A summary of our observations from the literature regarding low-cost medical devices for low resource regions is provided in Table 1.

3 ICT Tools to Scale Healthcare Solutions

The use of information and communication technologies (ICT) in health services has been termed eHealth by the World Health Organization (WHO) [51]. Cost-effectiveness and security are important aspects of eHealth propositions [52]. Healthcare outreach, especially in low-resource regions, could be improved with ICT to scale and democratize care. For example, ICT could help the rapid dissemination of clinically relevant information such as a new diagnostic procedure or matters of public health. In this section, we review some works that have proposed the use of ICT tools for affordable healthcare in low-resource settings.

3.1 ICT for Electronic Health Records (EHR)

Proper management of health-related data is crucial in overall healthcare delivery. Electronic health records (EHR) and other healthcare information systems provide the required infrastructure for data management and information flow. However, proprietary healthcare information systems might be cost-prohibitive for low-resource regions; the burden of software license costs can sometimes be very high. The proliferation of affordable ICT solutions with the ongoing open-source movement could prove a boon for healthcare ICT infrastructure in rural areas. Several works have identified how ICT advancements can be used for better data management and information flow for healthcare services in low-resource settings.

In [53], the authors discussed the use of free and open-source software like Care2x [54] and OpenEHR [55] to build hospital information systems, in the context of healthcare services for low-resource regions in Tanzania. The authors in [56] proposed an open-source health information system called DataPall for rural healthcare solutions in Africa. The DataPall system for keeping patient care records could run on a PC without internet access. The authors highlighted the role of healthcare information systems such as DataPall in providing evidence-based healthcare improvements. The authors in [57] also proposed an open-source cloud-based system named Eucalyptus to assist healthcare in low-resource regions. Eucalyptus could support both the information management needs as well as the elastic computational needs. The information management solution within Eucalyptus, for example, is obtained by integrating an open-source hospital management system such as Care2x. The reliance of low-resource regions on open-source solutions for EHR system implementations was also discussed in [58]. In particular, the following open-source EHR/EMR (Electronic Health Records/Electronic Medical Records) systems were considered: Care2x [54] and OpenEHR [55].
Medical Records) systems were reported to be commonly used: HOSxp [59], OpenEMR [60], and OpenVista [61]. The authors in [62] identified 8 different data collection systems used for maternal and neonatal care in the low-resource region of which four were free and open-source systems, highlighting the importance and prevalence of open-source healthcare data management solutions in low-resource settings. The authors in [63] qualitatively compared five popular open EHR systems: OSHERA VistA, GNU Health, OpenMRS, OpenEMR, and OpenEHR. The OpenEMR was found to be the most promising open-source EMR solution in comparison. It is generally beneficial to have multiple open-source projects for an application. A hospital or clinic in low-resource settings could choose from multiple options of open-source EMR/EHR depending upon the fit to their current needs. In the meantime, open-source EHR should be continually improved to be user-friendly, reliable, and effective, given the increasing usage of these EHRs for critical healthcare services in low-resource regions, among other places.

It is preferable if most of the (software) components proposed in a healthcare information system, e.g., within a proposed EHR, are open-source. For example, the authors in [64] proposed Intelehealth system for telehealth access in rural India. Intelehealth is an open-source platform enabled by cloud-based electronic health records. The platform allows proper information flow between different healthcare professionals and clinical centers. MySQL database, available at no cost, is used as a component of Intelehealth which makes the proposition suitable for low-resource regions. In [65], the authors discussed a teleconsultation system designed for low-resource regions of Bangladesh which allows the physicians to remotely access patients’ records and provide appropriate consultations. The system was built using PHP and MYSQL server components which are both freely available IT tools. Similarly, in [66], the authors proposed using open-source connectivity and database system for connecting different healthcare centers and professionals in low-resource regions of Indonesia. Internet radio packet was used for connectivity and PostgresSQL for database management. The free/low-cost software components make the proposition suitable for use in low-resource settings. On the other hand, the authors in [67] proposed to use an off-the-shelf database like Filemaker [68] to build an EHR/EMR solution for low-resource settings. However, the Filemaker solution is not free and the added cost of the database has to be assessed in the trade-off of costs versus better functionality or usage benefits that a commercial database could provide.

3.2 ICT to improve secondary healthcare functions

ICT tools could help in making secondary healthcare functions like knowledge management, information dissemination, and policymaking affordable and accessible. These secondary functions are especially important for healthcare operations in low-resource regions where the availability of trained personnel is limited. Several studies have discussed the role of ICT in knowledge management, information dissemination, and policymaking in the context of healthcare. Similarly, the role of ICT to improve logistics in healthcare has also been highlighted by earlier studies. Improved logistics in healthcare leads to improved accessibility.

The authors in [69] discussed how health information tools have benefited healthcare services in low-resource regions of Kenya. The improved data availability for local bodies helped to better assess the current healthcare systems, identify their bottlenecks, and propose improvements. ICT tools helping improve policy by monitoring the healthcare system are highlighted. In [70], the authors discussed the role played by ICT in the maintenance and operations of healthcare infrastructure deployments in Mozambique. As these examples depict, information assimilation enabled by ICT helps in policy and decision-making at a regional/national level. The authors in [71] also reported how ICT is important for improved healthcare outreach and efficiency in low-resource regions of Peru and Nicaragua. They also identified the need for increased access to communication infrastructure, information sharing, and continuous training of health professionals; ICT will have an important role in fulfilling these needs too. Interesting examples are shared by the authors on how ICT could relieve the burden on healthcare professionals. A healthcare center head, who otherwise would have needed to travel and thus created delays in the health services, could avoid the travel when facilities for emails and communications are easily available in a low-resource region. Similarly, many healthcare professionals could benefit from ICT-enabled solutions that reduce errors arising from manual paper works in healthcare. In [72], the authors also discussed the role of telehealth systems built using (open-source) ICT tools to improve healthcare in low-resource regions of Zambia. The proposed solution provided improved access to medical specialists, increased opportunities for education, and logistic improvements like decreased travel needs for both the healthcare professionals and patients. Though the examples discussed in this section are sometimes from a work of more than a decade ago, some analogous technology-based assistance for improved logistics would still exist today.

3.3 Network and server resources for healthcare solutions

The increasing availability of ICT hardware, services, and infrastructures like telecommunication is a prerequisite for improved healthcare availability in low-resource regions. Several previous works have reported how the availability of servers and telecommunications is improving e-health and telehealth services for low-resource regions. The authors in
discussed the role of telecommunication infrastructure and internet access devices in the context of health services in Africa. The authors highlighted how a basic network infrastructure enabled by telecommunication technologies like GPRS, WiMAX, and VSAT provides a backbone on top of which healthcare services and information delivery can be deployed. ICT’s role was identified to be crucial in various areas such as health system performance monitoring, resource planning, dissemination of health knowledge, policy-making, etc. The authors in [73] discussed the issue of communication infrastructure affordability. A combination of a Wi-Fi and WiMAX network was proposed as an affordable network solution for low-resource regions. Such an affordable yet modern wireless communication system can enable telemedicine service to bring worldwide clinical expertise to the point of care in low-resource regions. The authors in [74] discussed the role of ICT in the context of their EHAS (Hispano-American Health Link) program. The burden on healthcare professionals arising due to the lack of ICT tools was highlighted in this work too. The authors discussed the deployment of custom email servers, working over the Very High Frequency (VHF) band for communication, to help healthcare establishments in low-resource regions of Peru. The recent roll-outs of advanced telecommunication technologies such as 5G, if available in low-resource regions, can significantly enhance healthcare service delivery in those regions [75, 76].

Some specific features of ICT software advancements e.g. features in the database have also been advantageously applied in some works. In [77], the authors discussed their software tool Health Agent which is useful to automate telemedicine in rural areas. The functionalities of a relational database system, e.g. SQL triggers, are utilized for case-based alarming in the proposed solution. The data model for proper storage and access to health information is also highlighted. Similarly, software-as-a-service deployments and mobile applications for improved connectivity of mobile midwives are presented to make the maternity healthcare system more efficient. For any innovation, the availability of multi-language tools, e.g., owing to open-source tools and technologies for language translation [81], is considered important. In general, the need for healthcare information and user interface tools in local languages is identified as very crucial for healthcare services in low-resource regions where English might not be the primary language of the majority. These intuitive user interfaces and language translation tools are directly linked to ICT innovations. In [82], the authors discussed the role of an ICT-based knowledge management system for improved healthcare access in low-resource regions of Srilanka. The need for a knowledge management system for making healthcare pervasive in low-resource regions is made clear. Still, some problems like the skeptical attitude of some clinical professionals in using ICT resources, general unavailability of good systems and software, etc. were raised. New propositions should consider user-centric ICT propositions that are adapted to local needs to improve the trust and usability of developed propositions.

3.4 ICT for healthcare knowledge and language tools

The role of ICT tools in knowledge management and training of health professionals has also been a subject of discussion in some previous works. Proper knowledge management and affordable training are important for healthcare in low-resource regions because of the general lack of trained professionals and knowledge resources. In [78], the authors proposed a digital library solution to assist healthcare in low-resource regions. The library consists of reading materials on healthcare physiology, tools maintenance, operations, etc. This information is made available in the local language using an automatic language translation service. The authors in [79] presented an open learning platform called Openlearn to provide free training materials on healthcare management. A free training platform could in particular be beneficial for personnel in low-resource healthcare settings who cannot afford or access training with high costs. In [80], the authors presented different ICT innovations to support primary healthcare in India (relevant for low-resource regions also). Replacing manual healthcare information management with automated (ICT) solutions for efficiency is highlighted. Similarly, software-as-a-service deployments and mobile applications for improved connectivity of mobile midwives are presented to make the maternity healthcare system more efficient. For any innovation, the availability of multi-language tools, e.g., owing to open-source tools and technologies for language translation [81], is considered important. In general, the need for healthcare information and user interface tools in local languages is identified as very crucial for healthcare services in low-resource regions where English might not be the primary language of the majority. These intuitive user interfaces and language translation tools are directly linked to ICT innovations. In [82], the authors discussed the role of an ICT-based knowledge management system for improved healthcare access in low-resource regions of Srilanka. The need for a knowledge management system for making healthcare pervasive in low-resource regions is made clear. Still, some problems like the skeptical attitude of some clinical professionals in using ICT resources, general unavailability of good systems and software, etc. were raised. New propositions should consider user-centric ICT propositions that are adapted to local needs to improve the trust and usability of developed propositions.

3.5 Section summary

To summarize, several propositions have used ICT advancements for improving healthcare access and affordability in low-resource regions. The open-source software tools, increasing access to network/communication infrastructure, easy access to health information library, etc., are all ICT advancements also helping healthcare in low-resource regions. Some studies have shown the direct relation between ICT advancements and feasible healthcare innovations. In [83], the authors studied the quantitative relationship between IT infrastructure and telemedicine readiness in the context of healthcare systems in Libya. A positive correlation of 0.44 was obtained, highlighting the direct impact of ICT infrastructure on enabling new healthcare innovations in low-resource regions. Besides the general availability of ICT infrastructures, the authors also highlighted the need for associated trained professionals for its operation and maintenance. In [84], the authors interviewed several healthcare professionals working in low-resource regions of the Philippines. A need for proper access to clinical practice guidelines, health news, and events, health education policies,
Table 2: Some example smartphone applications developed for health monitoring and diagnosis. These applications are low-cost and could be useful to aid healthcare services in low-resource regions.

| Name                      | Target Complication                                                                 |
|----------------------------|--------------------------------------------------------------------------------------|
| iASHA [87]                 | Pregnancy (A decision support system to enable health workers to provide maternity healthcare services efficiently and transparently. |
| mBody Health [86]          | Diagnose disabilities                                                               |
| Mobile Stethoscope [23]    | Monitor Heart rate to diagnose heart disease                                           |
| Cardiax Mobile ECG [88]    | 12 channel personal ECG system to diagnose and monitor heart condition                |
| Runtastic Heart rate [89]  | Measures heart rate on a real-time basis                                              |
| Heart rate monitor [90]    | Checks heart rate on a real-time basis                                                |
| Blood pressure watch [91]  | Collects, tracks, analyzes, and shares blood pressure data                            |
| Finger blood pressure [92] | Measures blood pressure based on imaging of fingertip                                  |
| Finger Print Thermometer [93]| Determines body temperature based on contact at fingerprint                          |
| Body temperature [94]      | Keep track of body temperature and identify severity                                  |
| iOximeter [95]             | Pulse rate calculator                                                                |
| Eye care plus [96]         | Test and monitor vision                                                              |
| Test your hearing [97]     | Test hearing                                                                         |
| uHear [98]                 | Self-assessment of hearing                                                            |

e.g., were identified from the interviews. This information is made accessible with ICT infrastructures, and thus the role of ICT for healthcare in low-resource regions is highlighted.

4 Mobile Health

Mobile Health (mHealth) refers to the practice of health solutions and services supported by mobile devices such as mobile phones, tablets, PDAs, and wearable devices. The mHealth field has emerged as a sub-segment of eHealth. The services generally considered under mHealth include the use of mobile devices in collecting community and clinical health data, delivery of healthcare information to practitioners, researchers, and patients, real-time monitoring of the patient, and direct provision of care (via mobile telemedicine).

mHealth has emerged in recent years to be suitable for developing countries, resulting from the rapid rise of mobile phone penetration in the low-resource regions also. It can enable wider healthcare access to a larger segment of the population in low-resource regions by improving the capacity of health systems. Here we discuss some works that have focused on mHealth. We also list several health-related mobile applications that could be relevant for deployment in low-resource regions or regions with limited access to conventional healthcare services.

The authors in [23] highlight how mobile devices can be used as medical devices. The use of the available capacity of smartphones, e.g., the onboard sensors, web connectivity, and powerful processing unit, has made these mobile devices not just a medium of communication but also a medical device. Providing proof of concept with a digital stethoscope, the importance of available infrastructure to cope with critical diseases related to heart patients has been discussed. In the low-resource settings, mHealth could be the only way to offer services that would otherwise be unavailable [85]. Mobile phones with affordable network connectivity could be a vector for enhancing the continuity of care before the diagnosis and after the hospitalization for a continuous follow-up. mHealth applications allowing networking and video conferencing could help to increase efficiency (better logistics, more contact, etc.), quality of patient care (e.g., due to more follow-up even if remote), and patient satisfaction. There might be some constraints on mHealth applications when considering their usage in low-resource settings. The authors in [86], for example, investigated the effectiveness of mobile apps in rural areas with low literacy. Visual-based apps were recommended for better meeting the needs in low-resource regions.

We list some example mobile/smartphone applications (mobile apps) in Table 2,3 and 4 that could be relevant for healthcare in low-resource settings. We categorized the applications based on the target complications they address. Furthermore, we classified the apps based on their feature type. These apps can be used either directly by the patients and families, or by midwives and doctors.
Table 3: Some example smartphone applications for healthcare record-keeping. Measurement and tracking of health through record keeping are crucial aspects of healthcare delivery.

| Name                     | Target Complication                          |
|--------------------------|----------------------------------------------|
| iASHA [87]               | Pregnancy                                    |
| mBody Health [86]        | Monitor disabilities                         |
| Mobile Stethoscope [23]  | Monitor heart disease                        |
| Health assistant [99]    | Monitor BP, weight, water, temp, glucose, etc |
| Asthma tracker and log [100] | Asthma tracker                              |
| Diabetes Diagnostics [101]| Diagnose diabetes subtypes                   |

Table 4: Example smartphone applications related to lifestyle and healthy behaviors. The concept of healthcare is a continuum that includes the day-to-day life of an individual and thus applications helping in lifestyle and healthy behaviors are relevant for improving healthcare overall, including in the low-resource regions.

| Name                          | Target Complication                           |
|-------------------------------|-----------------------------------------------|
| Health assistant [99]         | BP, weight, water, temp, glucose, etc.        |
| Water Your body [102]         | Reminds user to drink water                   |
| Medisafe Meds & Pill Reminder [103] | Reminds user of medication times |
| Dosecast indication Reminder [104] | Drug management                             |
| MyFitnessPal [105]            | Keep track of food habits                     |
| SleepCycle [106]              | Keep record of sleep time                    |
| FitBit [107]                  | Track daily goal and progress over time for steps, distance, calories burned and more. |

5 Emerging Technologies

Some of the emerging technologies like artificial intelligence (AI), Internet of Things (IoT), Blockchain, etc., have already shown great promise for healthcare. The technologies also have a role in making healthcare inclusive and affordable. In this section, we review some works where emerging technologies for healthcare have been discussed. Though not always explicitly stated, these works have the potential translation of their usage for increasing the outreach of healthcare in low-resource settings.

5.1 AI for Healthcare

AI has shown its potential in a broad set of use cases. Much of this success is due to the availability of data, easily available computing power, and an improved understanding of different AI algorithms. Machine learning, which is concerned with learning from data, is one of the enablers of AI. Many advancements in healthcare due to AI have been brought by machine learning advances. In recent years, deep-learning, a type of machine learning based on multi-layered neural network architectures, has provided even clinician-grade solutions, e.g., to analyze medical images and physiological signals. For the healthcare application, AI has a role in several areas like automated diagnosis, clinical decision support, clinical workflow optimization, resource utility maximization, etc.

The use of AI for diagnosis has been one of the most explored application areas. The typical data flow for such a solution is shown in Figure 5.1. Data from a (multi-) sensor front-end is consumed by an AI application to produce diagnosis and decision support outputs. Based on a usage area, AI for diagnosis can be categorized into: (i). Inside-hospital application and (ii). Outside-hospital application.

5.1.1 Inside-hospital applications

The inside-hospital applications use AI for aiding diagnosis for day-to-day clinical workflows. Several innovations in this area are, for example, in the field of radiology. An example application is tumor/nodule detection in the lung CT scan [108]. In [109], the authors identify several application areas where AI could assist in radiology-based diagnosis. Some of those areas are thoracic imaging for lung nodule detection, abdominal and pelvic imaging for liver lesions detection, colonoscopy for colonic polyps detection, brain imaging for brain tumors detection, etc. While the radiology equipment might be a significant cost burden for low-resource settings, at least the automation of (pre-)diagnosis could offset the cost required for well-trained radiologists. Besides radiology, other application areas of AI in clinical
diagnosis and decision making include for example hospital discharge or readmission prediction \cite{110,111,112} using available clinical data, or arrhythmia detection using ECG (Electrocardiograph) signal \cite{113,114,115}.

5.1.2 Outside-hospital applications

The outside-hospital application categories are concerned with taking the (early/pre-) diagnosis to the ambulatory settings of free-living. A representative work is presented by the authors in \cite{116}. The authors propose a camera-based system to provide a clinical-grade diagnosis of skin cancer. A motivation for such a system is the possibility to extend the reach of dermatologists outside of the traditional setting and enable low-cost healthcare on top of ubiquitously available smartphones. The authors of \cite{117} describe a deep-learning-based atrial fibrillation detection solution using photoplethysmography (PPG) signals in an ambulatory setting. These example applications show how the power of AI can help take the clinical diagnosis to ambulatory settings. Such a step is crucial to bringing quality diagnosis solutions to low-resource areas. We refer to the review works in \cite{118,119,120,121,122} for the application of AI/machine learning in healthcare areas.

Besides diagnosis and clinical decisions, AI could be advantageous in other aspects of the healthcare delivery chain. Any AI-based solution to improve the healthcare delivery chain can translate to a direct benefit towards healthcare for low-resource settings. The benefits can be cost reduction, improved efficiency, the requirement of lesser resources and manpower, etc. An example discussing the use of AI to improve the entire healthcare delivery chain is the work of \cite{123}. The authors discuss how AI can be used for the diagnosis and treatment of Tuberculosis (TB) by improving all the aspects of the healthcare chain. AI technologies can help assure medication adherence using automated gesture detection technologies (e.g., from video surveillance). AI can be useful for the whole program management of TB containment and treatment in an area e.g., in the context of resource planning and monitoring. For an application like TB, raising awareness of the patients and population is also very important. For this purpose, using AI for the automated generation of educational audio-visual materials can be helpful. Other works have also outlined how AI and optimization can be helpful in aspects other than core clinical tasks like diagnosis and treatment. The authors in \cite{124} have proposed optimized planning for scheduling the work of Community Health workers where AI can play a role in the optimized scheduling. AI can be used in different health resource planning works like referrals, management of immunization programs, and several population/public health initiatives. Such efficient planning can be crucial when it comes to reducing the cost of healthcare in low-resource settings and improving throughput/efficiency. The authors in \cite{125} also discuss how AI can have a role in healthcare in low-resource settings for various functions like diagnosis, administration, resource planning, monitoring, etc. Specific example deployments like AI-based chat-bots to support medication has been presented. The challenge concerning the cost of AI-based solutions is raised but it has also been noted that overall cost reduction can be expected, justifying the fit of AI-based systems for healthcare in low-resource settings. An advantage for AI deployment in low-resource settings could be the relative policy-level ease of deployment. The example of clinical drone usage in Rwanda has been presented to show this point.

To summarize, the growth and increasing adoption of AI can prove to be very helpful for increasing the outreach of healthcare in low-resource settings. AI as a technology is being widely investigated to improve clinical diagnosis and decision making, either inside the hospital or outside. Besides diagnosis, AI can also assist in reducing costs and improving efficiency for other aspects of the healthcare chain. Though the initial cost factor and required technological knowledge for solution deployment can seem like a hindrance to getting AI technologies to the low-resource settings, AI provides several other benefits which could pay off overall.
5.2 Internet of Things (IoT) for healthcare

Connectivity and computational power are getting cheaper and more ubiquitous. This has led to a myriad of devices around us being more intelligent and inter-connected. The connectedness of everyday items and devices around us, which also get smart and intelligent, is referred to as the Internet of Things (IoT). Think of an automatic watering unit for the plant enamored by environmental sensors that we can monitor and control using a mobile application. Or a refrigerator that has an inbuilt camera to detect missing groceries and update the shopping list on our smartphone. IoT is already a reality today, and only growing in terms of scale and usage.

Healthcare is one of the areas where IoT can enable new solutions. Most of the research work on IoT for healthcare has mHealth or a wireless body area network (WBAN) application deployment scenarios. Wearable physiological sensors connected to the cloud and made available for remote access by the clinician is a typical application scenario. This, for example, has been discussed by [126, 127, 128, 129, 130, 131, 132, 133, 134]. Innovative deployments have been discussed in works like that of [135] where the authors present a health-kiosk available for healthcare in remote regions of India. These kiosks consist of multiple physiological sensors in low-resource settings. The edge device can provide various useful functionalities like smart data filtering to only forward relevant information to the clinicians in a remote location. It can also automatically detect any health criticality among the monitored population. Such deployments increase the (virtual) outreach of clinicians. An interesting extension of this smart edge-based IoT deployment is the possibility to monitor the entire (sub) population in the region, leading to population health analytics solutions. Besides personal physiological sensors monitoring the health of individuals, other devices can be a part of the IoT like a visitor counter device at the local health center, an EMR server of the health center, etc.

A review of IoT for healthcare, though not specific to low-resource settings, has been presented in the work of [137]. The authors discuss various IoT use-cases for healthcare applications. The potential of large-scale IoT for applications in community health monitoring discusses concepts like interactions between multiple body area networks. An interesting use case is IoT’s use for emergency healthcare services during a disaster. In low-resource settings where the reach of standard healthcare services is limited, connectivity of devices could help monitor and plan resource utilization, casualties mapping, etc. One other use case discussed is the possibility to track population-level information on adverse drug reactions. This can immediately be extended to applications specific to low-resource settings e.g., tracking outbreaks and the spread of specific diseases related to low-quality water supply, for example. IoT can also be applied for awareness campaigns by providing a platform for easy dissemination of information.

5.3 Blockchain technology for healthcare

One of the recent technological advancements with huge potential in the healthcare sector, positively impacting the increase of the outreach in low-resource settings, is blockchain technology. Blockchain technology enables a way to keep a record of the transaction without a need for an intermediary. This mechanism opens up various applications in healthcare that would otherwise have been difficult to deploy. As blockchain provides a trust mechanism between multiple parties, one of the most explored applications of blockchain in healthcare is the sharing of data. This application is very relevant for low-resource settings for two reasons. First, as healthcare services and providers are not resourceful, sharing data between different entities is difficult. E.g., healthcare facilities might not have enough software and resources to open up their data to third parties without incurring a major security and privacy threat. Second, the new applications that can be enabled with easy data sharing would be crucial in low-resource settings to enable applications like automated diagnosis, telemedicine, or any general mHealth applications.

The authors in [138] discuss how blockchain could provide privacy, traceability, value-management, and trust mediation for enabling mHealth applications in South Africa where the requirements for healthcare access extends to some deep rural settings also. In [139], the authors propose the use of blockchain to manage distributed information in EMR, providing the security and trust mechanism for sharing information. This is discussed in the context of managing EMR for cancer patients. Given the lack of inter-connectivity or secure direct connectivity between different data/information nodes, blockchain can provide a secure gluing layer. The benefit of decentralization to improve healthcare in low-resource countries has been discussed in [140]. Though not explicitly mentioned, blockchain can be the technology upon which a distributed healthcare infrastructure is built. The use of blockchain for data sharing providing functionalities like patient pseudo-anonymity, workflow automation, data integrity, accountability, etc. has been presented in the paper of [141]. Similarly, the authors of [142] present how the blockchain technology in a mHealth application provides the solution for the right data ownership, security of the shared data, convenience of sharing, etc. The authors in [143] use blockchain and smart contracts as a mediator to enable data-sharing across the providers (ensuring interoperability) to make healthcare more cost-effective and sustainable. In the MedicalChain whitepaper [144], the use of blockchain and
smart contract platform enabled by blockchain for data exchange for solutions like telemedicine is discussed. The use of blockchain in healthcare, in general, has been reviewed in several works [145, 146, 147, 148, 149].

As more works are pursued on the usage of blockchain in various aspects of healthcare like diagnosis, treatment, clinical workflow, logistics, prescription management, logistics management, etc., it would become clearer what promises this new technology will bear for healthcare in low-resource settings. From what we have already started to see, blockchain technology has the potential to bring positive changes to healthcare in a low-resource setting also.

6 Discussion

Quality healthcare access should be available for all. However, due to higher costs associated with healthcare resources and infrastructures, we are yet to reach the utopian dream of getting everyone on the radar of good healthcare access. In this work, we reviewed various works that have been geared towards making healthcare widely accessible in low-resource settings.

A major effort to control healthcare costs concerns reducing the price of costly healthcare devices. This is becoming feasible due to the reducing cost of semiconductors, the pricing reduction possible with improved mass manufacturing, and the investigation of new designs with the cost factor taken into consideration. We found that several efforts have been focused on building an add-on for the smartphone, so that the smartphone itself can act as a healthcare device, for example for early diagnosis. These works rely on the wider availability of smartphones in a low-resource setting. The reach of smartphones has been growing very rapidly even in the rural and low-resource settings [12] and thus the smartphone as an add-on could be transformative. The end-to-end healthcare delivery chain requires several devices. Therefore, reducing the costs of these devices is a major step, and a crucial one, towards universal healthcare access. However, the pressure of cost reduction should not compromise the device quality. The quality reduction might lead to an adverse outcome for the patient. The concern of quality is especially relevant for low-resource settings because these areas generally lack good regulations for devices and/or are lacking in trained personnel to enforce quality guidelines or maintenance [150, 151]. Another point to be noted is the overall representation of the device cost in the financial equation of the healthcare delivery. It might as well be that the device costs represent only a small portion of the overall healthcare costs, in a given care setting. Also, the device costs might be only a one-time capital expenditure which is overshadowed by the recurring operational costs. Therefore, all efforts toward affordability of the healthcare device have to take the following factors into account in further investigations: What fraction of the healthcare delivery cost is represented by the device costs? Can the cost reduction be done without reducing quality? How is the distribution of the capital expenditure and operation cost of the device? And how does new low-cost design impact these two factors?

A development for increased healthcare access in a low-resource setting is also the parallel development, or rather an explosion, of IT tools and technologies. Software-based services and telecommunication infrastructure can provide a carrier for innovations in healthcare targeted at low-resource settings. If we think of novel healthcare offerings like telehealth, these offerings have a good landing spot in the context of healthcare for low-resource settings. Several studies have already investigated how the availability of a new generation of telecommunication technology is going to help revolutionize healthcare [152, 153, 154, 155]. A bit of that revolution will be shared by healthcare for low-resource settings. Another development is in the field of open-source IT tools. An example is OpenEMR which has been positioned to provide a reliable EMR solution. Open-source solutions such as OpenEMR could fill the void created when the healthcare organizations in the low-resource settings cannot afford proprietary EMR solutions. Needless to say, it comes to the use of open-source software and tools for healthcare, utmost care should still be provided to various aspects like quality, privacy, etc. It would be unfortunate if the cost factor of a software tool is used to overlook any impending harms like compromised patient privacy or even patient safety. The efforts of healthcare for low-resource settings should embrace developments in the open-source world but with caution due to the criticality of the healthcare sector in general. Even though some recent studies have found the privacy and security concern to be of less significance to eHealth users in low-resource settings [156], this might only reflect the notion that having the resources/infrastructure is of the highest significance in regions where these are missing. Some studies have, however, found that patients in low-resource regions are concerned by the unauthorized secondary use of their protected health information [157]. Greater awareness about the implications of security and privacy breaches on one’s health information will likely increase the concern of patients on these factors.

A major carrier for increased healthcare access in low-resource could be smartphones. The smartphone revolution will likely usher changes in healthcare delivery, with a positive impact on cost reduction and affordability for people in low-resource settings. In section 4 we reviewed several healthcare-related smartphone applications. Various aspects like diagnosis, record-keeping, improving lifestyle towards a healthier life, etc., are covered by existing and upcoming applications. The smartphone has inbuilt sensors like cameras and microphones that could work as health sensors, something which has been receiving a lot of attention lately. For example, cameras could extract heart rate variability
and other physical health parameters [158]. Similarly, the microphone can be used in speech-related applications, for example, to assess sociability for depression severity estimation [159]. The smartphone-based applications that we reviewed in Section 4 covered a wide range of clinical conditions for cardiac care, optical care, pregnancy monitoring, thermal monitoring, and many more. The smartphone revolution can thus have a wide impact on healthcare. Though the concept of a simple application to diagnose a disease at home sounds lucrative, it is important to ensure the accuracy of such applications by validating with current standard devices. Similarly, most of the applications will be customer-facing. Therefore it is also important to think about how the accessibility is not impeded by factors like the literacy level of people in a particular region. Just like the mature technologies such as smartphones and telecommunications which have been helping improve healthcare access in low-resource settings, one can also remain upbeat with many upcoming technologies. In Section 5 we identified some technologies like IoT, Blockchain, and Artificial Intelligence which will all bring in another wave of revolution in healthcare. We reviewed different literature where the authors are investigating how new technologies will change healthcare services. It might not be too early to speculate that these new technologies will further help improve healthcare access in low-resource settings. Some recent works concur, for example with the potential of blockchain technology to reduce health disparities and improve global health [160].

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