Software Development for a Secure Telemedicine System for Slow Internet Connectivity

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To My Father

Who would be really proud of me if he was still with us.

To My Mother

Who is always proud of me anyway.

Declaration

I hereby declare that except where specific reference is made to the work of others, the contents of this dissertation are original and have not been submitted in whole or in part for consideration for any other degree or qualification in this, or any other university. This dissertation is my own work and contains nothing which is the outcome of work done in collaboration with others, except as specified in the text and Acknowledgements. This dissertation contains fewer than 65,000 words including appendices, bibliography, footnotes, tables and equations and has fewer than 150 figures.

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Abstract

Living in a technology-driven era, when everything seems to be just a few clicks away, access to essential health services still remains a distant reality to more than half of the world population. The rural areas of Bangladesh accommodates 70% of its population but qualified medical doctors cannot be retained there because of prevailing socio-economic factors that will be difficult to address within the foreseeable future. This compels the rural people in either not taking any treatment at all, or taking treatments from traditional healers, or taking modern drugs through consultation of unqualified people which often leads to maltreatments and misuse of antibiotics and steroids. If the illness deteriorates, they take all the trouble of going to a distant city hospital through rough terrains and waterways, at a huge cost to the family.

To address this problem, ICT-based telemedicine can come with a great promise, particularly in catering to primary and secondary care. A proper medical consultation at this stage can help improve the above mentioned concerns, save a lot of eventual health complications, even death in many cases.

It has been observed in the preliminary research that a number of telemedicine initiatives were taken in the past in Bangladesh, yet very few of these sustained down the line. Lack of appropriate system design, technology and implementation modality seemed to be the main causes. Therefore, the Department of Biomedical Physics & Technology of Dhaka University took up research and development in Telemedicine starting in 2011 through development of indigenous technology coupled with its dissemination to achieve a holistic approach to the solution. The initial work involved development of a basic telemedicine software with Electronic Health Record (EHR) and a few integrated online diagnostic devices like a stethoscope and ECG with individual software. Other basic medical tests were done using commer-

cially available devices and entering the data into the system through manual typing. A field trial taken up during 2013-2015 indicated initial success of the envisaged basic model. However, the software was basic and would not be able to cater to the requirements envisaged for its further expansion based on the experience.

The present work was taken up based on this background and the whole system design approach was redesigned with the following requirements:

1. It should be web based, with cloud storage of all medical records (Electronic Health Records-EHR) including written texts, images and acquired data from integrated medical devices. The latter at this point were stethoscope and ECG, both made locally by BMPT.

2. It has to be robust.

3. It has to be user friendly to its users, namely the rural operators, consulting doctors and administrators, with graphical user interface (GUI) and the maximum use of local language.

4. It has to give each patient an identity for future reference.

5. All data have to be secure and available only to appropriate persons.

6. It should integrate video conferencing facility within the same platform.

7. It should have a computer aided prescription generation tool linking data bases of drugs (medicines), and other medical or clinical advices. The latter will need to be created in this software.

8. It should have web-based monitoring facility for the administrators which should have some analytical features with graphical presentation of necessary data, which can be expanded as need arises.

9. It should be optimized for slow internet connectivity, as is encountered in Bangladesh.

Each of these areas was individually addressed by developing corresponding tools, and finally put together to make it an integrated, user-friendly telemedicine platform capable to work efficiently in Bangladesh. An Action Research (AR) approach applied in the socio-technical context dictated the most part of the research and development process. Participations of relevant stakeholders of the system were ensured in all the stages of "design to deployment" cycle of this project. In contrast to many typical workflows followed in HCI area, the present work concentrated on the software development through evolutionary improvements adopting existing technology and tools, rather than focusing on radical innovation by introducing the new form of technologies.

Based on the previous experience of BMPT in which the author of this work was also involved, a completely redesigned software, under the purview of this PhD work, was developed. Firstly a working prototype was developed and it was put to use by BMPT under the banner of Dhaka University Telemedicine Programme. Subsequently the software was expanded, modified and refined over the years to add newer features and to incorporate critical feedbacks coming from the users – the rural operators, consulting doctors and administrators. Till date, More than 11,500 patient consultations have been given using the software developed under the present work and the number of rural centres currently being catered is in excess of 30, with 10 doctors giving consultation from any place they choose - home, office or workplace, or even while travelling, using a smartphone.

Towards the end of the work a survey was carried out taking samples from the above users regarding ease of use, satisfaction, effectiveness of the software. The results were predominantly positive pointing out to the success of the present endeavour.

All low resource countries of the world have similar situations as Bangladesh and this software can easily be adapted to local needs through language translation of the user interface, where needed, and incorporation of appropriate database of available drugs. Any other modifications can also be made working together with people of the target countries.

The outcome of the present work, hence has a big horizon in the global scenario and the work will be deemed worthwhile if it can help all these people of the world who has been deprived of the facilities of the modern life over centuries.

Table of contents

List of figures

List of tables

Chapter 1

Introduction

1.1 Current Healthcare Status : Urban vs Rural Perspective

We, the humankind, are currently living in the era of technology. The ever-expanding horizon of modern technology is shaping our life in ways that were unimaginable to all just even a few decades ago. By the blessings of inventions like World Wide Web, we are globally more connected than ever. In a time when access to everything seems to be just a few clicks away, more than half of the world population still struggles to avail one of the most fundamental human necessities, which is access to essential healthcare services. About 100 million people are still being pushed into "extreme poverty" because of 'out-of-pocket' health expenses [2]. The inequity in accessing health services is even greater when we compare the health workforce density between urban and rural areas. Skilled health professionals tend to be concentrated in urban areas because of better opportunities and improved quality of living typically missing in rural setup. Though coverage of essential health services is slowly increasing, inequities in the distribution of health workers persist and are unlikely to be resolved in the near future.

Health service scenario in developing countries like Bangladesh is no different from the rest of the world, even worse in some cases. There is a huge gap between available and required number of physicians in the country's health workforce. There are an estimated 4.72 qualified physicians having MBBS degree per 10,000 population in Bangladesh [3]. Like the rest of the world, major portion of health workers, including physicians, is concentrated in the urban secondary and tertiary hospital facilities, thus leaving the 70% people residing in rural areas out of mainstream healthcare coverage [4]. For them, the statistics for the number of qualified physicians (having MBBS degree) per 10,000 population would be virtually zero. To provide a minimum of primary healthcare to rural people, the Government of Bangladesh has introduced community-based healthcare initiative across the country since 1998. Currently there are 13,136 community clinics in operation aiming to provide primary healthcare to those in need in the rural and hard-to-reach areas [5]. Services offered by these clinics are mainly limited to disseminating health education and health promotions along with limited curative care (treatment of minor ailments), few primary level screening and identifying emergency and complicated cases with referral to higher facilities. However, the services in these community clinics are provided by personnel with a mere three-month training, not by qualified medical doctors, except of course, through intermittent visits of medical officers in some complicated cases of emergency. Hence, people still need to travel to distant urban cities or districts seeking professional medical consultation at the expense of extra time and hard-earned money. Considering the limitations of offering diagnostic medical service due to unavailability of professional doctors at the facilities, the community clinic is still not the "one-shoe-fits-all" solution to delivering quality primary healthcare in rural and hard-to-reach areas of Bangladesh. Besides, considerable room exists for errors through these short-trained healthcare personnel leading to further complications.

Therefore, primary healthcare for everyone, both in developing and developed countries, is still a "service under construction". We may have come a long way in terms of technological advancement, but the much longed for "Health for all" [6] is still far away from becoming a reality. Human curiosity complemented by the finest technology of our era helped unmanned rover travel through billions of miles to reach the edge of our solar system, yet we have miles to go before reaching the goal of Universal Health Coverage[7] for the people of our very own planet.

1.2 Telemedicine: A Promising Solution

E-health service like telemedicine can be the missing piece of the answer that current global health system seeks to overcome the shortage of need-based health workforce. It can play a pivotal role in bridging the gap between healthcare service and the part of the world that really needs it but is deprived of. According to the latest WHO (2017) report, the largest need-based shortage of healthcare workers is in Southeast Asian and African regions. Telemedicine opens avenues to reach these underserved areas with the prospect of delivering health services with improved access to care and quality of care through remote diagnosis, treatments or referral, reducing distance traveled and time spent for obtaining health service from distant medical facilities. Even in remote areas of industrially developed countries, telemedicine can significantly improve the health services.

Telemedicine, aside from over 104 definitions found in peer-reviewed literature, in general, may be defined as the utilization of Information and Communication Technologies (ICT) to provide healthcare at a distance. The concept of telemedicine is not new and its history goes back to a time even before the term 'ICT' became a household name. The first official case of using telemedicine was reported in 1959 when a bi-directional video conferencing link was established using microwaves between University of Nebraska Medical School and State Mental Hospital [8]. However, even before that, people used to consult doctors privately soon after telephone was invented and made available for home use, which can be considered as the earliest examples of informal telemedicine service.

Throughout the world, many countries have effectively deployed ICT specific solutions for successfully delivering operational health services in remote and rural areas [9]. Telemedicine is one of them along with solutions like internet-enabled tools and mobile-based technologies [10] [11] [12]. However, very few effective and sustainable telemedicine initiatives have been introduced in Bangladesh to date, to address the scarcity of contemporary health service for the rural people. Financial limitations, organisational failures, lack of homegrown appropriate technology, low bandwidth network are some of the major reasons preventing many such initiatives from being successful and sustainable in the long run [13]. Though first formal initiative of telemedicine in Bangladesh dates back to as early as July, 1999, initiatives that followed until now are very few considering the potential and impact it can have to improve the current health service delivery model of Bangladesh. A number of large private hospitals in big cities have tried developing their own e-health and telemedicine services but their scope of service and operation is limited to providing specialized services to their registered patients only, and not to mention quite expensive in nature. In public sector, the Government of Bangladesh, through its Ministry of Health and Family Welfare, is working on introducing telemedicine service in district and sub-district hospitals, community health clinics and union information and service centres. This initiative is still at a preliminary stage and the service is limited to providing video consultation only. Besides, a few non-governmental organisations (NGOs) as well as some independent private companies have attempted small-scale telemedicine initiatives across some remote parts of the country.

Comprehending the scope and potential of telemedicine in delivering primary and secondary healthcare in the context of developing countries like Bangladesh, the Department of Biomedical Physics and Technology (hereinafter BMPT) initiated its research on design and development of a full-fledged telemedicine system in 2011. Once a basic software system along with some online diagnostic devices was customized and developed for telemedicine purpose by BMPT, the first field trial of the system was piloted for a few months in 2013, by setting up three remote telemedicine centres located around Faridpur, Bangladesh.

However, considering the population density and the extent of scarcity of health service delivery in Bangladesh, the impact and reach of these initiatives are merely a few drops in the ocean. Telemedicine, despite all the promises and possibilities it can offer, is yet to be accepted widely as a dominant force for alleviating current health crisis resulting from the shortage of skilled health workforce in developing countries on top of limited adaption and implementation in the region.

1.3 Human Computer Interaction (HCI) in Telemedicine System Development

Successful adaption and implementation of a telemedicine service relies on multiple factors that include (but are not limited to) social, cultural, economic, technological and organisational aspects of a telemedicine delivery model. Since the entire operation of a telemedicine service is performed using various means of Information and Communication Technology, adopted technological architecture of a telemedicine system is crucial and can be regarded as the backbone of the system. It has to cater not only the needs of every step of a typical medical consultation but also the organisational requirements that come along the way of telemedicine service workflow, and these all need to be incorporated within its software system. A telemedicine software system designed and developed in the context of local needs, combined with incumbent organisational dexterity, leads the way to a successful, effective and sustainable telemedicine service.

Developing a sophisticated, user-friendly software system is a daunting task. The popularity of desktop computing has revolutionized the way we perform our personal and professional work in modern times. It has also given rise to the development of numerous software programs that we use in our day-to-day life to perform various tasks. At the same time, the amount of poorly designed programs, lacking usability in the most elementary way, has also increased proportionally. To our utter disbelief, there is a world full of unusable, poorly designed programs. It is quite vital to consider the usability aspects of a program right from the beginning of a software development cycle. Otherwise, chances are it is never going to be incorporated at all. Proper usability never happens coincidentally [14].

Designing appropriate and useful computer systems that assist the users doing their work or making decision efficiently is the primary goal of Human Computer Interaction (HCI). This specific discipline of computer science deals with the design concerns followed by the evaluation and implementation of human-centric interactive computing systems and the study of human factors surrounding them.

In order to achieve the intended usability and efficiency, we must know what to develop, as well as how to develop the software system. Firstly, we have to understand the working system where the software is going to be implemented in. Any working system typically consists of a number of different user-groups with different needs and capabilities. These user-needs as well as the overall working conditions are not static and likely to change over time. Moreover, it is not always about the technical challenges, social and cultural aspects of diverse magnitude also play an instrumental role in any complex work situation.

The overall software development task starts with being able to understand the working system and the way users perceive information and cooperate with each other within the system. Then the development process starts by identifying and dividing the tasks into small fragments. An important portion of initial work in HCI is dealt with fact and considerations acquired from underlying disciplines i.e. cognitive psychology and software engineering, which forms the basis of rest of the areas related to HCI research. The next step involves applying these basic facts and considerations in practice, which paves the way for developing computer applications and systems with high usability [14]. In a software design, many aspects are considered i.e. function, human interface, ergonomics, graphics, algorithms, data structure, and so forth, and these invariably have impact on one another. What to develop is as important as how to develop it. The latter one is addressed by focusing on the way the software is developed. Active involvement and participation of end-users and related stakeholders throughout the lifespan of the development process is the way-to-go approach in most of the cases.

The role of HCI in developing user-friendly software for a telemedicine system is quite significant and needs utmost attention just like other genres of software development. Much of the success of a telemedicine project inarguably depends on the usability and efficiency of the software system being used to deliver the health service [15].

An ideal telemedicine system requires a seamless integration of many components of traditional healthcare delivery process built right into its software system. Typical procedure of a face-to-face doctor-patient medical consultation needs to be replicated in the most efficient and user-friendly manner so that both the caregivers and recipients of care feel comfortable and confident while using this emerging genre of healthcare service. While designing a telemedicine software system it is very important to note that the main purpose of the work performed by the involved caregivers (i.e. physicians, remote operators) is never to operate the computer. A computer or a computer application is merely a tool and will be accepted and used as long as it efficiently supports the endeavor of providing good healthcare for the recipients of care (i.e. patients). It means, among other things, the main focus of the user interface design for both the caregivers and recipients of care must concentrate on optimizing the healthcare work activities as such and not just optimize the handling of computer as a tool [16].

1.4 Motivation of the Research

Despite holding inordinate promise of improving the delivery of healthcare and establishing considerable influence on overall healthcare system, the full potential of ICT based solution is yet to be realised, especially across communities living in distant areas with limitedly available or sometimes unavailable resources. Due to the recent proliferation of mobile network and mobile based internet connectivity, many e-health and m-health initiatives are taking place targeting the remote population, however, those suffer from significant limitations and shortcomings. Mobile based healthcare services like tele-health line or "over the phone" consultation is one of the fast-rising healthcare solutions in developing countries like Bangladesh, but it falls short of providing the elementary assistive facilities that a typical medical consultation involves such as use of diagnostic devices, face to face communication, access to previous medical history, and so forth. Due to the restriction imposed by regulatory bodies in case of mobile consultation only very limited numbers and "Over the Counter (OTC)" drugs can be advised in the prescription and thus proving it to be insufficient for a proper plan of treatment and preventing it from becoming an ideal alternate to conventional primary and secondary healthcare service model. Internet-based telemedicine service has all the potential to fill the gaps that are not taken care of by mobile consultation. Existing telemedicine services, especially that are tested in developing countries, struggle to live up to their potential. Many of these initiatives fail to sustain in the long run despite having substantial promise at beginning. The financial and organisational failures and lack of efficient and user-friendly digitized telemedicine system become the major reasons that drive to the suspension of many telemedicine services around the world [17] and that mostly include developing countries. Most of the existing and legacy software solutions of the relevant projects adopted in developing countries have been found error-prone, inefficient and require extensive internal and external resources [11]. There is a common phenomenon to use engineered software system, which eventually fails to deliver as they are not suited for local needs, nor inclusive of participation relevant stakeholders' during design phase of the software solution. Most of them are not even evaluated post implementation and this goes the same for such projects implemented in Bangladesh as well. Majority of the operational telemedicine services in Bangladesh have been found to be email-based 'store and forward' and some other take place over video conferencing using third-party software and without any support of essential diagnostic devices and central electronic management of patient health records. The ones having provision to maintain patient health records are usually dependent on ready-made software tools imported from developed countries and devoid of mechanism for any sort of integration between the diagnostic devices used and telemedicine software system. As a result, the comfort in handling such telemedicine technologies is compromised for all user-groups of the system. In addition, the overall expense of availing such services is higher and remains beyond the reach of poor people. What is more crucial that very few of these telemedicine services take the rural people into account as the recipients and/or operator of the service judging from their technological incapability. Most of the rural areas of developing countries are still burdened with data connectivity constraints i.e. slow internet, bandwidth limitations etc. [18]. Even the most well-designed telemedicine system may fail to perform as per expectation if the connectivity at the remote health centre is poor.

Apparently, the needs for implementation of a telemedicine software system in developing countries differ significantly than those in developed countries. Basic requirements of a telemedicine system in developing countries revolve around providing primary and secondary healthcare while majority of the telemedicine research in developed countries mostly focus on the delivery of sophisticated tertiary care. The technology developed in the western world, no matter how sophisticated they are, may not work well in the developing countries due to the gulf of differences in the context of application and system environment between the two.

As a result, there is an obvious necessity within telemedicine research to address the unique technological needs of developing countries and come up with viable solutions by adopting homegrown and appropriate technology. More attention needs to be paid in the design of user-centric telemedicine software system, which may take care of all the concerns and functionality gaps identified in the existing telemedicine platforms. It can be made possible through conducting implementation research which would allow us to have proper insights about the user requirements and simultaneously apply those in the development of a telemedicine system for better evaluation and assessment of impact.

1.5 Aims and Objectives

The aim of this research is to develop a robust and user-friendly telemedicine software system incorporating support for online diagnostic devices capable of delivering primary and secondary healthcare in rural areas by taking into account all the technological, social, cultural, and organisational considerations that are unique to the developing countries. This to-be telemedicine system will be tested and implemented in Bangladesh with a target of providing much needed healthcare services among unreached communities of the country.

This research revolves around firstly analysing and identifying the technical limitations of current telemedicine services by taking its feasibility in the rural setup along with the prominent factors into consideration that may influence the design decisions and development procedures of a telemedicine system aiming to provide primary and secondary healthcare service in developing countries like Bangladesh. Secondly, developing a secure telemedicine software system based on the findings and functional requirements gathered in the first phase of the research and evaluating its qualitative usefulness to estimate its relevance for wider applicability.

This is a continuation of the prior telemedicine research work initiated by BMPT [19] [20] [21] [22] [23]. This research work will specifically address the design and usability issues faced by BMPT telemedicine project over the course of its trial period mentioned in one of the earlier sections. Combining the insights and experience gathered from the first trial run of BMPT telemedicine programme with the knowledge acquired from relevant telemedicine literatures, a full-fledged telemedicine software system with high usability will be developed. The development cycle of the intended software system has three major areas with core objectives of the research are as follows:

- Design and development of a secure telemedicine management system incorporating an array of both clinical and organisational functionalities required to operate a typical telemedicine service in the background of developing countries where user-interface design concerns are highly influenced by technological constraints like low bandwidth network besides other social, cultural and organisational factors.
- Design and development of efficient and effective user interface for the integration of two medical equipment developed by BMPT- digital stethoscope and 12-lead digital ECG, with the aforementioned telemedicine management system.
- Design and development of a real-time multimedia communication user-interface for doctor-patient teleconsultation prioritizing the special needs to better optimize the multimedia communication in case of operating in low bandwidth network. It will also be incorporated in the user-interface of aforementioned telemedicine management system.

An Action Research approach will be adopted throughout the entire development cycle of the telemedicine software system as it allows a researcher to concentrate on the real-world problem at hand, which also aligns with the application-focused research philosophy of BMPT. To minimize the mismatch between requirements of the end-user and the solution developed, active participation of all user-groups will be ensured from the initial prototype design phase to finally implementing it on the field.

Finally, a qualitative assessment of the developed software system will be performed in terms of usability and efficiency by conducting a survey among the end-users of the system.

The telemedicine software system, developed as the final outcome of this research, will be implemented in different rural telemedicine centres spread all over Bangladesh under the banner of Dhaka University Telemedicine Program to serve rural people with proper medical consultation via this software system. Even though this telemedicine software system will be developed for delivering primary and secondary healthcare services to unreached areas of Bangladesh, nonetheless, it can easily be adapted and deployed in other low resource regions of the world with minimal effort and modification.

Chapter 2

Telemedicine in Bangladesh

2.1 Introduction

Telemedicine, despite the immense potential to alleviate the inequity of healthcare delivery in developing countries, is still at its infancy. While telemedicine is being used for advanced secondary and tertiary care in the developed countries, developing countries are still struggling to find ways to implement telemedicine effectively within its application context that may fulfill the unmet demands of primary healthcare delivery in rural and distant areas. Like other developing countries, situation in Bangladesh is no exception too in terms of the scarcity of appropriate telemedicine research addressing the local needs. Here, the challenges for designing, developing and implementing a successful and sustainable telemedicine system are immense and possibilities are endless. Recognizing the possibilities, a number of initiatives have seen the light of day in Bangladesh since the first one had been inaugurated in July 1999, but, considering the necessity and scopes of the application, there is an apparent deficit of research initiatives on designing and developing the context-appropriate telemedicine solutions to meet the needs of the population [24].

The present work, aiming to develop a full-fledged telemedicine system for primary and secondary care delivery, takes a look at some of the current telemedicine projects at present operational or being tested in Bangladesh or in neighboring countries, to understand the existing delivery model of telemedicine adopted in the local context.

This chapter highlights the context and background of the present work followed by brief overviews of some of the similar kinds of projects that are relevant to the present work. This will help in understanding the outlines of the telemedicine delivery model adopted in Bangladesh by this research group.

2.2 Information Gathering Methods

A number of methods has been adopted for acquiring the information on the works and researches done by other groups related to the present study. Literature available online in the form of journal article, document, website content, YouTube video, Power Point slide etc., have been taken into consideration as the principal source of information for this study. Besides, information have also been collected from Key Informant Interview (KII) and direct field visits.

2.3 Telemedicine in Bangladesh: A Brief Timeline

The history of telemedicine in Bangladesh dates back to even before the first formal documentation of telemedicine reported in the literature in 1999. Many physicians used to practice informal telemedicine over the phone or via email/telegram before the Centre for the Rehabilitation of the Paralyzed (CRP) started the first official initiative of telemedicine in Bangladesh in 1999 [25]. A timeline of telemedicine initiatives taken in Bangladesh since 1999 is recorded as follows.

1999: The journey of telemedicine in Bangladesh began. The Centre for the Rehabilitation of the Paralysed (CRP) in Savar, Dhaka established an email-based telemedicine link with the Royal Navy Hospital, Haslar, UK using a digital camera and satellite telephone. [25]

July 1999: Telemedicine Reference centre Ltd. (TRCL) inaugurated a feasibility study and infrastructure development to establish national and international telemedicine services [26].

Mid - 2000: Grameen Communications initiated a rural tele-health service using wireless technology [26].

January 25, 2001: TRCL demonstrated their telemedicine system in the US Trade Show 2001 in Dhaka. They used a software called Icare and normal Internet connection for the purpose and started telemedicine service between Bangladeshi physicians and the doctors of USA on a trial basis [26]

April 2001: The Bangladesh Telemedicine Association (BTA) was formed but the initiative did not proceed further due to lack of proper attention from the government [26].

January 2003: Sustainable Development Network Program (SDNP) Bangladesh began their telemedicine initiative in January 2003 [27].

2003: Bangladesh University of Engineering & Technology (BUET) in association with Comfort Nursing Home started a telemedicine project. European Union (EU) provided the financial support to this email-based telemedicine service. The project is not functional anymore [26] .

May 2004: Bangladesh DNS diagnoses Centre, Gulshan-1 and Comfort Diagnoses & Nursing Homes started a telemedicine centre. However, the project did not last long due to a number of reasons including lack of monetary funds, patients' disinterest to the concept of telemedicine and poor campaigning of the service [26].

August 2005: Grameen Telecom (GTC) in association with the Diabetic Association of Bangladesh (DAB) launched a telemedicine programme. The programme linked Faridpur General Hospital with a number of specialist doctors practicing in Dhaka. BIRDEM Hospital, Dhaka, was connected to DAB's Faridpur General Hospital via a video conferencing link. The service is not in operation anymore [26].

2006: Medinova Private Hospital started offering an email-based telemedicine service for its patients. Under this telemedicine service, patients would receive remote consultation through telemedicine from a number of renowned physicians based in India [26].

November 2006: TRCL started another venture, this time with Grameen Phone, a leading mobile operator of the country. A dedicated health line, known as "Health line Dial 789", was set up for people to call to this number and receive teleconsultation over mobile voice communication [28].

September 2007: The Swedish Programme for ICT in Developing countries (SPIDER) started funding a two-year long telemedicine project to increase the access to healthcare services for unreached community in Magura district [26].

2010: In 2010, The first trial of Portable Health Clinic were carried out and 600 families were served in Ekhlaspur to develop the GramHealth Database [29] [30]

2011: Grameenphone and Telemedicine Working Group of Bangladesh (TWGBD) led by Prof. Reza Bin Zaid jointly started tele-dermatology project in some selected Community Information centres (CIC). [31]

2012: Grameenphone introduced telemedicine service in four upazilas across the country as part of its corporate social responsibility (CSR) efforts in 2012. It also funded the initiative to transform some 15 Union Information Service Centres (UISCs) of the government into telemedicine centres. With its network, the telecom operator also provided a bandwidth of at least one Mbps for video conferences between the consultants and patients [26]

June 2013: Dhaka University Telemedicine Programme (DUTP), a telemedicine programme born out of the research initiated by BMPT, started its first field trial with five rural telemedicine centres located in Faridpur and Madaripur district. [32]

2014: Distressed Children & Infants International (DCI), a US-based non-governmental organisation, established and introduced a telemedicine centre at Kalyanpur, Dhaka. A team of expatriate led by Dr Azizul Huq, a cardiologist from Atlanta, Georgia, started the initiative to provide telemedicine support for the underprivileged people of Bangladesh. [33]

2014: CRP started providing telemedicine support to its follow-up patients residing at the Upazila level in Bangladesh. These patients were required to visit divisional headquarters for receiving the same service earlier. This initiative was later partially funded by Access to Information (A2I) of Prime Minister's Office and currently operational.

2015: The Information and Communications Technology (ICT) division under its 'Info Sarkar' project launched 25 Telemedicine centres at different Upazila Health Complexes in January 10, 2015, to provide healthcare facilities to the rural people. [33]

2015: Jeeon Bangladesh, a Bangladeshi health startup company, started its pilot project with an aim to provide primary care in the rural areas of Bangladesh with four telemedicine centres located at the northern parts of Bangladesh. [34]

2015: Dhaka University Telemedicine Programme (DUTP) started its second phase of Telemedicine programme in November 2015.

2015: Apollo Hospitals Dhaka introduced a Skype-based tele-meeting service for the local patients of Chittagong, Bogra, Comilla, Sylhet, Khulna, Mymansingh, Narayanganj and Maijdee. The service offered consultation by the doctors of Apollo Hospitals, Dhaka directly to the patients coming to their local information centres. [35]

2016: Grameenphone introduced free health service "Tonic" for its customers. The service provides members to access knowledgeable and friendly advice from a doctor with over a 24-hour hotline, 789. [36]

January 2018: Banglalink, one of the mobile operators operating in Bangladesh, launched health-counselling services called "healthlink" for its subscribers through a 24-hour call centre. [37]

2.4 Overview of Some Telemedicine Projects

The present work tried to gather information from other telemedicine projects of similar kind implemented in Bangladesh by the Government and other private agencies or NGOs. The study also includes one relevant project that went for a field trial in a neighboring country (West Bengal, India).The works described in the following sections are presented with a summary of the projects followed by some observations and remarks regarding the overall operational modality and adopted technical architecture of the system wherever appropriate.

2.4.1 CRP Telemedicine Service

The telemedicine effort initiated by the Centre for the Rehabilitation of the paralyzed (CRP) holds a significant place in the history of telemedicine in Bangladesh. The centre, located at Savar, Dhaka, Bangladesh has a long-standing reputation for its dedication to serve physically challenged people of South Asian region by enabling them on physical, emotional, social, psychological and economic ground. To better facilitate its patients with medical consultation from experts around the world, CRP established a telemedicine link with the Swinfen Charitable Trust (SCT), a UK based organisation aiming to assist poor, sick and disabled people in the developing world, in July 1999. This initiative is known to be the first of its kind reported in the published literature that inaugurated the journey of telemedicine in Bangladesh [25]. This "Store and Forward" email-based telemedicine solution provided expert second opinion in case of complex clinical cases requiring extra attention. Since then the centre is providing its telemedicine service in association with a number of hospitals, to its patients for a range of clinical specialties i.e. neurology, orthopedics, rheumatology etc.

Besides seeking second option from foreign experts through telemedicine, CRP recently introduced extension facilities for its patients including patient follow-up through telemedicine. Partially funded by the Prime Minister's Office's Access to Information (a2i) Program, this telemedicine service is aiming to bring essential medical services to its patients remotely reducing time, cost and visit factors.

Update: CRP recently joined the Dhaka University Telemedicine Programme (DUTP) merging the telemedicine service for its follow-up patients into the current service model of DUTP. Under the new scheme, CRP has established 17 telemedicine centres that will operate under the supervision of DUTP. As a result, CRP patients residing around the country will be able to receive follow-up service from a team of CRP doctors by coming to any of the rural telemedicine centres run by DUTP. In addition to that, telemedicine centres located at the different divisional headquarters of CRP will be able to avail the regular health consultancy service provided by DUTP for their in-patients. It is worthwhile to mention that, once fully merged, CRP telemedicine service will also be using the telemedicine system that has been developed as the outcome of this present work.

Operational Modality

Telemedicine referral service in association with a number of foreign hospitals adopted by CRP is "Store & Forward" based and the whole communication is done via email following a video conference session at the designated time. This service is available for both its in-house patients and outside patients. In a typical case of referral service, the relevant documents are forwarded to the provider hospital via email and a video conference session follows in an appointed time. The advice and treatment plan are also received from the provider hospital via email.

The other telemedicine service run by CRP aiming to assist its follow up patients in the remote areas are also "Store and Forward" based and adopted an email-based communication. There are currently 72 Upazila Disabled People Development Centre (UDPDC) in whole Bangladesh, among which eight centres have been set up as a pilot booth for providing telemedicine services to CRP Follow up patients [38]. These centres contact with the head office of the CRP located at Saver on a regular basis following a predefined consultation schedule. Besides these UDPDC, Nine CRP divisional centres spread nationwide are also included in the programme seeking medical opinion for their patients. The telemedicine consultation between the UDPDC and head office takes place once a week and the patients need to enroll for the appointment beforehand. A panel of CRP specialist doctors from different areas of expertise sit together for a designated period of time and talks with the patients over video conference. The type of consultation confines to four specialties: Occupational therapy, Prosthetics and Orthotics, Physiotherapy and Speech and language therapy. The nature of the consultation is therapeutic only and they demonstrate to the patients some related physical exercises or routines that will be helpful for the ailment of the physically challenged patients. A single session takes around 30 to 40 minutes to complete and advices are sent to the UDPDC patients by email after the consultation ends. These advices contain visual images of suggested physical exercises with textual instruction explaining the procedure in detail. In the current mode of operation adopted by CRP, these advices are prepared in MS Word file by copy-pasting relevant visual instructions from different pre-compiled MS Word template file. The compiled advice file in word file is then sent to the email address of the UDPDC from where the patient attends the telemedicine video conference. Upon receiving the compiled advice file via email, a printed copy of the therapeutic advice is handed over to the patient from the UDPDC.

Technological Environment

There is a dedicated room set up for telemedicine service in the divisional centres of CRP including its head office, located at Savar. These telemedicine rooms are typically equipped with a desktop computer, a web-cam for video conference and a large LED monitor for the doctor-patient teleconsultation. The UDPDC are typically facilitated with a laptop/desktop and a web-cam for the telemedicine operations. Internet connection at the divisional centres are usually subscribed from local Internet Service Providers (ISP) whereas UDPDC mostly rely on mobile internet subscription including a few of them having broadband connection.

Software Being Used

CRP telemedicine service relies on Skype for the doctor-patient video conference. All the clinical documents exchanged between the sender and receiver centres are transferred via email. CRP is not using any other software for its telemedicine operation other than these two communication tools.

Medical Devices Being Used

In the current mode of telemedicine operations run by CRP, no diagnostic devices are being used for collecting clinical data at the patient end. In case of referring to foreign experts from abroad all the clinical tests and examinations are performed in separate facilities and the results are scanned or captured digitally in high definition for sending those via email.

Observation and Remarks

Telemedicine referral service offered by CRP is the pioneer one in introducing telemedicine initiative in Bangladesh, conducting the service for last eighteen years with admirable proficiency. Due to the nature of the service they provide, the whole operation has been a success so far even though they have adopted a basic “Store & Forward” telemedicine delivery model. Some observation and remarks regarding their telemedicine service are mentioned below:

- Lack of any patient management software has been observed in the current workflow adopted by the CRP. Patient records are usually maintained manually in different spreadsheet files, which is time consuming, difficult to organise and leaves room for unintentional errors.

- In case of serving follow-up patients through their recently introduced telemedicine extension service, the operational workflow could be more efficient by introducing software-based prescription management system as compared to the current procedure. At present, it is entirely done manually by copy-pasting visual images and instructions from pre-compiled templates to a new word file, making a customized advice for every patient individually. This process is lengthy and inefficient, which could be optimized to a great extent, introducing customized prescription management software. It could automate the whole process, saving valuable time of the doctors and the patients as well.

2.4.2 DGHS Telemedicine

Background

Beginning in 1983 with support from the World Bank, the Government of Bangladesh set up 421 Upazila Health Complexes (UHC), each with 30 to 50 beds and equipped with X-ray, ECG, Ultrasound scanner and pathological facilities [39]. Each had also allocated posts of about 10 General practitioners and specialised doctors. However, the Government found it very difficult to retain specialized doctors in these UHCs. In most cases only a few general practitioners were available at a time. Therefore, Directorate General of Health Services (DGHS), a government agency run under the Ministry of Health & Family Welfare (MOHFW) of Bangladesh, planned for a nationwide telemedicine service in 2010 starting with 6 telemedicine centres at 6 of the UHCs. Since then DGHS has gradually expanded its telemedicine service and currently manages the largest telemedicine network with 65 recipient telemedicine centres at the UHCs, while 28 centres act as the providers of the telemedicine service. These consultation providers include 9 specialized hospitals, 8 Medical College

Hospitals and 11 district hospitals. The DGHS headquarter in Dhaka coordinates the whole telemedicine operation.

From December 2010 to March 2018, a total of 43,232 patients coming to UHCs have been served with telemedicine service availing second opinion from specialist doctors through real-time video consultation.

Operational Modality

Fig. 2.1 A typical telemedicine room located at the UHC, run by DGHS

Under the operational model adopted by DGHS telemedicine service, UHC act as the receiver of the service and different hospitals located at the district and divisional level takes the role of telemedicine provider making their specialist doctors available for a certain period during week days. These telemedicine providers offer expert opinions to medical officers stationed at the UHCs for patients coming to the UHCs with complex and critical conditions. Both the receiver and provider of the service have dedicated rooms for telemedicine service in their respective hospitals. Telemedicine service provided under this government initiative is available to all patients coming to the UHCs and does not require them to pay extra fees for availing this service. However, this is not a service on demand and medical officers at the UHCs decide whether to ask for second opinions from telemedicine providers or not depending on the patient's condition. Once the medical officer feels that the patient's health problem demands for expert attention to diagnose the problem properly, the officer contacts any of the specialists available at the telemedicine centres at that time through real-time video conference. Telemedicine centres at UHC are provided with a supporting staff to help the medical officers initiate the video call with provider centres and manage other telemedicine related technical functionalities. After completing a tele-consultation with the specialized doctor at the provider centre, the medical officer writes down the prescription and hands it over to the supporting staff. The supporting staff then creates a new entry for the patient by filling up a form containing a set of information input fields related to the patient in the web-based health management software. Once the entry to the software is complete and stored in the server, the prescription is handed over to the patient. This service is available 6 days a week except government holidays from 9 AM to 2.30 PM. The whole management of the programme is looked after by a central wing operated from the headquarter of DGHS.

Technological Environment

A typical DGHS managed telemedicine centre as shown in Figure 2.1, located at the UHC. The telemedicine set up, either at a UHC or at the provider hospitals, consists of a computer, a HD camera and a 43" LED TV for real-time video conference. All the telemedicine centres, both providers and receivers, are connected with each other by optical fiber network that provides 2 Mbps dedicated broadband internet connection to each of the centres. There is a full-time supporting staff, with a qualification of engineering diploma or equivalent degree, appointed in every telemedicine centre who provides technical assistance to the doctors for video consultation. He/she is also responsible for patient related data entry to the central health management software at the UHC end.

Software Being Used

Currently no dedicated patient data management software is being used for recording data of telemedicine patients, rather the data are stored within the central data management software used by Health Ministry of Bangladesh. The software is developed based on an open source data management scheme, District Health Information System 2 (DHIS2) that has been introduced recently for keeping records of all health-related data managed and maintained within the ministry including recording and storing of telemedicine patient data as well. Besides entering patients' basic information such as name, contact information, family history etc.,and type of the disease, which the patient has been primarily diagnosed with, are selected from a predefined list of disease types during the registration of the patient visit and stored into the software system. This eventually helps the management to visualize demographic patient data by disease types, which may be helpful to identify certain pattern or epidemics by geographic location. Other than the disease type, no clinical information is currently being stored in the health database for telemedicine patients.

Peer-to-peer proprietary video conference solution purchased from third party vendors are being used for holding video conference between telemedicine centres. Computer system of each of the centres managed under this telemedicine programme is assigned with a real IP for the purpose.

Medical Devices Being Used

The current mode of telemedicine service offered by DGHS do not include support of any medical devices. The focus of the telemedicine service is only limited to helping medical officers at UHC with expert opinions only through video conference. However, a number of diagnostic devices including Tele-stethoscope, Tele-ECG, Pulse oximeter, Tele-Ultrasound, Tele-ophthalmoscope, Tele-glucometer etc. have been purchased from abroad recently and expected to be deployed in few telemedicine centres on a pilot-basis in the beginning; gradually expanding their use in rest of the telemedicine centres as well in near future.

Expansion to Rural Areas

Government recently introduced the concept of Community Clinics (CC) hoping to extend the basic healthcare to Union level. These CCs are primarily built by the local people with active support from the government and manned by a personnel having a few weeks of training. They are trained to prescribe common medications for fevers and diarrhea and refer patients to UHCs if needed. Recently, government distributed

Tablet PCs to these CCs and took them under the coverage of an integrated internet network, which was limited to UHCs only as mentioned earlier. Inclusion of these CCs within the network managed by DGHS was primarily in a hope that this would open avenues for the CCs to consult doctors stationed at the UHCs through video conferencing.

Observation and Remarks

While the government run telemedicine programme managed by DGHS has all the potential to becoming an efficient and effective service model to deliver quality healthcare to rural and semi-rural areas, some areas of concern were identified during the study of its delivery model and operational workflow are briefly mentioned below:

- The current system does not provide any unique patient identification number to patients being benefited from the service. As a result, all patient visits are treated and stored individually and independently within the data management system. As a result, if a patient receives telemedicine service from the UHCs multiple times, his/her personal records i.e. name, age, family history etc. will be recorded in the database repeatedly with each of his/her visit records which is obviously a waste of both time and resources.

- There is no mechanism within the current system to store patient's clinical data and chief complaints except the primary disease type as diagnosed by the doctors upon consulting over video conference between the UHC and provider hospitals. Prescriptions are also not stored in the database and paper-based prescription written by the duty medical officer is handed over to the patient. Storing clinical data including prescription in digital format centrally would not only be beneficial for diagnostic purpose only, it would be an invaluable collection of health data on a national and global scale.

- Though recent addition of a few medical devices waiting to be included in the DGHS telemedicine system is timely and appreciable, purchasing highly expensive devices from abroad may often not be an ideal solution as it adds the maximum cost of operation in the telemedicine programme. A huge amount of fund needs to be invested in the purchase and maintenance of these foreign devices as it is going to cost more money in case of repairing and fixing the dysfunctional ones. A better and fitting approach would be to encourage and invest in the local innovation of medical devices addressing the local needs of the programme, which would reduce the cost of purchasing and maintaining telemedicine devices to a great extent in the long run.

- The current telemedicine service is available up to UHC located in the Upazila level of the country. Each Upazila has a coverage of about 300,000 to 400,000 people, many of whom resides tens of kilometres away from the nearest UHC. As a result, people living in the union level (next lower administration tier)or remote villages are still out of the coverage of this programme. Unavailability of minimum Internet bandwidth required for extending the current operation to union or village level is one of the major barriers to the proliferation of this service.

- As mentioned above, this scheme needs a medical doctor at the receiving end who writes the prescription. The telemedicine is used only to get an expert opinion when necessary. On the other hand, it will be impossible to post and retain doctors at lower administrative tiers within the next few decades. Therefore, this model of telemedicine will not work for the remote villages.

- There were incidents of data hacking leading to a total loss of the health database of the telemedicine service in the recent past. Considering the confidential and highly sensitive nature of the health data being acquired and stored in the database, it is very important to give maximum attention to ensure and strengthen the security of the data to avoid any future data breach and data loss.

2.4.3 Portable Health Clinic

Ashir et al. [29] proposed a remote health consultancy system called "Portable Health Clinic (PHC)" which wanted to address the limitations of traditional remote health consultancy over mobile phone, especially deployed in developing countries like Bangladesh. They identified 'Disease diagnosis issue' as the primary missing item in the current mobile-phone based remote health consultancy system and developed the concept of Portable Health Clinic that takes care of the primary issue along with other relevant technical challenges such as maintaining an unique patient ID, archiving patient profile, logging patients location and generating e-prescription for the patients. This model is designed to demand lesser time from a doctor through some pre-diagnosis made at the remote end by a trained paramedic, using a kit of online diagnostic devices. Besides, they have identified health data portability as another technical challenge but are yet to integrate a solution to tackle it in their current system.

The proposed model has been tried and tested in a few of places spread across Bangladesh and India. In Bangladesh, the project has so far provided health checkup to 42,080 patients since 2010. [30]

System Design Overview

The proposed architecture of "Portable Health Clinic" comprises of a portable briefcase equipped with necessary diagnostic tools in the front-end and Gram Health software applications, database and a medical call-centre in the back-end. The low-cost PHC briefcase, called as "Portable Clinic", consists of several medical sensing devices a few of which are developed following international information standards and have the capability to automatically transmit the sensor data to 'GramHealth' database. The PHC also includes an android-based application with the facility of storing Electronic Health Record (EHR) of patients locally that can transfer data over mobile phone network whenever an active internet data connection is available. GramHealth software handles the process of maintaining patient Electronic Health Records (EHR), generation of e-prescription by doctors and mechanism to store them in a remote database. The doctors are located at a call centre and have access to GramHealth through the Internet or to a copy of the database hosted in their call centre server. An offline version of the software is also available at the remote health worker's end with the ability to collect patient data locally and upload them to the cloud server whenever an active internet connection is available.

Operational Modality

In a typical operational workflow adopted by PHC, a trained healthcare worker carrying a PHC briefcase attends the patients by going door to door or responding to an on-demand call. The general cycle of operation includes registering the patient into GramHealth database (DB) followed by a physical health checkup using the equipped diagnostic tools. A few of the measured data captured by BAN (Body Area Network)supported tools are automatically uploaded to GramHealth database while rest of the data are inserted manually through a user-friendly web interface. The recorded data are then analysed with a predefined set of logic called B-logic to grade the patients in four different classes according to the severity of patient problems: Green (Healthy), Yellow (Low risk), Orange (Medium risk) and Red (High risk). Depending on the level of severity only patients marked as 'yellow' and 'red' are considered for tele-consultation with the remote doctor. An on-duty Doctor at the call centre attends the patient over voice conference using mobile phone and/or video conference using Skype software. Once the tele-conference ends, based on the analysis of current and past EHR records of the patient, the doctor types an e-prescription using the software and sends it to the patient's end.

Observation and Remarks

The proposed model of the PHC aiming to bridge the gaps in the existing mobile-based healthcare systems for the unreached communities can play a significant role improving the healthcare delivery in developing countries. Its approach in optimizing the use of doctor's time by applying B-logic as an intermediate step between the doctor-patient consultations is a new model not attempted by others. However, some general remarks and observation regarding the proposed model and its workflow are mentioned briefly below:

- The main idea of this scheme is to reduce the number of patients referred to for medical consultation. However, a person usually comes to see a doctor when he or she feels bad. If the PHC indicates a low level of severity, and the patient is not allowed to consult a doctor, where would the patient go? However, as it is currently being used as a health checkup service, the delivery model has already shown potential in the field-test. For regular medical consultancy service, the delivery model might need to re-adjust accordingly.

- The adopted B-logic to determine risk satisfaction factors depends on the measurement data input entered from the PHC. Therefore, it depends on the expertise of the rural health worker. They have to be trained extensively and any error by the person or the device may end up in giving a wrong result.

- As the decision to go for a multimedia teleconsultation or not with a call centre doctor is entirely based on the result determined by the B-logic, it is of utmost importance to make sure that all the data are entered correctly avoiding unwanted input errors. Appropriate mechanism to prevent errors in the measurement data input should be in place so that data input errors caused by either the wrong entry of health workers or the malfunction of the device can be avoided.

2.4.4 Intelehealth

Goel et al [1] from John Hopkins University proposed a telemedicine system named as "Intelehealth" aiming to reach the underserved areas in developing countries for delivering healthcare through their developed system. The system was tried at a telemedicine pilot clinic run by Foundation for Innovations in health and Jadhavpur University in rural West Bengal.

Operational Modality

The proposed operational modality of the system adopts a slightly different path trying to shift the task usually performed by professional doctors to a less specialized health worker. The proposed software system was developed to accommodate this approach incorporating options to shift the task of collecting patient data and provision of basic health services from the doctor to the Community Health Worker (CHW) interacting with the rural patients on the ground. The proposed work tried to find and sort out the common clinical questions such as duration of complaints, occurrence, aggravating and relieving factors, associated factors etc. that may have predictable answers and structure them in a logical tree following a predictable pathway. These common set of questions were integrated into the Intelehealth Android client that the CHW uses to collect and send the patient data to remote doctors for interpretation. Answers acquired from these predefined set of questions nested into multiple levels maintaining a logical path are then uploaded to the cloud server and made available to be presented before the doctor in a natural language for interpretation and evaluation. Once the doctor goes through the comprehensive patient history along with his/her complaints, the doctor initiates telephonic conversation with the patient taking help from the CHW. The focus of this task shifting approach was to minimise the amount of time a doctor spends in talking with the patient collecting his/her clinical history and complaints as they have identified the employment of doctors for remote consultation as the highest cost component of a telemedicine programme.

System Design Overview

The proposed Intelehealth system has been designed and developed utilizing a few open source software tools such as OpenMRS in combination with a custom built android client and a web application for the doctors to access patients' data. The system architecture is shown in the following Figure 2.3.The system clients interact with a cloud-based Electronic Health Record (EHR), OpenMRS. The android client used by the CHW connects to the OpenMRS server for exchanging and transmitting data through a RESTful API. Data collected within the android client are primarily stored in a local SQLite database and transferred to the server for longitudinal storing. The android client was built on using mind map UI framework for the development of data collection protocols that facilitates the task shifting process within the client tool through implementing a set of logically arranged nested questions that the CHW uses for data collection. FreeMind, an open source mind-mapping tool was used to export the data collected from the questionnaire in JSON format for transmission over the web. The web App designed for doctors to access patient information are also in coordination with the OpenMRS server through OpenMRS core API. All the data being uploaded to the cloud are stored in the back-end MySQL server adopted within the OpenMRS platform.

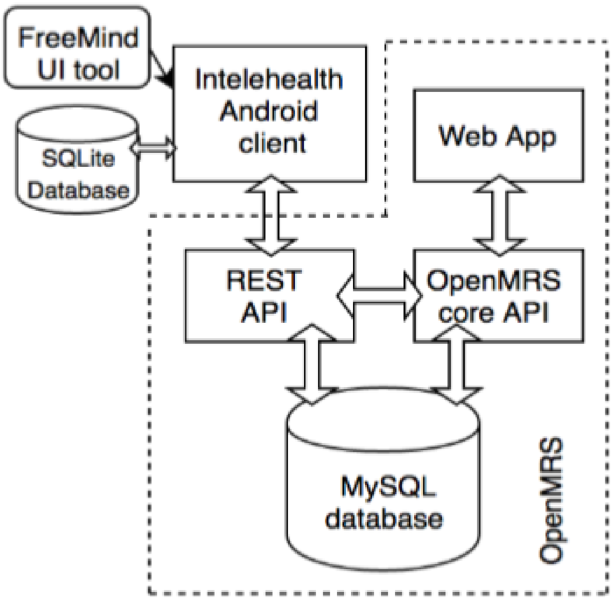


Fig. 2.2 Intelehealth System Architecture adopted from Goel et al [1]

Observation and Remarks

The proposed model of Goel et al revolves around the task shifting approach adopted within the telemedicine service workflow that is supposed to optimize the amount of time spent by the doctors, thus minimizing the overall cost of the telemedicine programme. However, the success of the proposed task shifting approach may depend on a few variables that must be addressed accordingly for the proposed system to be successful in the context of developing countries.

- The main focus of this scheme are twofold:
  - Minimise a doctor's time in giving consultation to a patient
  - Have electronic record of a patient's illness as much as possible
- The adopted task shifting approach involves an array of questions nested in multiple levels incorporated into the client software that the CHW needs to fill up appropriately based on patient's feedback in response to those questions. However, the questions are mostly clinical and require a certain depth of clinical knowledge to understand and convey them to the patients properly. The CHW needs to be highly trained to achieve the knowledge and skills as such to diagnose the patients' problem accurately. Involvement of unskilled

and inexperienced CHW on the ground may result in to wrong diagnosis of the patients followed by suggesting wrong treatment that may put the whole intention of the programme into jeopardy. Even if a CHW is well trained, he or she is not expected to have the deeper understanding of the human body and its physiology as a doctor. There is a chance of misdirecting a problem where small deviations in symptoms may lead to a different tree in the flow diagram.

- Preparing the CHW for the adopted approach would require a long-term training involving a large amount of monetary involvement. Hence, the proposed model may be suitable for small-scale telemedicine projects but may not be appropriate for large-scale programs aiming to sustain for a longer period in the context of developing countries.
- In the proposed system, the doctor-patient consultation is suggested to occur over telephonic conversation. Without the support of video consultation, and direct prescription writing facility, the doctor may face restriction in prescribing medicines other than "Over the Counter" drugs according to the government rules and regulations applied in different developing countries. Besides, when dictating the name of a medicine over telephone, the listener may easily make mistakes.

2.4.5 Jeeon Bangladesh

Jeeon Bangladesh [34], a Bangladeshi healthcare startup, started its journey in 2015 with the long-term vision of delivering quality primary care to rural people of Bangladesh. The company has set up total 32 centres located in three northern districts of Bangladesh – Kishoreganj, Netrokona and Sunamganj [40]. As of May 2018, they have served total 4146 patients since it began its health service for the rural communities. Jeeon's telehealth service, called "Projotno", links Village Doctors (VDs) or informal healthcare providers (IHP) to formal doctors through a tablet. As per their adopted operational modality, the point of service for healthcare deliveries at the rural areas are typically the medical stores located at the village bazaars at union level. A mentionable number of pharmacists of these readily available medical stores is typically Rural Medical Practitioner (RMP) with a basic level of training on medical use and common medical practices. However, their certification as an RMP are no longer recognized in the country. Jeeon is trying to incorporate these informal health service providers into its service model assisting them with the service offered by professional certified doctors. They select one pharmacist running such medical stores from each bazaar within their operational area and train them to use their developed telemedicine system, which is an android-based mobile application called "Projotno", to link the rural patients with the remote doctors sitting at the Dhaka call centre. The people at the rural areas can visit these medical stores and avail the service via these VD or IHP. After collecting a few vital signs, medical history and chief complaints, the VD submits the data to cloud server opening a visit request to an online doctor available at the call centre. Upon receiving the request, the doctor calls the patient via VD and talks about the complaints over the phone or through SKYPE voice/video call. The doctor then writes the prescription in the web-application. Once it is stored in the cloud, the prescription gets immediately available to VD in his/her tablet.

Operational Modality

Jeeon's telehealth service, called "Projotno", links Village Doctors (VDs) or informal healthcare providers (IHP) to formal doctors through a tablet. As per their adopted operational modality, the point of service for healthcare deliveries at the rural areas are typically the medical stores located at the village bazaars at union level. A mentionable number of pharmacists of these readily available medical stores is typically Rural Medical Practitioner (RMP) with a basic level of training on medical use and common medical practices. However, their certification as an RMP are no longer recognized in the country. Jeeon is trying to incorporate these informal health service providers into its service model assisting them with the service offered by professional certified doctors. They select one pharmacist running such medical stores from each bazaar within their operational area and train them to use their developed telemedicine system, which is an android-based mobile application called "Projotno", to link the rural patients with the remote doctors sitting at the Dhaka call centre. The people at the rural areas can visit these medical stores and avail the service via these VD or IHP. After collecting a few vital signs, medical history and chief complaints, the VD submits the data to cloud server opening a visit request to an online doctor available at the call centre. Upon receiving the request, the doctor calls the patient via VD and talks about the complaints over the phone or through SKYPE voice/video call. The doctor then writes the prescription and store it in the cloud, which gets immediately available to VD in his/her tablet.

Software Being Used

Jeeon has developed its own telemedicine software platform that includes a mobile application for VD, called "Projotno", to be used at the rural areas and a web-based interface for its call centre doctors to access patient information. They have in-house patient management system that maintains patient health profile for each served patients. The web app for the doctor has provision to view patient visit details and issue e-prescription in reply. The mobile client is an android-based application while the web application for the doctor is powered by Node JS server in the backend and Ajax powered HTML/CSS interface in the front-end. The web app also has separate interface for administrators to track and monitor the overall telemedicine consultations and report generation facilities.

Medical Devices Being Used

Currently Jeeon is using locally available common primary vitals measurement tools such as height scale, weight scale, blood sugar measurement device, thermometer etc. for initial diagnosis of the patient's health condition. Measured value from this device are entered manually in their android application by the VD.

Observations and Remarks

- Jeeon is trying to build a sustainable business model for delivering primary care in rural areas of Bangladesh through empowering the undocumented Informal Health Professionals (IHP) having RMP certificate that is officially unrecognized by the government. These people usually have a low literacy level which might prove to be problematic for carrying out the critical responsibilities they are entitled with such as operating tablet, data input and handling of electronic devices measurements.

- As all RMPs are males, female patients are not very comfortable in getting this telemedicine service. Besides, women in the rural areas have a tendency to neglect their problems more than the men and they are less likely to come to the bazaar areas for treatment.

2.4.6 Dhaka University Telemedicine Programme

BMPT started its telemedicine research back in 2011 when it learnt that the Directorate General of Health Services (DGHS), a government agency run under the health ministry of government of Bangladesh, was facilitating all Upazila Hospital Complex (UHC) with modern ICT tools such as computers, webcams, high speed internet connection etc., for strengthening the communication between the centre and the hospitals in order to improve the management and to provide telemedicine support of specialists over multimedia conversation. BMPT proposed to improve the telemedicine activity through development of online medical diagnostic devices, which obviously have to have digital data outputs. With a discussion with experts of DGHS, BMPT developed 5 online devices, namely, Stethoscope, ECG, X-ray Viewbox, Microscope and Colposcope [19] [20] [21] [22] [23].

A detailed overview on the context and background of BMPT telemedicine research has been described in the next chapter. In the beginning the focus of the research was to equip the UHCs with a few useful telemedicine-ready diagnostic devices that could improve the overall health delivery over video conference as it could provide some clinical information helping the doctors take better clinical decisions. However, the focus of the research extended from developing only diagnostic devices for telemedicine to designing, developing and implementing a full-fledged telemedicine system keeping the rural context of Bangladesh and the government's struggle to retain quality doctors in these healthcare deprived areas in mind.

At this point, some practical decisions were taken that makes this model of telemedicine by BMPT distinct from many other efforts. While the Government works with its own infrastructure, which BMPT could not have access to, and since it did not have sufficient funds to put into the scheme, BMPT had to go for an independent and self-sufficient model and invited entrepreneurs in rural areas who would invest in setting up the initial infrastructure for rural telemedicine centres. They would also carry out necessary promotional activity, while BMPT would provide necessary medical consultation services through its recruited doctors. The entrepreneurs would charge a fee to patients, which should cover the expenses of the entrepreneur and the doctor. Initially BMPT started this activity in collaboration with an NGO (Samama), but later took over the whole operation itself.

First prototype of BMPT telemedicine system including a number of medical devices and a basic software tool went into operation in association with a local NGO in June 2013. It had a basic patient record and prescription writing system, a free audio software (Audacity) [41] for acquisition and transfer of audio data from Stethoscopes and in-house software developed for acquisition and online transfer of ECG data and used Skype for video consultation [23].

The first phase of BMPT telemedicine included five rural telemedicine centres stationed in five different unions in two different districts (Faridpur and Madaripur). This phase was run successfully for two years involving these five rural centres and total 1574 patient visits were served during that period through this telemedicine programme.

However, despite running successfully for two years, the programme was faced with issues of different magnitudes in terms of usability and efficiency of the telemedicine system involving both hardware and software besides other organisational concerns. The unavailability of necessary and reliable bandwidth in the telemedicine coverage areas was one of the major challenges for a successful telemedicine delivery. It became evident as time progressed that a holistic approach to developing a telemedicine software system involving technical, organisational and socio-economic concerns specific to the delivery areas is necessary for a long-term vision of establishing a sustainable, efficient telemedicine programme in this part of the world. This is where the present work takes over the responsibility of designing, developing and finally implementing the system on field adopting a user-centric development approach. This work also takes into account the relevant ground-issues and concerns that evolved along the course of this work.

The knowledge and experience gathered from the operation of BMPT telemedicine in its first phase played a guiding role and laid the foundation for the present work and further development to follow.

In the preliminary research of the present work through examining the deployed system and taking feedbacks from the related user groups of the system, a number of major issues within the telemedicine system and the workflow adopted in the first phase of BMPT telemedicine were identified that required attention and needed to be incorporated within the scope of the present work. A brief mention of the major issues and concerns regarding the first phase of BMPT telemedicine in terms of its technical infrastructure and operations are listed below. A more detailed explanation of these issues will be presented in the next chapter where an in-depth overview of the system environment and requirements analysis has been discussed.

- The user-interface for the user groups of the telemedicine software system was found to be inadequate and often difficult to navigate through different sections of the application. There were numerous issues identified within the application interface in terms of usability and user-friendliness of the system that could hinder the overall efficiency of the telemedicine delivery from reaching to a satisfactory level of user experience.

- The medical devices either improvised or developed by BMPT for telemedicine were being used independently and there were no integration mechanism incorporating the measurement data into the telemedicine central repository. The developed Digital Electronic Stethoscope relied on a third-party audio processing software for data acquisition and transmission over the internet were performed via e-email or through SKYPE chat as a file attachment. The Digital ECG developed by BMPT was able to acquire and send data in near-real time but required custom-built desktop software to be installed in both the sender and receiver's computer for sending and accessing the real-time data. Dependency on different, standalone software and absence of mechanism to store the data in the telemedicine server were making the whole experience of using these devices less user-friendly, inefficient and incomplete in terms of user satisfaction and longitudinal data management.

- The software only offered basic clinical workflow incorporating options to send clinical information from the rural telemedicine centre and receive e-prescription in response to relevant requests sent to an online telemedicine doctor. There were no organisational or administrative functionalities incorporated within the telemedicine software that are typically required to monitor and manage a telemedicine programme efficiently.

- The various sets of data stored in the telemedicine database were found to be organised inefficiently and inappropriately, which could be a major problem in terms of scalability and efficiency in dealing with the growing number of database records in the future.

- The privacy and security measures for ensuring the confidentiality of the patient data and other sensitive information related to telemedicine programme was at a basic level in the developed prototype of the telemedicine software used in the first phase of the telemedicine programme. Access to different parts of the application was not properly defined and implemented in the application level, which possessed the risk of exposing confidential data to inappropriate user group of the system resulting in the risk of data breaching of sensitive clinical data of telemedicine patients.

- SKYPE, a popular third-party software for voice and video communication was being used for doctor-patient multimedia consultation over the internet. The telemedicine programme experienced difficulties communicating over SKYPE when Bangladesh government banned the software for few weeks from using it within the country in response to a national security breach. The telemedicine programme had to switch to other alternatives temporarily which affected the communication protocol and interrupted the overall operational workflow in a negative way. Necessity of an integrated multimedia communication mechanism within the software system was realised during that period.

- The operational workflow of the telemedicine programme suffered frequently due to low bandwidth network and poor internet connectivity at the rural telemedicine centres. The software was slow to respond and took a long time in the rural setup of ICT and internet infrastructure resulting in a long delay for submitting the patient data from the rural centre as well as receiving interrupted clinical consultation from the telemedicine doctor over the internet.

2.5 Overall Observation and Remarks

Studying different telemedicine operational models as illustrated briefly in the previous section revealed a few characteristics and point of concerns that are briefly mentioned below:

- The lone telemedicine initiative taken by the government of Bangladesh is limited to providing expert second opinions to hospitals down to the Upazila level only. The rural people living in the distant villages are still out of the coverage of this telemedicine service in a sense that they still need to spend a significant amount of time and money for coming to the UHCs from their villages. The rural people living in the remote villages who are coming to the UHCs may still be deprived of getting proper care as the scarcity of doctors remains as opposed to the growing number of patients coming every day to these UHCs for all sorts of healthcare. With such a large network of human and monetary resources, the initiative should be extended further in the remote areas up to union level involving the Community Clinics and focus more on providing primary care to these underserved communities.

- While “Store and forward” based model might work well for second opinion-based telemedicine service, it would not be adequate for real-time telemedicine services for delivering primary care. However, the longevity of the referral service provided by CRP using a basic “Store and Forward” mechanism shows that it is not always about sophisticated, complex solution that is required for a successful telemedicine system, adopting even a simple and concise solution may take a project long way if the primary requirements are met with it. Understanding the application context is very critical to come up with the right solution for a specific model of telemedicine delivery. CRP provides a service to a special group of patients who are disabled and had taken initial therapy at CRP. What they are taking is follow-up medicine, which is the reason for its continuation. The situation for normal patients coming for doctor's consultation is different. Most often they do not take it seriously. Instead, they are happy to take medicines suggested by the pharmacist or a less qualified village doctor.

- Most of the telemedicine initiatives do not have adequate diagnostic devices support. Some projects are utilizing locally available devices for measuring primary vitals such as height, weight, temperature, blood pressure etc. However, no other telemedicine projects except BMPT telemedicine programme seem to have the very common and vital instrument like a digital online stethoscope, or advanced diagnostic devices like a 12-lead Digital ECG included in their diagnostic devices support. Developing these devices through local innovation using appropriate technology gives an extra edge to the programme than other similar initiatives. These can be sold at a much lower price than a similar imported one and can be repaired locally at component level, making repairs low cost as well. Besides, designed with local weather and power line abnormalities in mind, these local devices gives a long working life, a decade or two is typical. Imported ones have to be thrown away once these become out of order, draining local resources and simultaneously increasing e-waste causing a big problem for the environment.

- Existing telemedicine projects in Bangladesh seem to rely solely on third-party multimedia communication tool such as Skype for doctor-patient video consultation. A few them seem to rely more on phone conversation over the mobile network only which gets the job done to some extent, but when addition of visual interaction is available, its use could definitely enhance the results. Besides, a video consultation is much better from a psychological point of view of the patients. Telemedicine is still a new concept in the whole world, and people are used to consulting a doctor face-to-face. It has been observed during the trial run of first phase of BMPT telemedicine that rural patients feel more confident about the telemedicine consultation if they can see the doctor over video conference instead of conversing over the mobile network only without seeing the doctor's face.

- Projects that are aiming to reach the rural people are either adopting a centre-based telemedicine delivery model or door-to-door service delivery model. Each of these approaches has distinct advantages. For example, A centre-based service delivery ensures the maximum availability, while door-to-door service provides more flexibility, especially in reaching the women, children and aged population who are less likely to go out for receiving primary care due to household responsibility or having dependency on the male member of the family in case of seeking medical care. So, a telemedicine delivery model adopting both of the approaches would be best suited for reaching the maximum number of people.

- Most of the telemedicine systems are based on a paramedic, or a village doctor at the rural end. These people have limited education but are already used to give consultations to patients based on their old practice and experience. They do not have the extensive knowledge base to understand the body physiology and the effects of drugs or medicines in depth as a qualified medical doctor. Therefore, these rural practitioners can often make mistakes and give a wrong input to the doctor connected in telemedicine. The doctor may be misguided through such approaches leading to wrong diagnosis and medication. Besides, it is said that 'Little learning is a dangerous thing'. Sometime they may disagree with the prescriptions of a doctor and make these comments to the patient, which may break down the confidence of the patients on this new field of telemedicine. Therefore, Dr. Reza bin Zaid of Telemedicine Working Group found it easier to work with people who did not have such training or background in medicine. In the Dhaka University Telemedicine programme, a similar view was taken and so far, it is working well. It also makes it easier and low cost to recruit local telemedicine operators and to train them. DUTP requires a prospective operator to have a HSC level education and computer skills. They are given a training on Telemedicine and in taking basic physical measurements in 3 days only! The outcome has been very satisfactory.

- Many of the telemedicine projects require the doctor to remain seated in a call centre for serving the rural patients. Considering the scarcity of the doctors in the context of the developing countries, it may be a better option to incorporate provision for the doctors to serve from even home or own chambers, which would be cost effective too saving money from appointing full time doctors for the call centre. Despite the scarcity of doctors, a large number of doctors, especially women, no longer continue the practice after marriage or having children. Introducing provision for working from home would open avenues to incorporate these doctors into the health service again, thus addressing the health crisis as well as providing meaningful option to these out-of-practice doctors to contribute for the people and the society again.

Considering the scarcity of telemedicine research addressing the local needs of the developing countries like Bangladesh, it is encouraging and appreciable to see that different bodies including government and non-government entities are coming forward lately to find an answer to the current healthcare crisis for the deprived majority. The present work would take note of the gaps and point of concerns observed in the contemporary telemedicine delivery model implemented in Bangladesh from a technical point of view and come up with a viable technical solutions addressing the major gaps in the current platforms.

2.6 Conclusion

This chapter discussed the background of the present work and highlighted the gaps in the previous work identified during the preliminary research. This chapter also presented a comparative study of a few major telemedicine delivery models, which have either been tested on field or already implemented serving the common people. The following chapters will describe the works that have been carried out taking aboard insights from the projects described in this chapter.

Chapter 3

Understanding the Context and Requirements

3.1 Background

About 70% of Bangladesh's 160 million people live in rural areas, scattered widely throughout the country, and they lack common amenities usually available to people living in towns or cities [42]. In order to deliver health care to these rural people the Government established 421 sub-urban Hospitals called 'Upazilla Health Complex (UHC)' (with 30 to 50 beds), each to serve about 400,000 people [43]. Each of the UHCs are to have around 10 to 15 qualified doctors including specialists and basic health care equipment and facilities including X-ray machines, ECG equipment, and pathological laboratory. However, because of existing socio-economic conditions the Government finds it very difficult to retain the requisite number of qualified general practitioners in the UHCs; retaining specialists is even far-fetched. Many UHCs are found to run with only 2 or 4 doctors [44], a fraction of the designated 10 to 15 posts, and one can understand the pressure of patients and the resulting dissatisfactions and frustrations. In 2010 the Directorate General of Health Service (DGHS) of Bangladesh Government set up computers with high speed internet in all the UHCs [45]. These were designed to help management and also to provide Telemedicine; the latter only through video conferencing.

The Government has also established a little over 13,000 rural community clinics (CC) with local partnership, each to serve 6000 people and planned to provide one stop service outlet for Health, Family Planning and Nutrition [5]. These CCs are also to provide routine immunisation and limited treatment of minor ailments, screening of Non-Communicable Diseases (NCD) such as Hypertension, Diabetes and identifying emergency and complicated cases for referral to higher facilities. The CCs are manned by one or two persons with general education and trained for a few weeks to provide the above support. In some CCs, where midwives are available, normal delivery is also provided. Doctors from UHCs are supposed to visit the CCs occasionally to provide consultancy services. However, the pressure of patients in the UHCs due to a dearth of doctors there makes it rather infrequent. Recently the Government provided all the CCs with Laptops so that they can have telemedicine through video conferencing with the doctors in the UHCs. Again, the qualification of the personnel in using the computer facilities in the CCs and the dearth of doctors in the UHCs put a question on the success of this programme.

Bangladesh has about 4.7 doctors per 10,000 people on average [3] but this figure is heavily biased to towns and cities where the figure may be as high as 20 per 10,000 while it is virtually 'zero' in many rural areas. Because of prevailing socio-economic situation, it is unlikely that the rural scenario will improve significantly in the near future. Therefore, telemedicine appears to be a realistic solution for a considerable time to come, to provide an improved medical care to people of the rural areas.

After being informed about the network facilities between DGHS and UHCs in 2010, BMPT took up a research programme to enhance the Government's telemedicine project through developing a few online diagnostic devices. With consultation with doctors of DGHS, BMPT developed four online devices to transfer real time data over internet within a year. The devices are, digital ECG equipment, electronic stethoscope, digital X-Ray View box and a digital microscope. The ECG equipment was designed from scratch which was connected to a PC through its USB port and transferred data to a remote PC through internet. It also obtained its power from the PC through the same USB connection. The other three were improvised from available manual devices and components. These devices were designed so that doctors stationed at the distant urban city may also get hold of some clinical data of the patient besides the usual teleconsultation through video conferencing to support them better in decision making for disease diagnosis and treatment plan.

Initially the research began with the above work plan, but it didn't take much time to realise the limitation of providing telemedicine service this way with the support of a few telemedicine-ready diagnostic devices only. Rather the necessity of having a complete telemedicine software system incorporating all the major requirements of a standard doctor-patient consultation beginning from storing vital clinical data (Electronic Medical Records -EMR) of patients to interfacing the diagnostic devices with the software system became evident as research progressed. Initially the first phase of BMPT telemedicine project started with a basic software prototype developed as the outcome of another research project of the department in 2012 [23]. But, Acknowledging the importance of a full-fledged telemedicine software system in materializing the possibility of serving maximum number of people deprived of basic health care through telemedicine, this PhD research took over the task of designing and developing the software system of the telemedicine project initiated and implemented by BMPT in the field at about the same time, around 2014.

It was also realised that the software for telemedicine has to be appropriate for conditions prevailing in Bangladesh, using the existing ICT infrastructure effectively to serve the health care needs of under-served people in rural areas. Therefore, this also provided the opportunity of improving the system through user-feedback, which made the research work application oriented and more practical.

This naturally brought in the long-term vision of disseminating the research outcome among other developing countries too, where majority of people still do not have access to quality health care.

3.2 Telemedicine Service Models

3.2.1 Other Telemedicine Service Models

A few telemedicine programmes are operational in Bangladesh but most of these lacks necessary diagnostic device support, which is very crucial in delivering quality treatment. Besides, all of these require doctors to be present at a central office to provide consultation. Under this model it was found to be difficult to retain doctors and several initiatives failed just because of this. Experience in Telemedicine, which mainly involves primary and secondary health care, has not been attractive to doctors so far as this is not going to strengthen their CV very much under the present scenario. Again, there are models developed by others (John Hopkins University, USA) which require 6 months to one-year training of the remote telemedicine operators, a model which again may not be feasible at this point in time when Telemedicine is still in its infancy and is not well known and does not provide an attractive career prospect to the operators either. Besides, in this model, the operator prepares a brief disease history and tentative diagnosis of the patient following a long list of questionnaires, which has the advantage that all such information is recorded for future. However, these may mislead the doctor in some cases, and when the doctor asks the same questions again, the patient seems to become annoyed. Furthermore, this model has the risk of the operator acting as a doctor in the long run and prescribing medicines him/herself, which is now practiced widely by unqualified village quacks and medicine sales men in countries like Bangladesh.

Based on the above scenario and through a forward-looking vision, BMPT had its own model of deploying telemedicine in the rural areas which is briefly described below.

3.2.2 Telemedicine Service Model of BMPT

The aim of the telemedicine research initiated by BMPT was to design, develop and implement a sustainable telemedicine delivery model that can serve the rural population in a mass scale through empowering local entrepreneurs. Remote telemedicine centres set up in rural areas in combination with mobile health care workers attending door to door were supposed to act as the primary points of care for delivering primary and secondary health care.

Telemedicine service mechanism proposed by BMPT will specially address this issue. With regards to diagnostic devices, it planned to include some off-line and some on-line equipment. Among the off-line devices are gadgets and equipment for the measurement of height, weight, blood pressure, blood glucose etc., which are available widely at low cost. Digital devices with on-line data transfer capability are not widely available, and those procured from specialised manufacturers in the developed countries are very expensive. Besides, if something goes wrong, the whole device has to be purchased again in most instances. Therefore, BMPT, as indicated before, already made some devices with this aim. It also plans to add more devices to this range of products. These would be available at low cost. Besides, BMPT has a philosophy of not patenting the innovations, with the aim of teaching capable scientists and engineers from other Third World countries in order for these devices to become available at low cost and be able to get repaired easily in those countries.

During the time frame of the present thesis, only the digital stethoscope and digital ECG that are specially customised or developed by BMPT for telemedicine use, were incorporated in the telemedicine programme of BMPT. At the other end, doctors or caregivers will be able to connect to the telemedicine software system from anywhere as opposed to being stationed at a call centre which is the case in a typical telemedicine service. Doctors may attend the patients even from their home through using telemedicine software system that was planned to be designed and developed as the outcome of this research.

A robust, user-friendly telemedicine software system is the backbone of a well-accepted telemedicine project. Much of the project's success depends on the usability and efficiency of the software system in use. To design and develop a telemedicine software system as such, one must carefully observe and understand the application context and system working environment on which it is going to be implemented. Specific local needs, technological environment, skill level of users, cultural and social behaviour of people, etc., heavily differ from place to place and context to context. Deploying a well-designed telemedicine software system in the wrong context and not the one for which the system has been developed and tailored , may well lead the whole project towards failure. Once the telemedicine software system is designed, developed, deployed accordingly and reached a certain level of maturity through close monitoring and feedback, the same model can be conveniently replicated in other parts of the world, especially in places having similar kind of system environments and application context.

The following few sections of this chapter give an overview of the working system environment and application context followed by the dissection of system and user needs mentioning the key points of concern that have been identified in the preliminary research. These will be taken into consideration and evaluated accordingly before diving into the design and development process of the intended software system for telemedicine service.

3.3 An Overview of the System Environment

3.3.1 Application Domain

The main application domain of the telemedicine programme initiated by BMPT is primarily concentrated to rural areas of Bangladesh and the application environment is illustrated in Figure 1. The point of service stations from where telemedicine service is being delivered, preferably located at the union level across the country, are commonly termed as "Rural Telemedicine centres". Interested entrepreneurs willing to establish telemedicine centres in their own locality are called through advertisements published in national dailies followed by a final selection of a number of them through a systematic recruitment procedure adopted by BMPT. These telemedicine centres are set up either as a stand-alone telemedicine service point or a side venture besides a related primary business i.e., a pharmacy. The person operating the system and linking up patients with doctors through internet are the 'Telemedicine Operators' who are required to demonstrate a moderate level of computer literacy and an academic qualification of HSC or above. The person who manages the telemedicine operation from the rural centre may be either the entrepreneur him/herself or having someone employed.

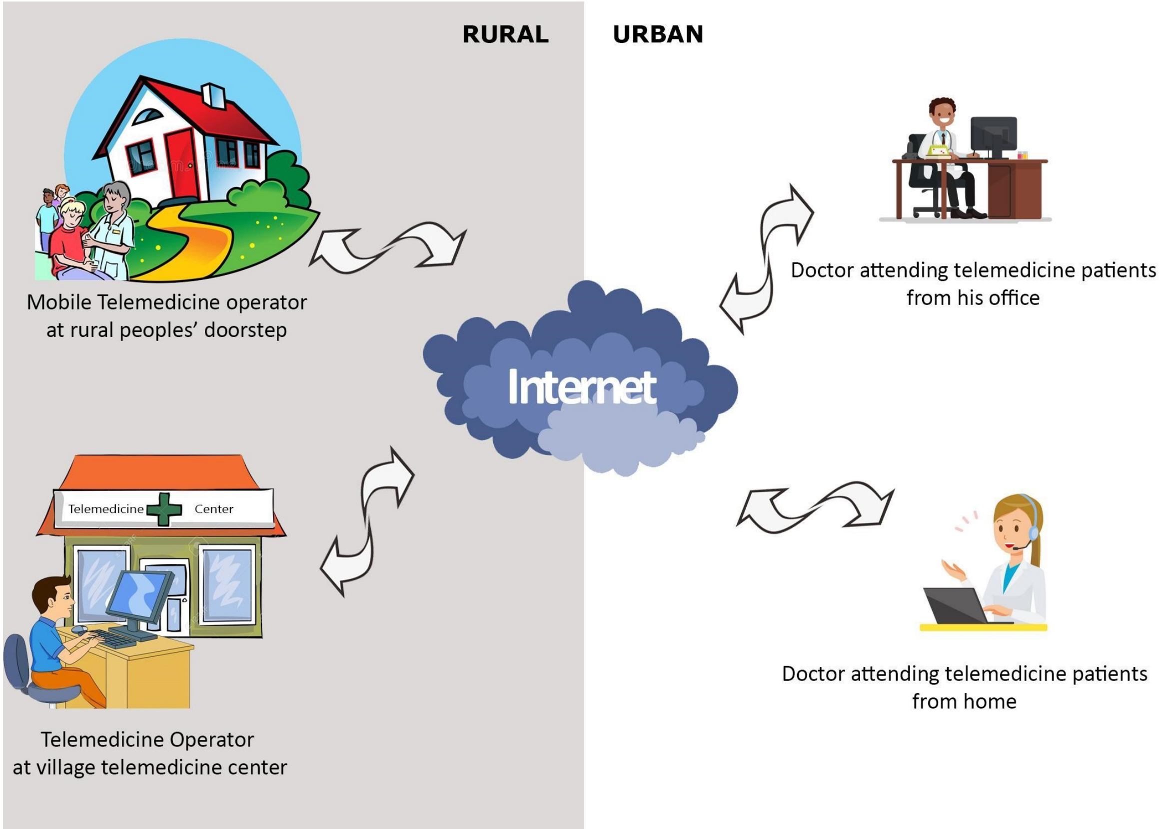


Fig. 3.1 Application environment of BMPT telemedicine programme operating in Bangladesh

There is another kind of telemedicine operator who are not stationed to a telemedicine centre, rather assigned to go from door to door in nearby villages carrying a briefcase equipped with a set of portable diagnostic tools. They commonly use smart-phone or tablet device to connect and communicate with doctors enrolled to the telemedicine program of BMPT through telemedicine software. These mobile telemedicine operators usually operate under the supervision of a telemedicine entrepreneur and are employed as a mobile telemedicine operator of the telemedicine centre.

On the other hand, doctors, who are enrolled to the telemedicine programme, typically live in the urban parts of the country and check patients online through video conferencing from either their home, chamber or hospital. There is no call centre or as such and doctors may give consultation to the patients even while traveling using tablet or smart-phone through mobile internet.

3.3.2 Clinical Application Domain

The clinical applications of telemedicine in general are diverse and vary within a large spectrum of clinical domains. The proposed telemedicine service is primarily focused on providing primary and secondary health care to its recipients residing in rural and remote areas of Bangladesh through teleconsultation. Tele-consultation services provide users with remote clinical consultation involving doctor-doctor or doctor-patient communication over multimedia communication network. This specific teleconsultation service of BMPT will offer doctor-patient interaction where either patients come to the rural telemedicine centre or are attended by a mobile telemedicine operator going to their doorsteps. Doctors will consult the patients from urban area through video conferencing and developed software system will act as the medium of communication between them.

3.3.3 Diagnostic Devices to Be Used

Rural telemedicine centres were to be equipped with a set of medical devices essential for taking primary vital data of the patient, which may include the following:

- Height scale (with improvised arrangement for babies)
- Digital/analogue weight machine
- Mercury/electronic thermometer
- Meter for measuring Blood Glucose, Hemoglobin etc.
- Analogue/Digital, manual/automatic blood pressure measuring device
- Pulse oximeter

The outputs of all the above-mentioned devices were to be entered manually into the computer through typing. As mentioned before, these devices are available locally in Bangladesh at low cost and may be easily replaced if the device becomes out of order.

Since this model of deployment of telemedicine does not depend on established infrastructures such as the UHCs, availability of X-ray equipment and pathological laboratories were kept out of the plan initially. Only devices with online data transmission capability were deployed. This list includes the following:

- Electronic Stethoscope (improvised and developed by BMPT)
- 12-lead computerized diagnostic ECG (developed by BMPT) [22]

In future other online devices will be added when developed. Of course, there should be facilities for attaching images from X-ray, microscope, ultrasound, or of previous handwritten (or typed) prescriptions, test reports, if any.

3.3.4 Technological Environment

Telemedicine centres located at the rural end will typically consist of Windows operating system based desktop computers or laptop for performing various telemedicine related operations such as registering patient records, making entry of primary vitals, sending multimedia files to doctor, printing prescriptions and attending multimedia conference in a doctor-patient tele-consultation etc. A good quality headphone can be used in the multimedia conference with doctor as well as to allow listening to low frequency sounds captured from digital stethoscope. A rural telemedicine centre is also supposed to have high resolution web-cam that will be used to digitize relevant medical documents of patients from their paper version i.e. blood test reports, X-ray images; and also to capture high resolution skin images for diagnosis besides its usual application of attending a video conference.

All the diagnostic devices to be used in rural-telemedicine centres for the purpose of recording primary vitals provide output independently except for the two devices developed by BMPT. Digital ECG and digital stethoscope both have computer interfaces that displays output signal in the computer screen and can be manipulated further to be able to 'store and forward' them to the remote doctors. The 12-lead diagnostic ECG developed by BMPT connects to desktop or laptop computer through USB interface and digital stethoscope is connected to the computer via computer sound port, or through a USB sound card to the USB port. ECG device is operated through a user-friendly computer interface which is developed in JAVA programming language and capable of transferring recorded ECG data in near real-time to the doctor's end via World Wide Web.

Initially it was anticipated to transfer real-time sound data through internet using popular audio/video software like 'Skype', 'Google Hangout', etc. However, it was later revealed that such software usually filters low frequency sounds in order to improve speech intelligibility and therefore, were not suitable for transferring heart sounds which are predominantly of low audio frequency. As a result, an alternative solution was later figured out in which sound from a digital stethoscope is captured and saved to the local computer using an open-source audio editing software tool like 'Audacity'. This provided option to capture the uncompressed audio data that retains the whole of the audio frequency information and later forwarded to remote doctor for listening, and if necessary, for further analysis and evaluation.

The scheme incorporation of the medical devices at the rural telemedicine centre end is illustrated in Figure 2. As most of the remote telemedicine centres will be located at the rural areas of Bangladesh, there is an apparent shortage of reliable ICT infrastructure in those areas which are prerequisite to the delivery of high performance telemedicine service. With the gradual expansion of mobile telecommunication infrastructures by multiple mobile network operators in recent times, the current condition of telecommunication network availability in rural areas is slightly more encouraging than before for introducing innovative e-health services like telemedicine. However, the technical challenges related to successfully operating a telemedicine service is still daunting and require utmost attention in the design and development of such services. Mobile internet service is the primary source of internet connectivity in these rural areas. Though the recent introduction of 4G internet service offered by the mobile operators promises a better future in terms of connectivity and delivery of better ICT based services, the reality depicts a different scenario. Most of the rural villages and remote areas are still out of 3G internet coverage and constantly faced with low bandwidth and slow internet connectivity issues. Overprice of mobile internet service packages offered by these mobile operators is another obstacle in spreading telemedicine service widely.

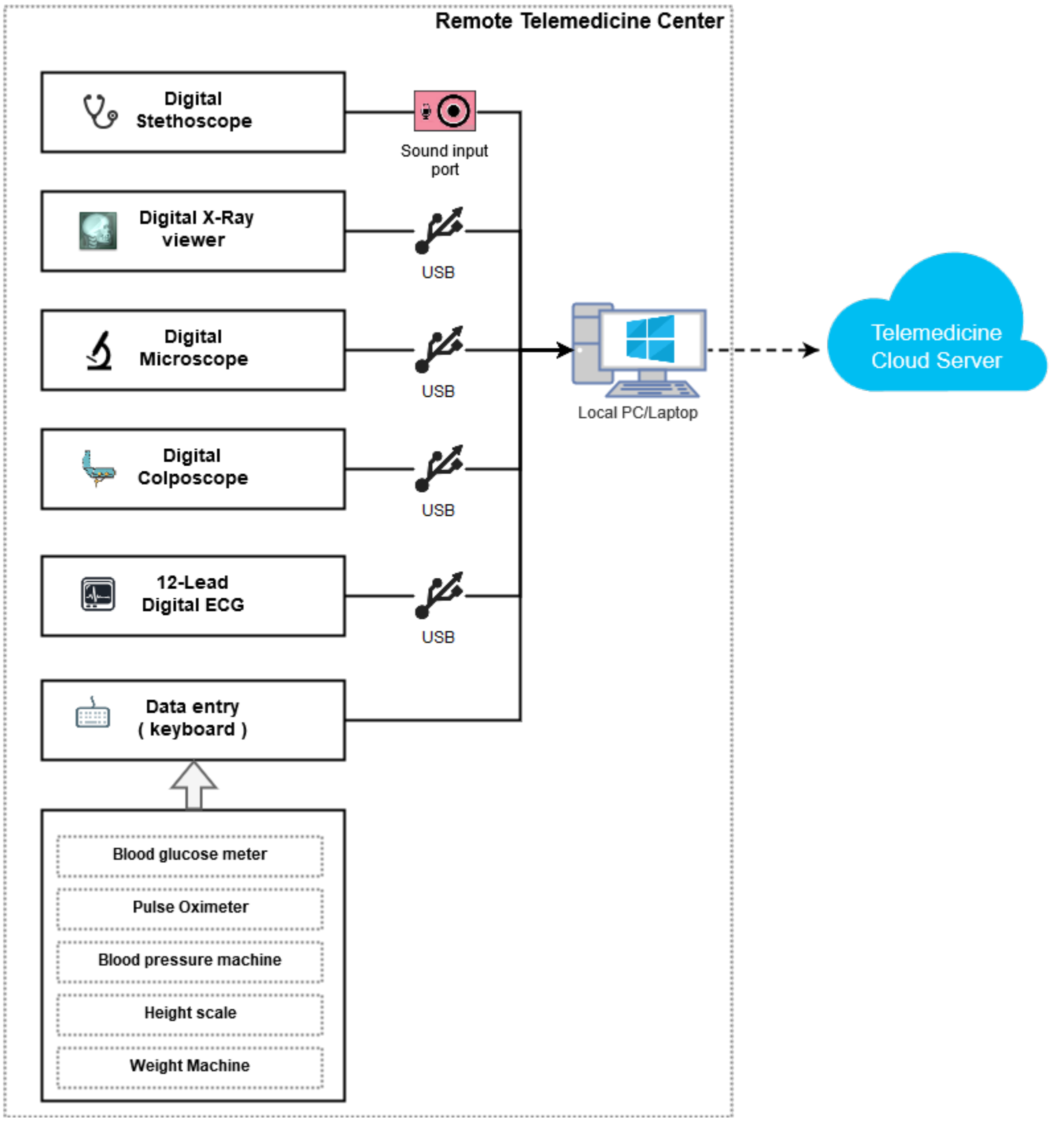


Fig. 3.2 Schematic diagram of medical devices incorporated to a rural telemedicine centre operated under BMPT Telemedicine Programme

3.4 Technical Limitations of Other Tele-consultation Efforts in Bangladesh for Rural Applicability

There has been a number of telemedicine initiatives taken in Bangladesh since the first telemedicine operation inaugurated by CRP back in 1999. However, considering the current gaps in traditional health care settings and unfulfilled demands to serve the mass population, the total number of telemedicine initiatives materialized and went into operation so far are very few and with limitations of varying degree when it comes to reaching the rural and remote areas of the country. This study tried to find out the major limitations commonly observed in existing telemedicine services in regards to delivering telemedicine to rural parts of Bangladesh which are briefly described below:

- **"Store and forward" based:** A good number of telemedicine service in Bangladesh are store and forward based. While 'store and forward' may work well in case of obtaining second opinion, it does not work well in the context of delivering primary and secondary care through real-time or semi real-time telemedicine service. This mode of telemedicine service usually takes a long time to get response from the doctor, which also limits its scope to be applicable for rural population.

- **Dependency on third-party video-conferencing software tool:** Tele-consultation using third party video-conferencing tool is a common mode of delivering telemedicine service in Bangladesh. Many initiatives of remote consultation in Bangladesh as well as in developing countries are taking place using readily available video-conferencing tool only without any other technical support. Most of these telemedicine projects rely on free video conferencing tools i.e. Skype, Google Hangout etc. to arrange doctor-patient consultation via internet. Besides having a number of advantages, there are some notable disadvantages too in adopting this kind of video communication tools, especially for delivering service in rural areas. These video tools usually require decent internet speed and stable bandwidth to operate satisfactorily. It is very common to experience jitter and data loss during an ongoing call because of low bandwidth and slow internet connectivity which compromises the quality of audio and video of the conversation. This kind of interruption and performance loss may be overlooked in day-to-day informal conversations but will seriously affect the process of symptom analysis in case of doctor-patient tele-consultation.

- **Lack of maintenance of Patient Health Records (PHR):** Maintaining individual patient health record is one of the major features that many telemedicine projects operating in Bangladesh currently lack. In a telemedicine service, because of having no feature of maintaining PHR, consultation usually takes place over the phone or through video-conferencing and the details of treatment plan are conveyed verbally or through SMS to the patients. As a result, there always remains the possibility of misinterpreting the prescription when the medicine or treatment plans are suggested verbally over the phone or sent via SMS. Retrieving prescription in case of SMS getting accidentally deleted or losing the written document is also one of the major issues these telemedicine projects face when they lack support of a long-term prescription storing database.

- **None or limited support of integration for diagnostic devices:** Current telemedicine services often do not have any diagnostic device support that may equip the doctor in taking informed decision about patient problem. Even if they have, they usually lack any sort of integration with the telemedicine software in terms of data output and storing them in the software database. As a result, due to lack of proper integration of diagnostic device output with the software system, manual approach needs to be taken to input the device measurements or convey them to doctor through other means i.e. SMS, email, chat etc.

- **Operating Platform dependency:** Most of the telemedicine software that are being used in delivering telemedicine in Bangladesh are developed by targeting a specific, single operating system i.e. Android, Windows based etc. As a result, for example, a desktop-based software that has been developed for being used in a remote telemedicine centre is not suitable or compatible for a mobile phone and vice versa. Most of the telemedicine projects implemented in Bangladesh adopted either a mobile-based remote health care service or centre-based service delivery where usually desktop application is being used. Hence, being dependent on a single platform-based software limits the scope of reaching wider population and serve them remotely.

- **Not suitable for low-bandwidth network:** Current telemedicine software tools are often developed assuming that a stable and adequate bandwidth will be readily available to perform its operation. But in reality, it is very often not the case, especially in the rural areas of Bangladesh where good connectivity of internet is still not ensured in every nook and corners of the country. In order to operate and serve in the rural areas, it is very crucial to ensure that the telemedicine software will perform well even in low-bandwidth setup, the lack of which has caused many projects to perform poorly in rural environment. Several groups use software developed in affluent countries which suffer from problems of bandwidth when deployed in countries like Bangladesh.

- **Lack of user-friendly interface:** Lack of user-friendly user interface is a common issue experienced in every kind of software projects and not only limited to telemedicine software. The users who are involved in the use of telemedicine software are generally people from non-technical background and with varying level of literacy. If the technology is complex and difficult to use, it naturally creates a negative perception among the users about the whole operation and the success rate of the project declines. In developing countries like Bangladesh, it is common to use engineered software originally developed for different contexts and considering different user-groups in mind. This kind of software is often bloated with features or options that doesn't go with the current context of application and often lacks options that are required but not included as it was never intended to be deployed in that particular working system environment. Therefore, the overall user-experience and efficiency of the software in empowering its users very often turn out to be pretty poor and unsatisfactory.

- **Difficult to customise:** There is a common tendency to use imported, foreign software solution to run telemedicine services in developing countries. Use of such proprietary, commercial solutions comes with many constraints besides its added advantages. These solutions are usually very expensive and the source code is not open to customisation by the client. So, in case of further modification, which is likely to be often needed after purchase, the service provider needs to contact the vendor and make necessary customisation in exchange of a hefty amount of money. This model of software customisation may work for service providers with huge fund and financial support but are less likely to be sustainable in the delivery of rural telemedicine service as the overall operational cost is increased in this approach.

- **Organisational needs are often not addressed:** A functional telemedicine service is not only about the clinical aspects of it, but also the organizational functionalities related to delivering the service. Successful execution of both clinical and organizational functionalities is what contributes to the sustainability and success of a telemedicine service. As telemedicine initiatives in Bangladesh till now are mostly mobile phone based or video conference based, organizational functionalities such as monitoring patient visits, management of human resources involved with the project, statistical analysis of the patient turnouts, financial report etc. are missing in the current system.

3.5 Technical Need Assessment for the Present Work

3.5.1 Key User-groups of the System

After carefully analysing the environment on which the developed telemedicine software will be used, three types of user groups were identified whose direct involvement and interaction with the telemedicine software will constitute overall telemedicine service workflow. Patients are not considered as one of the core user groups as they will not have any direct interaction with the telemedicine software, but they are an important stakeholder of the overall telemedicine system. The identified user groups are classified below followed by a brief description of their roles in the system:

Telemedicine Operator

Telemedicine operators may be considered as the 'hands and eyes' of the telemedicine system on field. They are the ones who will build the bridge between patients and doctors by connecting them through telemedicine software, thus initiating the typical workflow of a remote teleconsultation. He/she is the first-line user of the telemedicine system with whom the patient will interact and is responsible for collecting and sending patient data to doctors for necessary diagnosis and evaluation and for organising patient-doctor consultation through video conference. The operator will measure the primary vitals using available medical instruments and enter the data manually in telemedicine application. In case of capturing data from digital stethoscope or digital ECG, telemedicine operator may take instruction from the doctor over video conference for the placement of stethoscope or ECG electrode at correct locations on the patient's body. Once a patient is diagnosed, evaluated and finally prescribed by the doctor, it is the telemedicine operator's responsibility to print the prescription and hand it over to the respective patient.

Doctor

Doctors will provide intended clinical teleconsultation to all the patients that will come to the remote telemedicine centres. After getting a consultation request from a telemedicine operator through telemedicine software the doctor will talk to the patient directly through internet with the help of telemedicine operator located at the other end of the communication channel. After talking to the patient along with analysing primary vitals and related clinical data of that patient, the doctor will decide about the treatment plan accordingly and send it over to the telemedicine centre by using telemedicine software. The prescription will be archived too so that it can be accessed anytime in future if required. Doctor may also help the operator to record stethoscope sound or ECG signal of the patient over video conference by guiding the operator in finding the correct placement of stethoscope or ECG electrode at locations on the patient's body. The doctor may first want to listen to patient's low-quality heart sound in real-time through Skype and then asks for 5/6 seconds of good quality heart sound recorded and stored using 'Audacity' if it seems necessary to the doctor. In case of receiving real-time ECG signal from the rural telemedicine centre, the doctor, most likely a General Practitioner, may direct the operator to retake any lead signal that appears to be noisy or incorrect. Once satisfied with the captured ECG signal, the GP may combine the 12 lead graphs and send it to the cardiologist for assessment. Based on the assessment received from the cardiologist, the GP will advise the patient regarding the future course of action – whether to take it easy with some simple medications or see a cardiologist at an advanced centre.

System Administrator / Project Coordinator

System administrator or project coordinator will take care of the whole telemedicine operation that will take place on and off the telemedicine platform. This user group will administer the tasks of managing other user groups as well as monitor all operational activities. These activities include monitoring patient data, analysing patient visit statistics, managing all telemedicine centres and telemedicine operators enlisted under them, evaluating the performance of the telemedicine centres etc. System administrator will also act as the main contact person for all sorts of logistics and hardware/software support to the telemedicine centres and manage financial aspects of the telemedicine programme as well.

3.5.2 Determining the Clinical Service Workflow

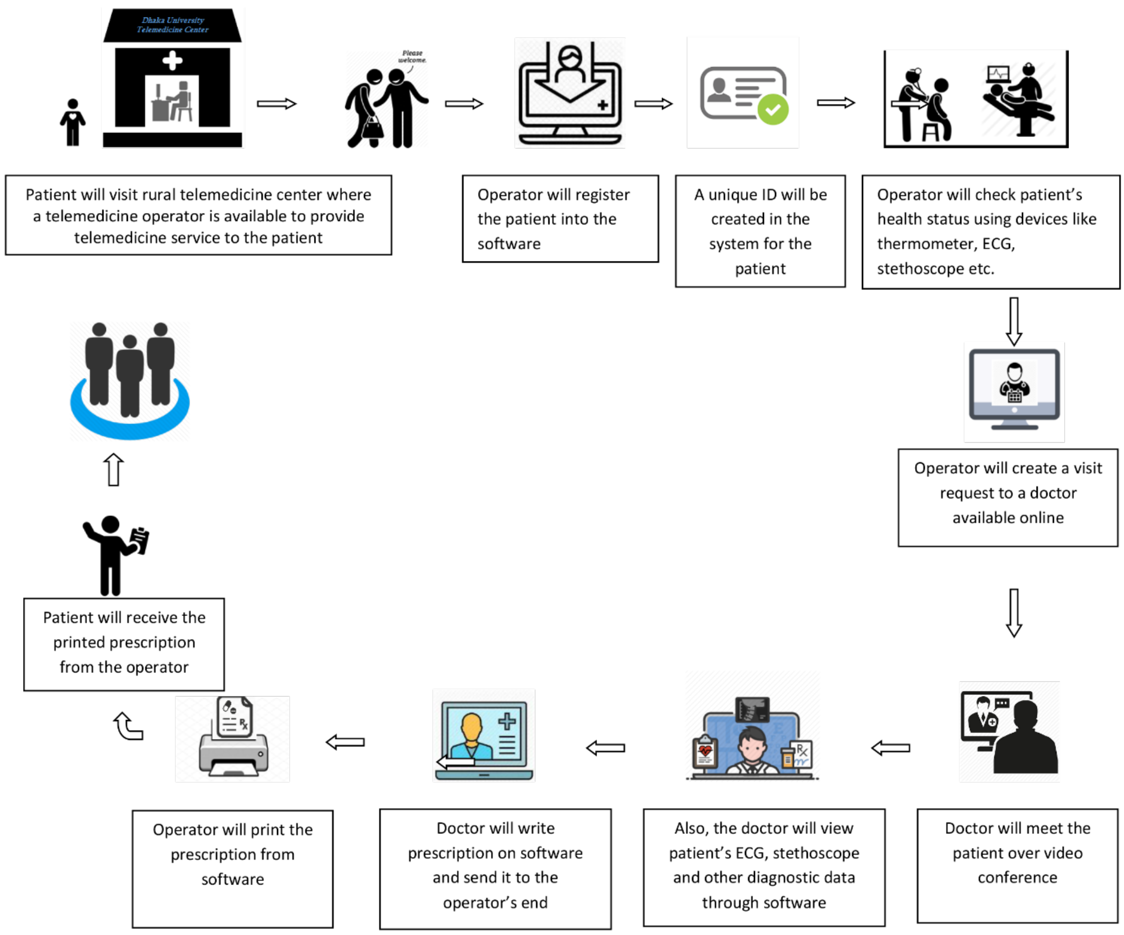


Fig. 3.3 Telemedicine service workflow adopted by BMPT to serve in the rural telemedicine centre

After analysing the system environment and its different elements the service workflow as shown in Figure 3.3 was found to be suitable considering the context and resource available for serving the rural people with quality primary care delivered from rural telemedicine centres. According to the assumed service workflow shown in the figure above, a patient will typically visit his/her nearby telemedicine centre for consulting a doctor through telemedicine. The operator present at the rural centre will first register the patient into the telemedicine software system with necessary details i.e. personal information, contact address etc. Once the registration process is successful, a unique ID will be generated for that patient and all information and consultation data related to that patient will be tracked and stored against that unique ID. In the next step, the operator will check patient's health status using medical devices mentioned in section 3.3.3 and will input the measured data in the telemedicine software and finally send it to a doctor available at that time. Upon receiving the request to see a patient the doctor will talk to the patient over video conference and check the patient's consultation data sent by the operator from the software. After completing the conversation, the doctor will write prescription in the software and send it to the patient. Once stored in the cloud, the prescription will be immediately available to the operator's end for printing and the operator will hand over the printed prescription to the patient, thus completing a cycle of serving the patient from a rural centre through telemedicine.

In case of mobile operators, instead of patients coming to the telemedicine centre, mobile operators will go door to door and replicate the similar service workflow.

The present work will concentrate on materializing this service workflow for delivering telemedicine service to rural communities and build the appropriate telemedicine software system. The functional and non-functional requirements that need to be fulfilled and incorporated within the software system have been identified and mentioned in the following section.

3.5.3 Synthesis of System Functionalities

By taking into account the system environment, application context and the service workflow to be adopted within the telemedicine service model of BMPT, the major needs of the telemedicine software system have been pinpointed and are mentioned below. Limitations of current telemedicine software, mentioned in section 3.4, which are typically observed in existing telemedicine service model adopted in Bangladesh, also have been taken into consideration to overcome those shortcomings in the present work.

Primarily the software system needs to (but not limited to):

- Be user-friendly for all user groups matching the respective minimum literacy level or computer skill envisaged.
- Record and store relevant clinical data and present them in a meaningful way to appropriate user-groups.
- Perform fairly well even in a low bandwidth network environment; especially ensure a satisfactory level of communication between doctor and patient over web video conference.
- Interface with diagnostic devices developed by BMPT.
- Ensure the privacy and security of patient data and sensitive clinical information.
- Be portable, easy to install and available on demand.
- Provide provision for analysing telemedicine data for monitoring and evaluation of the project from clinical, organizational and financial perspective.
- Have provision for exchanging data with other information management system such as billing, inventory management etc.
- Be modular in design and open to easy customisation for different application scenario in future.
- Be compatible with all major computer platforms including the use of mobile phone, if possible.

3.6 Factors to Consider During System Design and Development

After conducting verbal communication with several users from different user groups in the beginning of the system design process, some key factors were revealed and identified which have been taken into consideration while designing the telemedicine software system. These factors have been broadly categorized as: Human factors, organisational factors and Technical factors. Since the development process adopted an evolutionary approach, some factors were also identified once the software went live for operation and were addressed appropriately.

3.6.1 Human factors

- **Poor acceptance of new and unfamiliar technology:** It is a common tendency of human minds to be skeptical of new concept or technology in the beginning. Same goes for the concept of telemedicine as it is still not as widespread as conventional health care services even in developed countries, let alone in developing countries like Bangladesh. In the same way, breaking the barrier of discomfort in using a new software system is a major challenge in the beginning to proliferate among the target users.

- **Varying level of academic and computer literacy among user groups:** User groups identified at earlier sections of this chapter have varying degrees of both educational and computer literacy. Though the use of modern technological gadgets like personal computer, smart-phones, tabs are slowly becoming popular in the rural areas too, a major portion of the rural population is still not accustomed to these gadgets and have very little or no knowledge of using them. Though doctors and system administrators are much more educated compared to rural telemedicine operators, many of them, especially the older generation, are still not comfortable with the use of computers or modern gadgets.

- **Preference to native language over foreign language as a medium of interaction:** The initial study conducted among the different user-groups reveals that telemedicine operators are more comfortable interacting in their native language, Bangla over English. Other two user-groups are more comfortable in both of the languages but most of them suggested that they would prefer Bangla if there was an option to choose between the two for interacting with the software interface of the telemedicine system. However, medical terms and names of medicines and tests have to be in English. So there has to be a mixed language approach.

- **Lack of confidence in handling medical equipment:** Due to the lack of technical literacy and first-hand experience on operating medical equipment provided to them for telemedicine such as digital ECG machine, digital stethoscope etc. rural operators are likely to feel less confident in handling them to acquire and send digital data to the doctors. Though a proper training on the use of these devices will help to a great extent to reduce the confidence gap, it's still very critical to emphasize on the smooth integration and interfacing of the devices with the software system so that operators can complete the task of data acquisition to data sending without facing any major challenges.

- **Possibility of error prone data input and storing:** As doctors are not physically present on the ground, telemedicine operators are required to collect a number of patient data including patients' general details, disease history, primary vitals related to their current health problems etc. As a result, doctors might feel concerned about the quality of the data being collected by telemedicine operators considering their limited training, lack of necessary skills, confidence and prior medical experience. Poor quality of data may very often lead to incorrect diagnosis by doctors and may even result in life threatening consequences. Therefore, remote telemedicine operators need to be supported in every stages of data collection and data input within the software interface and safeguarded by appropriate data validation logic on software level.

- **Patients' tendency to forget specific details:** It has been observed during the course of trial run of telemedicine operation that rural patients very often forget their patient identification details i.e. patient ID, which is primarily used to identify a patient within the software system. As a result, it becomes difficult for the telemedicine operator to find the right patient profile for subsequent visits. The failure of finding the right patient profile often forces the telemedicine operator to initiate a new registration for an old patient, which is not desired at all. When this is done, the clinical data is divided and stored under different profiles for the same patient, which prevents the doctors from viewing complete patient history and may apparently affect the final diagnosis and treatment. Duplicate patient profile also contributes to generating incorrect analysis from organizational point of view as the number of registered patients within the software system is shown incorrectly than what it actually is.

  In addition, it has been found that a large number of rural patients, especially the older generation, visiting telemedicine centres during the trial run could not provide their exact date of birth while registering them along with a set of personal details for the first time into the software system.

- **Patients' preference on video communication over audio-only communication:** It has been observed throughout the lifespan of the trial run that patients want to talk to doctor face to face instead of talking over the phone or audio conference. Even if the video quality is low and the picture is, hazy it gives a psychological boost to patient's mind that he/she is indeed talking to a real doctor, which is missing in a typical audio-only tele-consultation. Being able to see the doctor online also leaves positive impact for the whole telemedicine project as well and people tend to recognize and accept the telemedicine service comparatively faster than other voice-only consultation.

3.6.2 Organisational Factors

- **The underlying business and operational model:** The underlying business and operational model of the telemedicine project has a direct influence on the software user-interface design and its intuitive logical information flow. Telemedicine models can vary widely, from remote tele-surgery to health care workers going door to door to provide home-based service. The variation in workflow of different telemedicine models reflects on the user-interface design of the system. The different steps of operational and business model adopted in the project needs to be translated accordingly into relevant user needs and incorporated within the information flow of the system to achieve maximum effectiveness, efficiency and satisfaction out of it.

- **Cost-efficient software development:** Financial sustainability is one of the major factors that are paramount to the longevity of a successful telemedicine project. Most of the telemedicine initiatives taken in developing countries rely highly on grants received from public, private or international body along with small revenues generated from out-of-pocket patient fees. Due to the limited nature of grants in most of the cases, there is an obvious need to reduce the capital cost invested in the necessary software if a telemedicine project wants to sustain the operation for a longer period. However, due to the variant nature of telemedicine models deployed in different contexts it is difficult to find ready-made software solution for context specific needs. That eventually prompts the telemedicine providers to develop their own software solution, which needs to be developed continuously as new requirements keeps arising throughout the lifespan of the project. As a result, a significant amount of capital needs to be invested in the software system development. Choosing and utilization of suitable open source software projects wherever and whenever possible is a viable approach to reduce the development cost significantly. This allows the telemedicine providers to enhance the functionality of their software platform without being locked into any proprietary licensing deals or being dependent on a single vendor.

- **Optimization needs of doctors' allocated time:** Employing doctors in the telemedicine programme is found to be the costliest component of the project during the trial run of DUTP. Hence, optimizing the time spent by a doctor for reviewing a single case is critical to the reduction of overall cost of the project. Higher patient flows are directly linked to the financial sustainability of the telemedicine project. The more efficient doctors will become in utilizing the system, the less time it will take to serve a single patient, thus allowing the doctors to review more cases within allocated time. Time required for reviewing a single patient may increase drastically due to poor usability of the system. If the user-interface of the system doesn't meaningfully assist a doctor to accomplish his tasks i.e. viewing patient data, writing diagnosis, suggesting drugs, sending prescription etc. in an efficient and effective manner, it will eventually result in to the dissatisfaction of the doctors and cost extra time for reviewing patient cases along the process.

- **Overall project monitoring and analysis needs:** Evaluating the performance of a telemedicine project in a systematic way is crucial to the success and sustainability of a telemedicine project. All telemedicine projects irrespective of its clinical and application context requires some means to monitor and analyse the delivered service quantitatively. Useful tools to visualize the project performance and generate customised report based on a set of varying parameters help project managers to take decisions related to financial and operational management.

  The clinical data accumulated and stored in the database, as telemedicine project keeps running and operational, is essentially a big data and can be immensely useful to the researchers for data analysis in the future too, which may also help a Government in its health care planning and in situations of emergency.

3.6.3 Technical Factors

- **Unreliable nature of Internet connectivity:** Doctors and system administrator user-groups residing in urban cities are usually under a better coverage of internet connectivity, but rural telemedicine operators are not. Availability of reliable and stable internet connectivity is hardly observed in rural settings due to lack of necessary ICT infrastructure that is essential for providing satisfactory internet experience. Broadband internet is usually available in urban areas but is yet to penetrate the rural places. Satellite internet connection can be an alternative option to deliver better internet service, but this mode of connectivity is very expensive in nature and quite difficult to implement without state-level support and financing. Considering the recent proliferation of mobile networks across farthest corners of the country (Bangladesh and many other Third World countries), mobile internet seems to be the viable option to look forward to for executing telemedicine services in rural areas. But it has its pros and cons too. Mobile internet speed in rural areas is very unstable and may vary from few Kbps to 1-2 Mbps. Due to its unreliable nature it is very challenging to maintain quality telemedicine service. Video consultation suffers the most among all telemedicine system functionalities in a low bandwidth network as a decent audio-video communication requires an internet speed of at least 128 Kbps or more on a reliable connection. However, the quality of audio data is more important than that of video data in a typical patient-doctor interaction.

- **Cost and requirements of internet data usage:** Cost of mobile internet data is higher compared to broadband internet services. Mobile internet data is usually available in the form of different volume packs none of which usually offers any unlimited usage policy. It makes the internet experience for telemedicine service even more difficult and costly, as transfer of multimedia data along with text-based clinical data demands a significant amount of bandwidth usage.

- **Absence of uninterrupted power supply:** Frequent failure of power supply in rural areas is another matter of concern that interrupts the regular workflow of a telemedicine system. Frequent load shedding occurs in these areas in regular basis, hence technical infrastructure of telemedicine system needs to be kept at a minimum level to minimize technical complexities that may result in from unreliable power supply.

- **Unavailability of technical assistance:** Rural telemedicine centres are generally located at remote areas that are far from urban cities and access to technical assistance in case of need is unlikely to be available there. Due to the lack of support mechanism it is difficult to troubleshoot and fix problems for both hardware and software system at the remote operators' end. So, installation complexities and operational footprint has to be as minimum as possible at the end-user's end so that they can interact with the software system without much hassle and do not need to worry much about the maintenance of the software at their end.

3.7 Final System Design Architecture

After a thorough and careful scrutiny of the system environment and role and responsibilities of different user-groups of the system, it was decided that a cloud-based software system incorporating clinical, organizational and medical device integration functionalities would best suit the current needs of intended telemedicine service to deliver primary and secondary care in rural areas because –

- A cloud-based telemedicine software system would remain available and accessible to all user groups of the system 24X7.
- As telemedicine operators would typically reside in distant rural areas it is difficult to support them with technical assistance in case of installation failures or troubleshooting. Adopting a cloud-based solution would save the users from going through any sort of software/plug-in installation on local computer system which will eventually lead to spending less time on installation related troubleshooting that might be required for local installation of the software.
- It would be easier to implement the future updates and modifications on the telemedicine platform requiring minimum interruption or adjustment in the client-end computer system.
- If designed accordingly, it can be accessed and used from a variety of devices and operating systems eliminating the dependency to a specific type of computer device or OS. Any computer system with active internet connection and a supported web-browser would be the only requirements for interacting with such telemedicine platform.

The schematic diagram of the software system architecture in Figure 3.3 depicts the key components of the system and their relationship with each other when the present work will be completed. A brief description of each of the key components within the software system are described below and each of them will be explained elaborately in later chapters.

3.7.1 Telemedicine Management System (TMS)

Telemedicine Management System (TMS) will act as the central point of interactions for all user-groups. Communications among the end-users will take place through it. This will be a cloud-based software application that can be accessed through user-friendly interface via internet from any modern web-browser and any Operating System platform. Only authentic users will be allowed to login to the system using provided login credentials and access relevant data and features through user-friendly, intuitive interface. After successfully logging in to the system each user-group will be presented with a separate, customised dashboard user-interface tailored according to his/her own roles and responsibilities. While telemedicine operator registers and send patients' clinical data through his/her dashboard user-interface, doctors will also receive them and will be able to send treatment plan in prescription format after talking to the patients through video-conferencing user-interface built right into the telemedicine management system. Telemedicine Administrators having a separate user-interface will be able to monitor and manage all operational activities taking place within the cloud-based TMS.

There would be a separate mobile-friendly user-interface for mobile operators who visit door to door and connect the patients with doctors through the TMS. All the features and functionalities that are available in the desktop version of user-interface for telemedicine operators will also be available from the mobile-friendly user-interface as well. In case of power failure in the centre, the same user-interface can be used by remote operators present in the rural health centres. This mobile application user-interface would interact with the TMS database through REST API which will also be developed as a part of this present work. The TMS can be easily

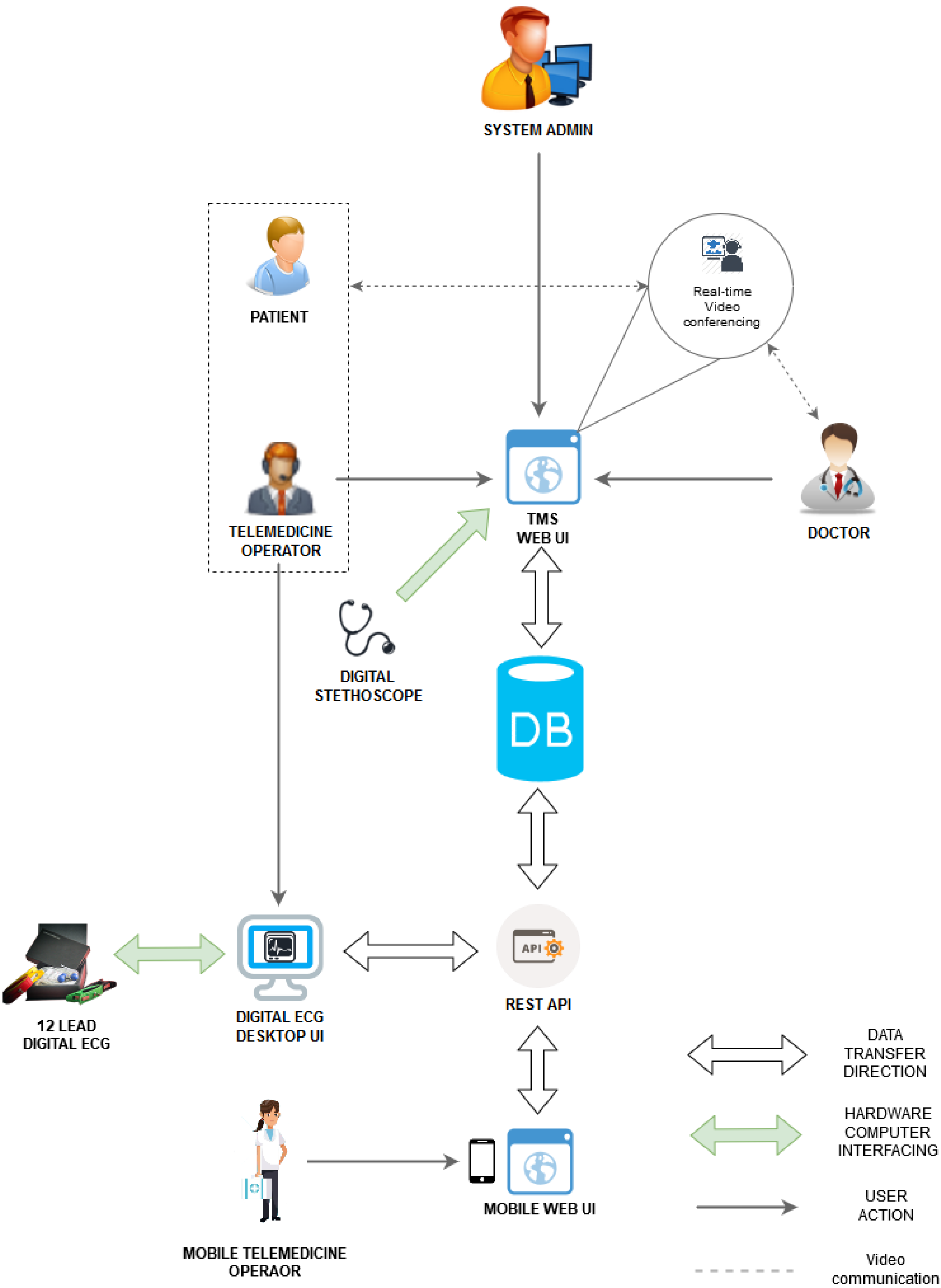


Fig. 3.4 Final design of the telemedicine system intended to be achieved from the present work

extended for other platforms i.e. android, IOS etc. as well utilizing the developed REST API layer.

3.7.2 Integration of Medical Devices Output Within the TMS

- **Integration and interfacing of digital electronic stethoscope:** A web-based user interface for acquiring, storing and forwarding digital stethoscope sound would be developed and integrated within TMS user-interface. Telemedicine operators should be able to capture, listen and finally store and forward the sound along with other clinical data for doctor's examination and evaluation. Stethoscope sound is stored in the cloud as a sound file besides other device measurements. A separate user interface specifically for doctors' analysis has to be developed with useful functions i.e. display of heart sound wave form, zooming, stethoscope sound player etc. Upon receiving a patient's clinical data, doctors should be able to play and listen to the heart sound of the patient as well as view the sound signals captured from the stethoscope.

- **Integration of 12-lead diagnostic ECG data:** A data transfer protocol for transferring 12 lead ECG data captured from the BMPT ECG Device to the aforementioned Telemedicine Management system has to be developed. In order to achieve that, necessary modifications both in the user-interface and software algorithm have to be made in the JAVA-based ECG software to access telemedicine patient information from within the ECG software interface. Telemedicine operators should be able to store recorded ECG data against a patient's visit directly from the desktop-based ECG user-interface. A web-based user interface for displaying 12 lead ECG data has to be developed and integrated within the user interface of aforementioned Telemedicine Management System so that doctors can view ECG data online along with other device measurements.

3.7.3 Real-Time Multimedia Communication User-interface

Real-time multimedia communication user-interface has to be integrated within the TMS for doctor-patient tele-consultation. Telemedicine operators should be able to directly make a video call after sending a patient's visit data and diagnosis measurements to an online doctor right from the telemedicine software interface.

Upon accepting the call, the doctor should be able to talk to the patient for detail enquiry about the health problems of the patient. The Multimedia communication tool has to be integrated seamlessly within the TMS user-interface so that operators and doctors can communicate over the web without needing them any separate real-time communication software .

3.8 Research Approach

As opposed to many telemedicine research projects focusing on the development of a system prototype in a controlled lab environment,the primary target of the present work is solving real problems for real users of an ongoing telemedicine project. The research was focused on identifying and solving end-users' needs on a 'first come, first served' basis. The identified tasks were usually filled with many small and delicate problems and needed attention on a day to day basis. The priorities were set by judging the impact it would have if accomplished and how much the overall gain would be compared to current situation. In short, the present work focused on the current work problems and solved the most immediate ones in hand. This is in contrary to many typical workflows followed in HCI area that try to figure out the possible future concerns and their solution by introducing new forms of technology to solve those problems. Throughout the lifespan of this research work, HCI is not about radical innovation but about evolutionary improvements which eventually leads to the development of a telemedicine system with high usability and efficiency.

There are three major ways to conduct research in HCI. They are: experimental studies, survey studies and observational studies [46].

Experimental study is conducted in an environment where all the variables are controlled except variables that are going to be tested within that specific environment. The strength of this approach lies in its ability to unambiguously localize an effect in a specific design condition. This approach is especially useful to study isolated design factors, but this is not always feasible or possible as it requires a situation where all the variables need to be explicitly controlled.

Survey studies are useful when it comes to describing a system and finding its strength and weakness which eventually allows applying the gathered suggestions for the improvement of the system. It might be subject to biases at times but can be refined significantly when comparisons of responses are made among different groups of subjects.

Observational studies are easy to perform but the conclusion is open to interpretation by researchers. Usually one or multiple systems are selected and users of the system are observed by the researchers. Analysis can be at a purely verbal descriptive level or based on quantitative measures. But reaching to a conclusion out of these studies are mostly tentative as conditions interacting with the system are unlikely to be controlled by the researches.

The present work is mostly conducted by performing observational studies which are complemented by survey studies whenever and wherever possible. It obviously adapts to a qualitative approach as the research work is performed within an ongoing telemedicine project. The strategies in different parts and stages of the present work varies slightly from one another based on many different conditions. Variables like involvement of multiple stakeholders, time constraints, factors prevalent in the socio-technical context of developing countries like Bangladesh influenced the possibilities to pick the appropriate direction and methodology. However, for most part of the work, the adopted approach can be labeled as Action Research(AR) applied in a socio-technical context.

Action Research

Action research has its academic roots in sociology, social psychology, organizational studies and education. Adapting to this approach helps a researcher to effect positive changes on the situation within which the research is taking place, while simultaneously conducting research by developing understanding between the researcher and the subject. Hopkins described action research as an informal, qualitative, formative, subjective, interpretive, reflective and experimental model of inquiry[47]. In this mode of approach, every stakeholder of the system is a knowing and contributing participants. In short, action research provides a researcher with a framework for qualitative investigations in complex working situations [48].

It has four distinguishable stages, which are being repeated over and over again during the lifespan of a project. These four stages can be defined as:

- Recognise the problem and devise a plan to address it
- Execute the plan
- Observe the result
- Reflect and revise based on the observation

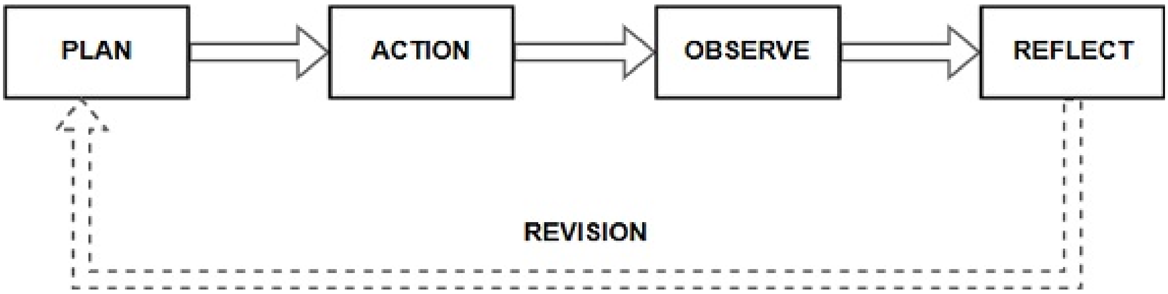


Fig. 3.5 : 4 Stages of action research

The development of Telemedicine Management System mostly followed these four stages of action research to identify the primary goals and actions were taken to achieve them. The rest of the work is also the outcome of the necessities recognised during the execution of the mentioned approach. However, throughout the lifespan of the present work, qualitative methods were complemented by quantitative methods whenever and wherever deemed suitable.

3.9 Conclusion

This chapter gives an overview of the background work that has been conducted prior to the present work and discusses the nature and limitations of other telemedicine services of Bangladesh, which are trying to reach the rural people offering distant primary care. It then explains the service model of BMPT that aims to address the current issues of rural telemedicine service. It analyses the system environment present in the adopted service delivery model and summarizes the different factors concerning the system environment that might directly or indirectly influence the design, development and deployment process of the telemedicine system that the present work intends to achieve. Finally, the last two sections of the chapter describe the technical need assessment in the light of what have been observed in the preliminary research. Furthermore, it proposes an appropriate design of the telemedicine software system for BMPT telemedicine service addressing the context specific factors and concerns typically present in a socio-economic environment in developing countries like Bangladesh. The chapters to be followed will elaborately describe and explain the parts of the work that has been carried out to develop a secure telemedicine system based on the dissection of the system environment and functionality requirements identified in this chapter.

Chapter 4

Telemedicine Management System (TMS)

4.1 Introduction

Most of the current telemedicine systems of Bangladesh are video-conference based. These services often lack the essential support of integrated Information Management System (IMS) or Electronic Health Records (EHR). As a result, these services do not have any longitudinal mechanism to store and organise patients' health records. Also, it is necessary to handover printed prescription to patients as this is a document with credibility, also for record keeping. Without a written prescription, patient may not understand the names of medicines which may result in taking wrong medication.

The clinical and organisational requirement gaps typically found in telemedicine systems deployed in Bangladesh were explicitly identified and defined in an earlier chapter. Addressing those shortcomings, a web-based application, to be called as Telemedicine Management System (TMS), was developed. The developed TMS is an integrated Information Management System in which all the functional requirements, as identified in chapter 3, were incorporated. The TMS would also act as a communication channel between doctor and patients via telemedicine operator. Taking service of this application, a telemedicine operator would help a patient from remote areas to connect to a doctor for his/her basic healthcare needs and immediately get a prescription after the consultation takes place over internet. At the same time, the TMS also provides an array of functionalities to telemedicine coordinators for managing the organisational taks of a telemedicine project.

From the very beginning of the development cycle of the TMS an user-centric Action Research (AR) method was adopted to continuously recognise the gaps in the developed system. The identified gaps were addressed accordingly based on the feedbacks coming from the real users interacting with the software system on field.

This chapter describes the major functionalities and high-level architecture of the TMS followed by a brief visual introduction to different components of web user-interface of the system. The chapter then discusses the security measures that were taken to make the TMS a safe and secure platform for telemedicine operations. The security measures include the data privacy of patient health data stored in the database as well as the overall security of the application. This chapter also discusses the adaptive measures being taken to address the slow internet connectivity issue for providing better telemedicine service in rural areas, as discussed in chapter 3.

4.2 Core Features and Functionalities

4.2.1 General Features

1. **Multi-lingual system interface:** The developed TMS user interface is multi-lingual supported meaning that text instructions and commands used within different parts of the user-interface easily can be translated to any language suitable for the target system users based on their language preferences that requires minimal customisation and less time. As a part of this present work TMS user-interfaces have been primarily translated to Bangla, the native language of Bangladesh, besides English being the other language of preference. However, names of medicines and diagnostic tests have been kept in English to avoid misinterpretation and confusion as English names are preferred everywhere for both of these. User-interface language preference can be easily switched between these two languages anytime from relevant user settings.

2. **One integrated platform for all system users:** All functional and non-functional requirements identified within the scope of this present work as described in chapter 3, has been translated into usable functionalities and incorporated within the TMS. These functionalities are integrated into a single platform and can be accessed through user specific appropriate user-interface upon logging in to the system with appropriate user login credentials. After successful login users are automatically redirected to the dashboard interface appropriate to their user type.

3. **Responsive user interface:**All the user-interfaces of the system has been designed following Responsive Web Design (RWD) approach. All these interfaces render well on a variety of devices and window or screen sizes. As a result, TMS can easily be accessed and used from a variety of computing devices i.e. desktop computers, laptop, smartphone, tablet etc. conveniently through interacting with responsive user interface.

4.2.2 Clinical Functionalities

For Rural Telemedicine Centres

1. **Patient registration:** TMS provides option to register new patients once they come to take telemedicine service for the first time. Healthcare worker register a patient by filling up a registration form that includes a set of personal information as well as health information such as current and previous disease history. The patient registration form includes a mixture of both optional and required type of data.

2. **Create and send consultation requests:** Once a patient is registered into the system by providing necessary information, telemedicine operator can create new consultation requests against that registered patient and send it to a doctor enlisted within the telemedicine program. The new consultation form includes option to input patient's primary vitals along with patient's chief complaint. The telemedicine operator measures the primary vitals of the patient using available set of diagnostic devices and enter the measured data

into the consultation form manually. This last activity is done on each visit, whether it is the first one or a later one.

3. **Access to individual patient profile:** Telemedicine operator can access patient profile of all patients registered in the same centre. Patient profile consists of all the health data and patient information collected and stored in TMS database since the patient is registered into the system. Patient's registration data can be edited and updated from individual patient profile. All previous consultation history as well as new consultation request are also accessible from patient profile interface.

4. **Multiple methods to search registered patients:** Multiple methods have been developed to search patient data from the system database in case of patients forgetting their patient ID. Besides searching by full unique patient ID, patients can also be searched with last four digits of patient ID, mobile number, first name and last name. Ajax (Asynchronous JavaScript And XML) enabled search results show a preview of patient's basic details such as full name, mobile number, patient ID and age as well to find out the appropriate patient in case of multiple patients having the same name.

5. **Acquire and send Digital Stethoscope sound to doctor:** User-friendly interface for capturing and storing digital stethoscope, the one developed by BMPT, has been developed and integrated into the consultation request form of patients. Besides filling up the primary vitals data, telemedicine operator can capture and attach stethoscope sound with a new consultation request which is finally sent to a doctor for evaluation of the patient problem and condition. Stethoscope interface also provides the option to capture and reset stethoscope sound recorder as many times as needed until telemedicine operator is satisfied with sound quality. The captured sound then can be saved in the database along with other clinical data of the patient and can be sent to the doctor to better evaluate the health condition of the patient.

6. **Mechanism to upload and send digital images of paper-based clinical document:** Option to upload and attach digital images of paper-based health data

i.e. test reports, previous prescriptions, x-ray image etc. has been developed and integrated within the new consultation request form. This addresses the data portability issue regarding paper-based health data and makes them available for doctor's inspection and evaluation. Health data Images are compressed and optimized accordingly in the client-end to reduce bandwidth data usage before uploading them to TMS cloud storage.

7. **Access to all prescriptions for viewing and printing:** Once the doctor creates and sends a prescription in response to a patient consultation based on the evaluation of health data followed by an audio-video consultation, the prescription gets immediately available in the operator-end for viewing and printing. Only when the prescription is stored in the cloud and accessible to the operator, the patient is counted as a served one. Patients' prescriptions that were prescribed in the past can also be searched and accessed by patient ID and date of consultation.

For Telemedicine Doctors

1. **Access to list of waiting consultation requests and the attended ones:** Telemedicine doctor dashboard presents to a doctor with two separate lists, one of awaiting consultation requests and the ones already attended to. List of awaiting consultation requests are sorted and shown in chronologically descending order. Doctor has the option to accept or cancel an awaiting consultation request. Already attended consultation requests are also available for viewing in case of re-evaluating a treatment plan.

2. **Access to full patient history:** Upon accepting a consultation request, a telemedicine doctor can access and view full clinical history of that patient including his/her personal information, previous consultation data, prescriptions, attached images etc. along with the current consultation data. The Doctor can also hear the stethoscope sound opened in a separate player window where there are options to view the stethoscope sound in wavelet form and to analyse the sound data in further detail. Doctor also has access to

recorded ECG graph of the patient in a separate web-based ECG viewer if sent and available with consultation request.

3. **Access to a user-friendly, intuitive interface for prescription generation:** A user-friendly, intuitive interface has been designed and developed to assist the doctor quickly and efficiently. The doctor can generate a software aided prescription accessing the prescription writing interface while carrying out and evaluating a specific consultation and make use of a previously formatted prescription panel to prepare and send the relevant medical advice Specific rules and logics have been set to avoid common errors and mistakes that a doctor may usually commit during typing a prescription. Doctor can either take help from the provided database of medicines, diagnostic tests and advice suggestions, can edit them or write directly in the prescription editor in case of their unavailability within the provided database.

4. **Access to suggestions for prescribing medicine:** A complete database of medicine approved by government regulatory body of Bangladesh has been built and made available to doctors to assist them during the process of prescription preparation. Relevant medicine names (local brand names) appear as a suggestion while the telemedicine doctor starts typing in the medicine suggestion form. Medicine suggestion is also available by generic name of medicine to increase doctor's convenience in prescribing.

5. **Access to suggestions for diagnostic tests and advice:** Telemedicine doctors also have access to a list of common diagnostic tests and advices usually given to patients as a part of the patient treatment plan. Commonly used names of diagnostic tests and medicine advices are pre-populated from database and made available inside the prescription writing interface

4.2.3 Organisational Functionalities

Organisational functionalities developed within the TMS can further be classified into three categories based on the type of telemedicine administrator the functionalities have access to. There are three types of telemedicine administrators in the current service model adopted by BMPT: Local/group entrepreneurs, telemedicine project coordinator and super administrator. Access to organisational functionalities within TMS are defined according to the requirements of each of the administrator type.

1. **Manage clinical data of registered patients:** Telemedicine administrator can view and manage all clinical data of registered patients that are stored in TMS database. Local/group entrepreneurs can access to only those patients who have registered and sought consultation from any of the telemedicine centres they manage. Project coordinator or super administrator has access to patient database of all the centres managed and maintained under the telemedicine programme. The operations allowed for managing clinical data are restricted to viewing only. All the administrators of the system can view profile information and consultation data associated with patients of their respective centres.

2. **Visualisation of telemedicine consultation statistics:** Multiple easy-to-use data visualisation tool has been developed to visualise patient consultation statistics that enable the administrator of the telemedicine project to monitor and evaluate telemedicine service quantitatively from organisational perspective. These visualisation tools provide useful means to observe telemedicine consultation activities at a glance. A number of charts visualising consultation statistics can be generated applying different, predefined parameters. Access to these easy-to-use visualisation tools are also restricted by administrator type. Local/group entrepreneurs can visualise the statistics of their respective centres only while project coordinator or super administrator can visualise the data of all centres.

   There are two versions of visualisation tools developed for the purpose. The simpler version visualises consultation statistics by some predefined parameters such as day-wise, centre-wise and doctor-wise representation of total number of completed consultation within a specified date range. This tool is helpful for administrators to get a quantitative overview of the completed consultations.

The advanced version is capable to generate more complex visual charts with greater number of inclusive or exclusive parameters consisting of patient data collected during the patient registration i.e. gender, occupation, religion, age-range etc. The data to be visualised can be concentrated to a specific demography or telemedicine centre. The date can be represented in a number of classification type such as gender-wise, occupation-wise, religion-wise etc. This advanced tool is helpful not only for the organisers, it may also be used as a research tool to generate visual statistics to quantitatively understand the acceptance of telemedicine service among specific class groups. These data, visualised in a meaning way using this developed tool, may also prove to be useful in government planning and decision making in the future.

3. **Management of rural telemedicine centres:** Rural telemedicine centres are the focal points from where the telemedicine service is actually gets delivered to the rural patients. A few modules have been developed to help local entrepreneurs, organisers and administrators to better manage rural centres and its intended activities. Each telemedicine operator operating in rural areas are assigned under a rural telemedicine centre and all the activities performed by them can be monitored from that specific centre's dashboard. Performance of these rural centres can also be monitored through developed visualisation charts and data table.

4. **Management of enlisted telemedicine doctors:** All the doctors who give treatment to rural patients through telemedicine service need to be enlisted to the telemedicine software first. Options have been developed to perform actions i.e. add, update, activate or suspend a doctor within telemedicine software. A doctor profile is also maintained and created/updated by telemedicine administrator which is accessible to remote operators' end to help them take informed decision to choose the right doctor for a patient. The administrator also has access to doctor monitoring tool to oversee the doctors' performances in terms of how many patients they have served individually within a given date range and the prescriptions they are providing to patients. Only project coordinator and super administrator have access to this functionality module.

5. **Management of medicine, diagnostic tests and advice suggestions database:** Telemedicine administrator are provided with the options to add new medicine, diagnostic tests or advices directed to patients that assist the doctors write prescription faster and efficiently. Database of medicine, tests or advices can also be updated or deleted through respective module interfaces. Only project coordinator and super administrator have access to this functionality module.

6. **Role-permission based user-management:** Though there are three types of system user who will primarily interact with the telemedicine software system, changed circumstances may require more users to be included in the system in future. Keeping that in mind all identified actions and modules to perform them have been developed following a modular approach so that access to these modules can be given to or revoked from any user role. There is a provision available to telemedicine administrators to add new-user type with the ability to assign custom access and permissions suited to that specific user role. Telemedicine administrators with super admin privilege can perform this action from his/her dashboard interface which requires no knowledge of programming or any modification in the software codes.

4.3 Technical Description

4.3.1 Application Layers

Telemedicine Management System (TMS) is a PHP-based web application built in a modular fashion so that it can be easily be extended with more options and features when required in future. MVC-based Laravel framework [49] was used as a foundation for the development of the application. At the core of the TMS, there is a relational database storing all types of information related to TMS and telemedicine activities that are performed using this developed platform. For the developed software system, Open Source MariaDB [50] was chosen as the relational database server, but it can be easily switched to popular alternatives like MySQL or PostgreSQL with minimal effort and customisation.

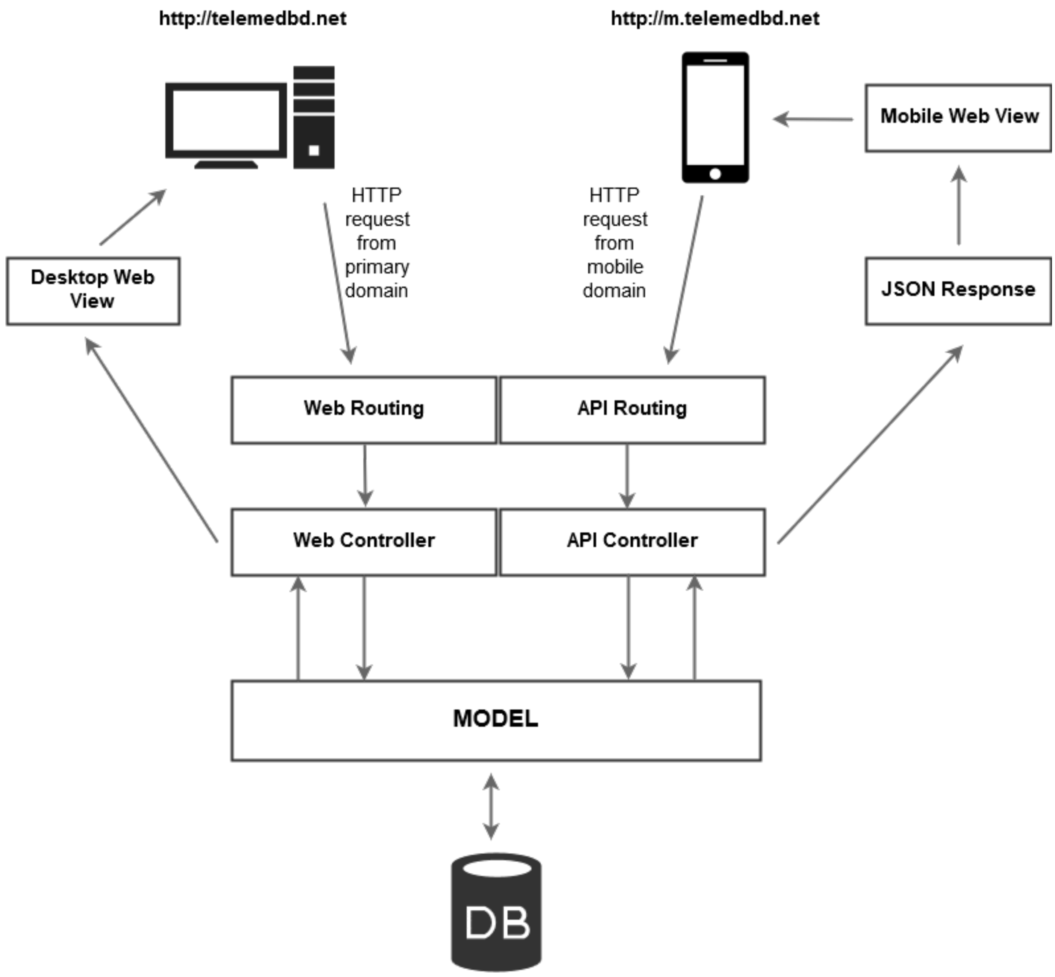


Fig. 4.1 Application layers of the developed Telemedicine Management System

The communication flow from web browsers to the TMS database has been illustrated in Figure 4.1. The figure illustrates how requests coming from two different domains via two different interfaces, the primary TMS application web interface and mobile interface of the application, communicate with the central database of the TMS. The requests coming from the web browsers of TMS users go through different layers of the application and finally receive the appropriate response in return.

Most data stored in the database are accessible through object-oriented Data Model class. Data Model class provides data to relevant Controller classes upon receiving requests with appropriate permission. There are two types of Controller classes which deal with all the incoming requests and comes up with appropriate response depending on the type of the incoming request. Two URL Routers, Web Router and API Router, direct all the http request coming from the client side to the appropriate controller class for performing intended database actions and further processing of the incoming requests.

Primarily, only web controllers were designed and developed to deal with and respond to http requests with appropriate HTML output. Later on, the application functionality had been extended for accessing the TMS data from other different platforms as well through Restful API layer. For example: A mobile-phone friendly user-interface for mobile telemedicine operator was developed so that operators going door to door can access the TMS from their smartphones/tablet conveniently. For developing that mobile-friendly interface, HTML and jQuery-mobile was used in the front-end, which is hosted in a different domain, and interacts with the TMS database through a set of API classes developed as a part of this present work. API requests are served from a different sub-domain and passed to API controllers after they are filtered through API routing. All API requests are returned with appropriate response in JSON format.

4.3.2 The Data Model

The data stored in TMS relational database can be broadly categorised into three types: Clinical, Organisational and Security data. These data are normalised and stored into different data tables according to their type and characteristics. These data are stored across different appropriately named data tables to better classify and manipulate the data for various telemedicine operations within the TMS. Every data table has its correspondent Data Model Class through which these data can be stored, retrieved and manipulated. All the data is stored in UTF-8 character encoding to ensure data input for wider number of languages. A brief description of each category of the data being stored in TMS database are given below:

- **Clinical data:** Clinical data consists of those directly related to clinical examination and procedures involving telemedicine patients. These data are combination of both structured and semi-structured and unstructured data. Clinical data stored in TMS database include patient's registration data, health data and treatment data. They are briefly described below:

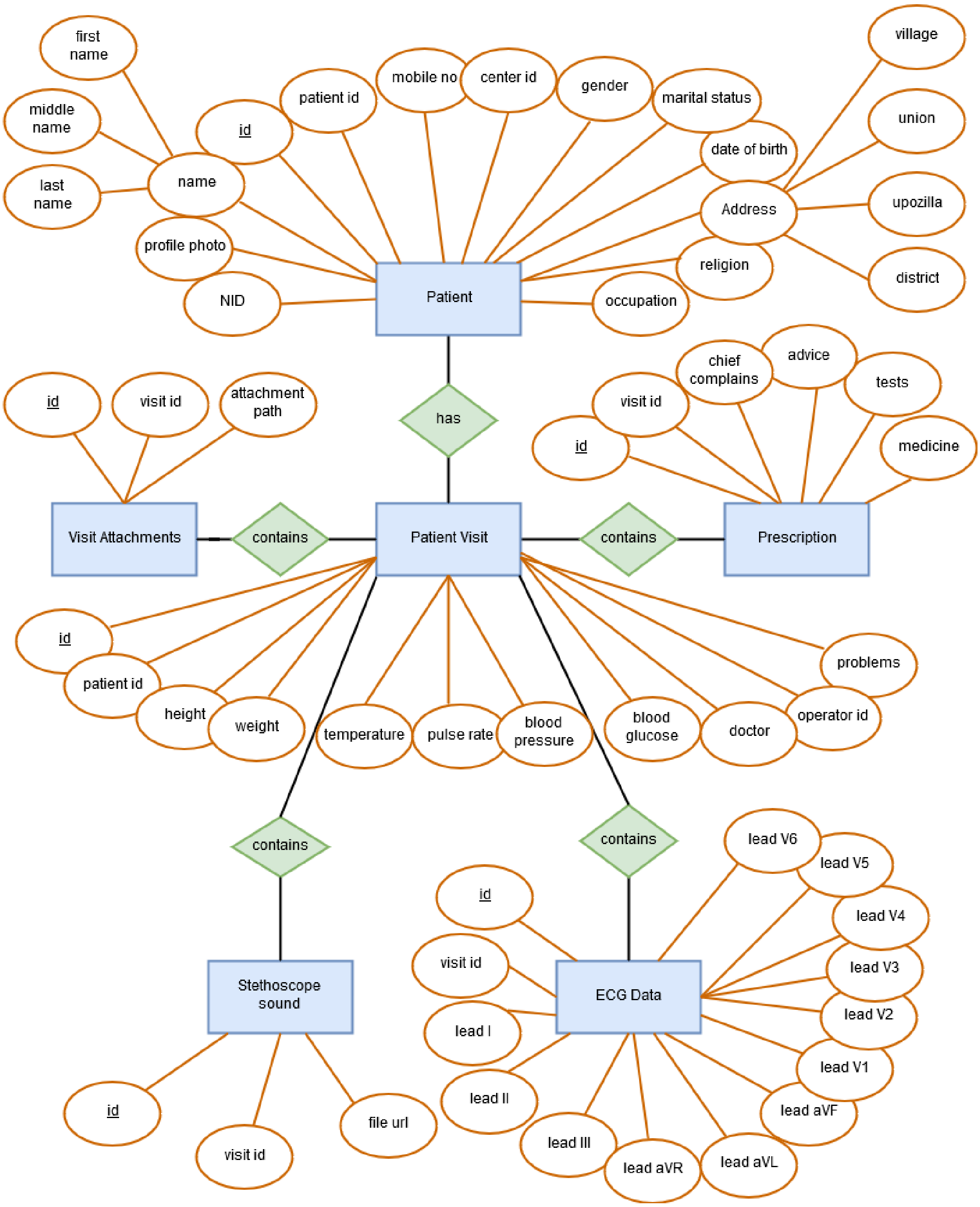


Fig. 4.2 Entity-relationship diagram of TMS clinical data, illustrated adopting Chen Notation

– **Registration data:** A set of registration data collected during registering a patient are stored in 'Patients' table and usually doesn't change often i.e. Name, gender, religion, occupation etc. These data are stored once when a patient comes to take telemedicine service for the first time and can be updated if required in future.

- **Health data:** Health data includes patients' health related information for each of the tele-consultation that includes primary vitals measurement data, health problem description, digitally converted paper-based clinical data and test reports, stethoscope sound, ECG data and identifier for the doctor assigned to a specific tele-consultation. Among them stethoscope data are stored as audio files and previous test reports and hard-copy clinical data such as prescription are stored as image files in TMS cloud and relative paths to access them are stored in relational database.
- **Treatment data:** Treatment data consists of prescribed medicine, diagnostic tests and advices against a completed tele-consultation record and stored in a single data table in different columns.

  Relationship between these clinical data are illustrated in an entity relationship diagram in figure 4.2 using Chen Notation. This diagram explains the relationship between different data tables containing clinical data.

• **Organisational data:** Organisational data include information related to telemedicine centres and users of the system i.e. telemedicine operators, doctors and system administrators. Data to interlink the relationship of the users by User-role and permissions are also stored in TMS database and fall under this category.

  The entity-relationship diagram of organisational data tables stored in the TMS database are illustrated in figure 4.3 explaining their relationship with each other using Chen Notation.

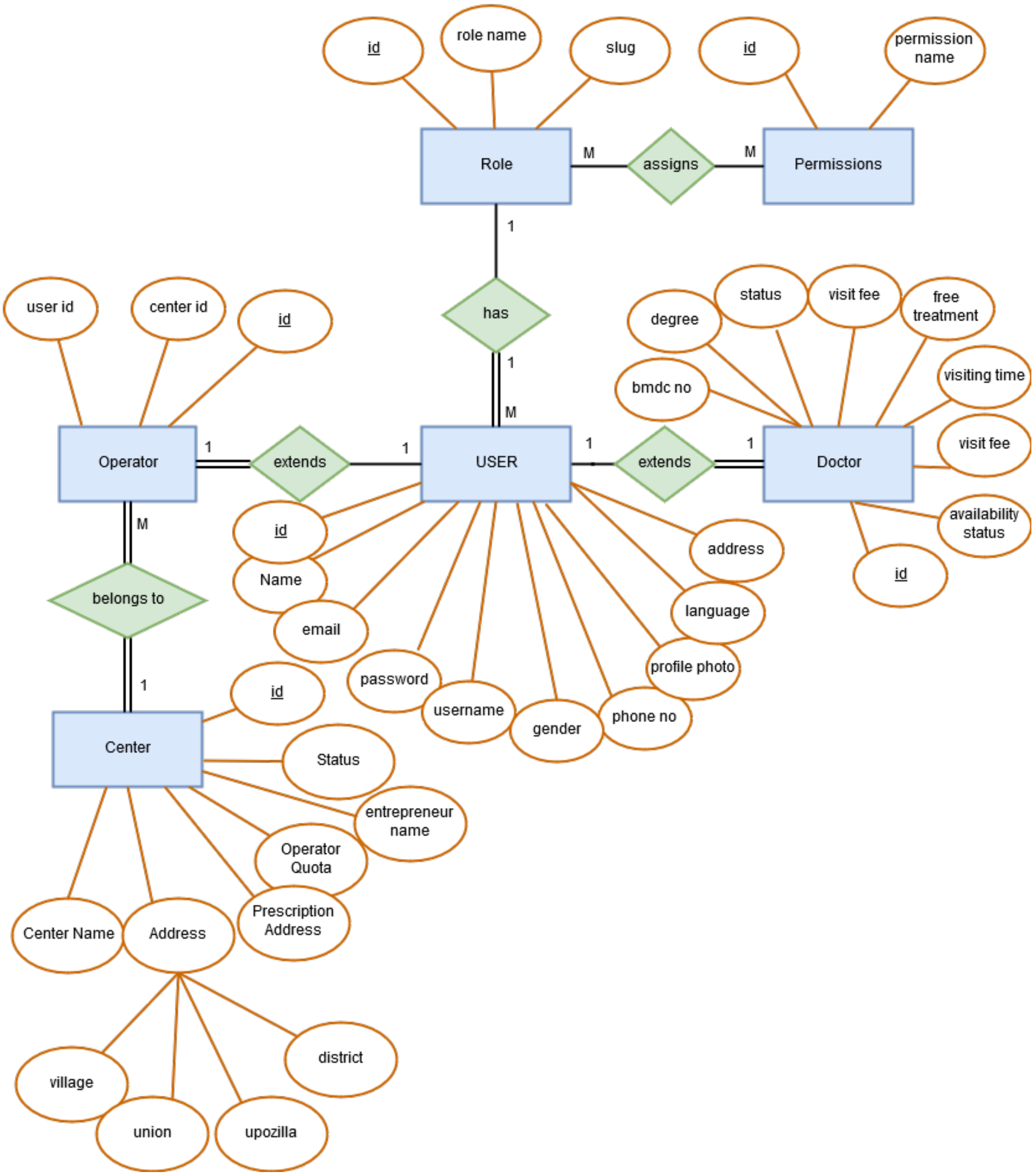


Fig. 4.3 Entity-relationship diagram of organisational data adopting Chen Notation

- **Security data:** Besides clinical and organisational data, some security related data are also stored in TMS database for keeping record of authenticated users of the system and their login details including IP address of the accessed devices and persistence data to remember a specific session for future login. Also, the data to keep track of number of failed login attempts from a specific IP address are also stored in the database by the system to prevent brute force attack or any malicious login attempt within short span of time.

4.3.3 Application Program Interface (API)

Application Program Interface (API) layer has been developed as a mechanism to interact with TMS database from another platform i.e. Android, IOS etc. besides accessing it from the developed web interface of the TMS. The developed RESTful API uses HTTP requests to GET, PUT, POST and DELETE data from the database. The developed functional endpoints of the API layer cover all the actions that are required to perform adopted telemedicine workflow by telemedicine operators and doctors from TMS web application. However, database actions related to organisational functionalities have not been translated into API functional endpoints yet and will be a part of the future development of this project.

4.3.4 Implementation Constraints

The TMS web application can be deployed in the cloud with minimal effort and customisation. However, it has a few system requirements that need to be satisfied for its successful deployment in the cloud. These requirements are mentioned below:

- Web server: Nginx 1.10.3 or higher
- PHP: Version 7.0.0 or higher with OpenSSL PHP and PDO PHP extension enabled
- Database: MySQL version 5.5+ or MariaDB version 10.0.0+
- Laravel Framework: version "5.5.*"
- Dependency manager: Composer version 1.0.0 or higher

4.4 User Interface

Telemedicine Operator, Telemedicine doctor and Telemedicine Administrator are three major user-groups that interact with the TMS web user-interface. These three user-groups can access the group-specific functionalities through relevant user-interfaces upon logging in to the system with appropriate login credentials. Some content related to telemedicine program are open to all in the form of publicly available web-pages and do not require any special permission to access and view. The high-level navigational diagram of the TMS web interface are shown in figure 4.4.

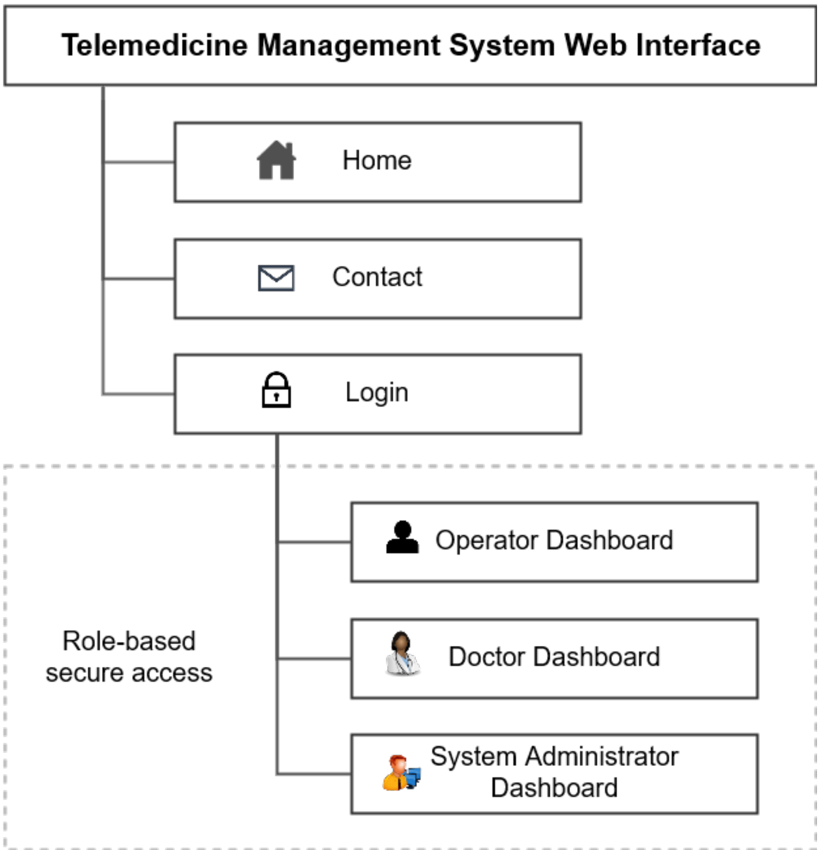


Fig. 4.4 High level navigational diagram of the developed Telemedicine Management System Interface

The design principle adopted during the design of the web interface was to keep things simple and as concise as possible so that all the users of the system can focus on the tasks in hand instead of getting distracted by unnecessary elements present in the interface. All sections of the web interface contain necessary and relevant text guidelines and assistive description. As a result, navigating through different sections of the interfaces becomes a pleasing and comfortable experience for all the user-groups of the system.

The web interface of TMS consists of more than 50+ webpages nested on multiple level. Each of them contains options and features to perform a single or multiple task. Instead of explaining all the webpages and their intended functionalities, only the most significant ones are described and presented with visual screen-shot of the web-pages. Within Administrator Dashboard interface a good number of web pages are related to performing basic CRUD (Create, Read, Update, Delete) operations i.e. create, view, update and delete a User/Operator/Doctor information etc. These pages are also omitted from explaining further in the following part of this section.

The primary user interface language of Telemedicine Operator Dashboard is in Bangla while Doctor's user interface contains both Bangla and English as most of the drug names and Diagnostic Test names are better to be kept in English to avoid confusion and misinterpretation of prescribed treatment plans. Components of Telemedicine Administrator Dashboard are described in English by default. However, all user-groups of the system can switch between Bangla and English based on their individual language preference.

4.4.1 Telemedicine Operator Dashboard

Access to telemedicine operator dashboard interface is exclusive to telemedicine operators working in the rural-end of the telemedicine operation. Telemedicine operators can perform various tasks including patient registration, searching previous patient-records, sending consultation requests by filling up necessary primary vitals data, getting immediate access to prescriptions stored in the cloud once sent from the doctor's end, option to print the prescription in proper format etc. All these data-retrieval operations are limited to the patients registered under the respective centre of the telemedicine operator only. The navigational diagram depicting different layers of navigation within the telemedicine operator dashboard is shown in figure 4.5.

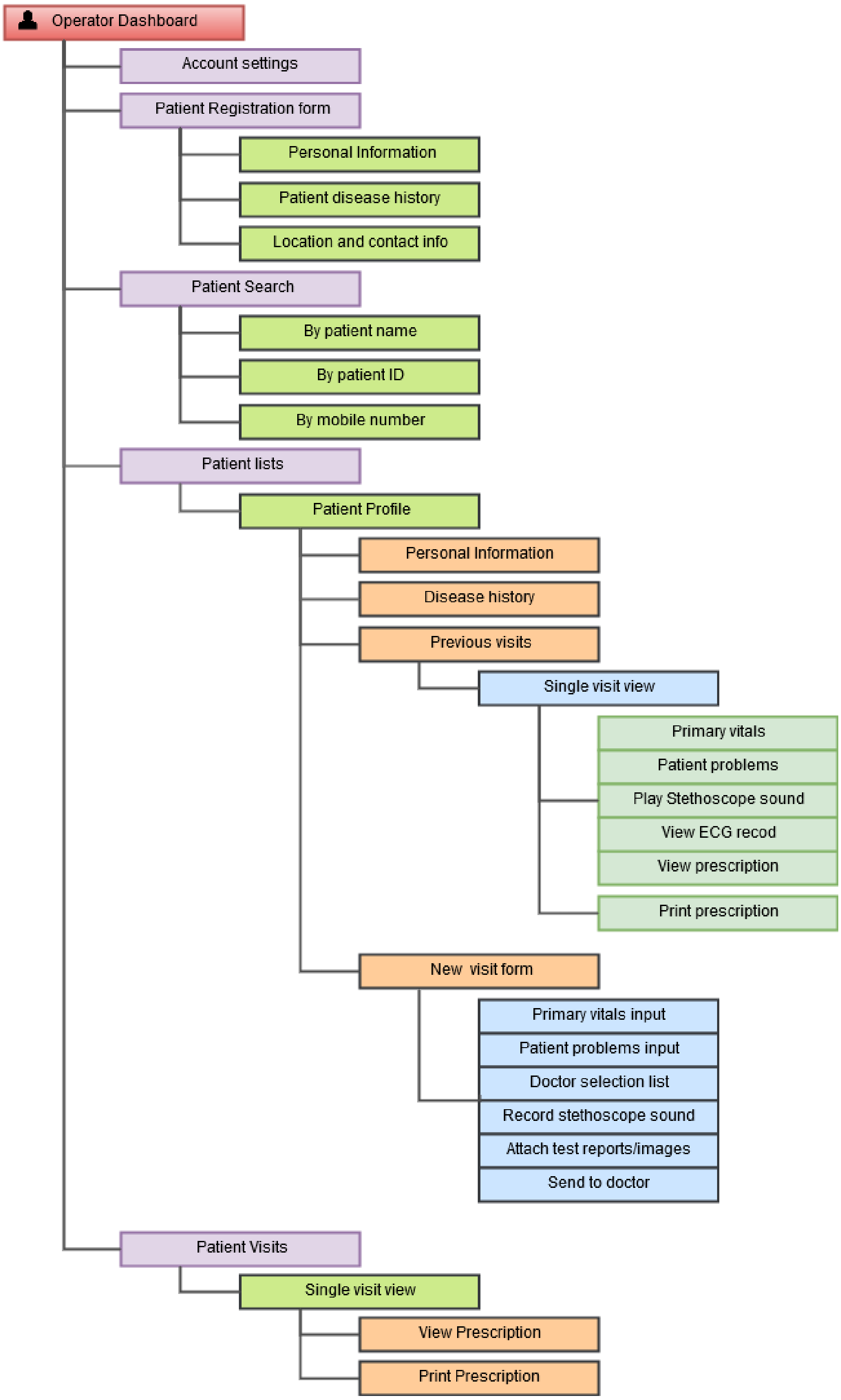


Fig. 4.5 Navigational diagram of telemedicine operator dashboard interface

As rural telemedicine operators usually reside in areas with poor internet coverage, conscious efforts have been made to keep the operator dashboard interface lightweight and as concise as possible, making sure that different webpages accessible to the telemedicine operator load faster in the web browser and require minimum bandwidth over slow internet connection.

Patient Registration Form and Patient Search Module

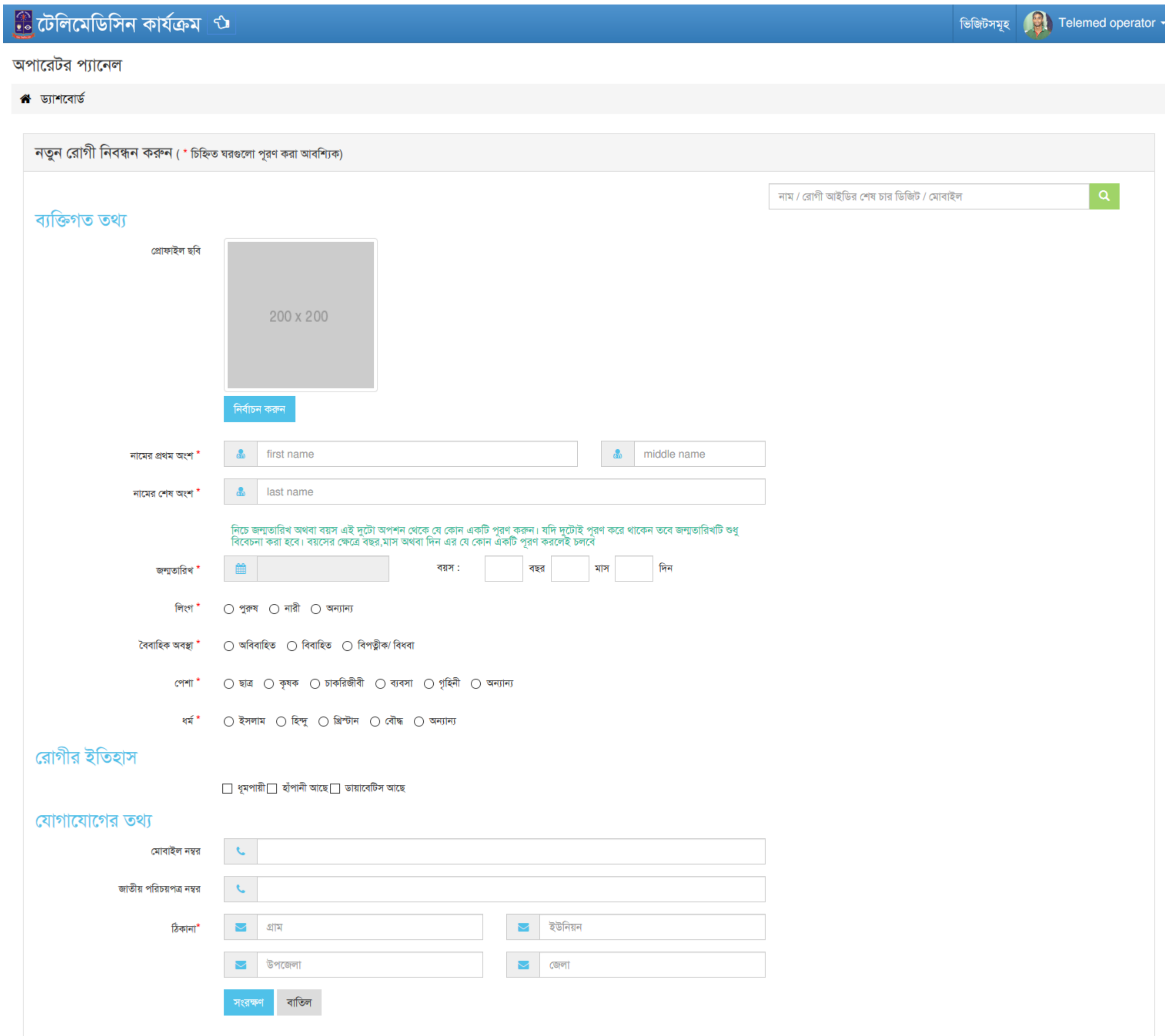


Fig. 4.6 Telemedicine operator dashboard containing patient registration form and patient search module.

The top-level page of telemedicine operator dashboard contains the two most-used components; patient registration form for registering new patients and search module for searching patients registered previously. Successful submission of both, new patient registration or search result, leads to the patient profile page of the relevant patient. Option to submit New consultation/visit request to a telemedicine doctor are located in the profile page of the patient.

Patient Profile

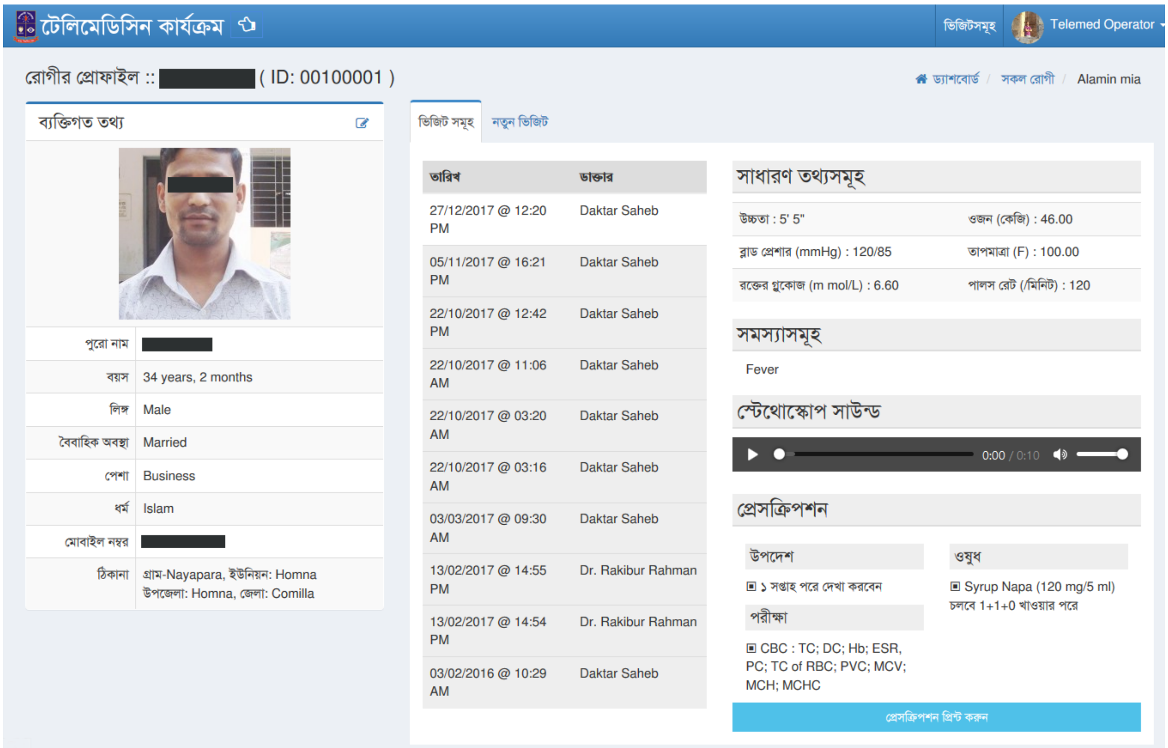


Fig. 4.7 Individual patient profile page

A single patient profile page contains the full health records of a patient including all clinical and registrations data. Registration data recorded during the registration process of a patient are displayed in the left. The right section is presented with two tabbed container. One contains the full history of previous consultations and the other one holds the new visit/consultation request form, which is used to create a new consultation request to a telemedicine doctor. Upon clicking on an item from the consultation history, full information regarding that specific visit are displayed in the rightmost section of the container. There is an option to print the prescription at the bottom of every visit information. This is specifically deemed helpful for retrieving an old prescription, in case the patient loses the previous one. Clicking on the right tab of the tab container shows the new consultation request form.

New Consultation / Visit Request Form

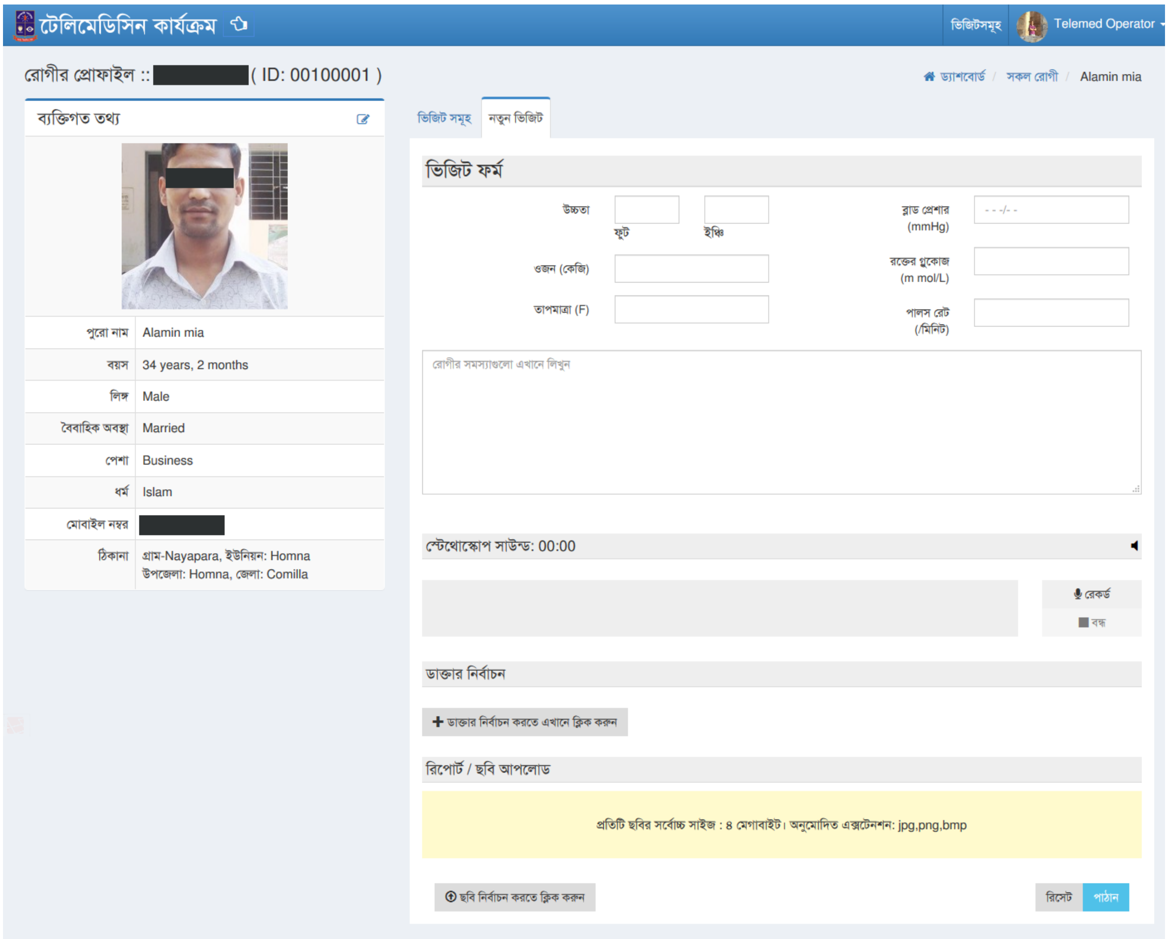
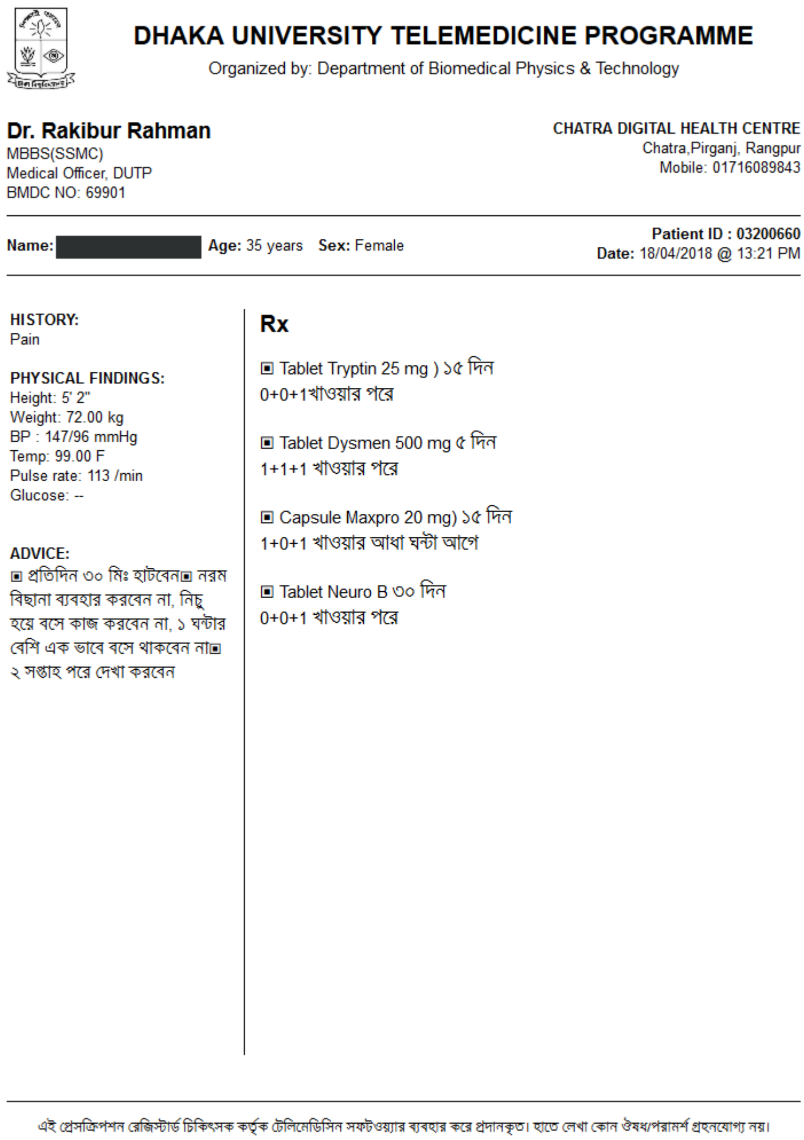


Fig. 4.8 New consultation/visit request form for telemedicine patients

New visit/consultation request form located within the tabbed container of patient profile are used to submit new visit request to an online telemedicine doctor. The form contains options to input primary vitals of the patient measured manually. These primary vitals are taken by a rural operator using a set of diagnostic devices such as Height scale, glucose measuring machine, blood pressure measuring machine etc. There is a writing editor to elaborately describe the patient's health problem, exactly as described by the patient. Besides, stethoscope sound can also be captured directly from within the visit request form. The operator records the heart sound using the web-based sound acquisition tool and attach it with other form data. Paper-based health data, after taking images of them using mobile phone or scanner, can also be uploaded and attached with a visit request form.

Prescription



DHAKA UNIVERSITY TELEMEDICINE PROGRAMME

Organized by: Department of Biomedical Physics & Technology

Dr. Rakibur Rahman
MBBS(SSMC)
Medical Officer, DUTP
BMDC NO: 69901

CHATRA DIGITAL HEALTH CENTRE
Chatra,Pirganj, Rangpur
Mobile: 01716089843

Name: [redacted] **Age:** 35 years **Sex:** Female

Patient ID : 03200660
Date: 18/04/2018 @ 13:21 PM

HISTORY:
Pain

PHYSICAL FINDINGS:
Height: 5' 2"
Weight: 72.00 kg
BP : 147/96 mmHg
Temp: 99.00 F
Pulse rate: 113 /min
Glucose: --

ADVICE:
▣ প্রতিদিন ৩০ মিঃ হাটবেন▣ নরম বিছানা ব্যবহার করবেন না, নিচু হয়ে বসে কাজ করবেন না, ১ ঘন্টার বেশি এক ভাবে বসে থাকবেন না▣ ২ সপ্তাহ পরে দেখা করবেন

Rx

▣ Tablet Tryptin 25 mg) ১৫ দিন
0+0+1খাওয়ার পরে

▣ Tablet Dysmen 500 mg ৫ দিন
1+1+1 খাওয়ার পরে

▣ Capsule Maxpro 20 mg) ১৫ দিন
1+0+1 খাওয়ার আধা ঘন্টা আগে

▣ Tablet Neuro B ৩০ দিন
0+0+1 খাওয়ার পরে

এই প্রেসক্রিপশন রেজিস্টার্ড চিকিৎসক কর্তৃক টেলিমেডিসিন সফটওয়্যার ব্যবহার করে প্রদানকৃত। হাতে লেখা কোন ঔষধ/পরামর্শ গ্রহনযোগ্য নয়।

Fig. 4.9 A prescription displayed in printable format

Figure 4.9 shows a prescription generated by the TMS application for printing. Once the doctor issues an e-prescription after consulting with a patient over video conferencing, The e-prescription becomes available to the rural operators in a printable format as shown in the figure 4.9. The different components of a prescription i.e. medicine, tests, advice, physical findings etc. are stored separately in different tables in the database and the prescription format is generated on the fly once requested by an authentic user of the TMS, having permission to access that specific prescription. The printable format of the prescription follows conventional layout of paper-based prescription widely adopted by the doctors practicing in Bangladesh. The prescription is designed black and white to discard the necessity of using a colour printer. Use of any background image has also been carefully avoided for cost-effective printing. There is a footer text mentioning that the prescription is software-generated and no handwritten medicine name, test suggestions or advices are acceptable. This has been mentioned as a safety mechanism to avoid an unacceptable and potentially risky habit, typically observed among the local pharmacists of Bangladesh. A number of them tend to override the medicine name suggested by doctors with different medicines themselves.

4.4.2 Telemedicine Doctor Dashboard

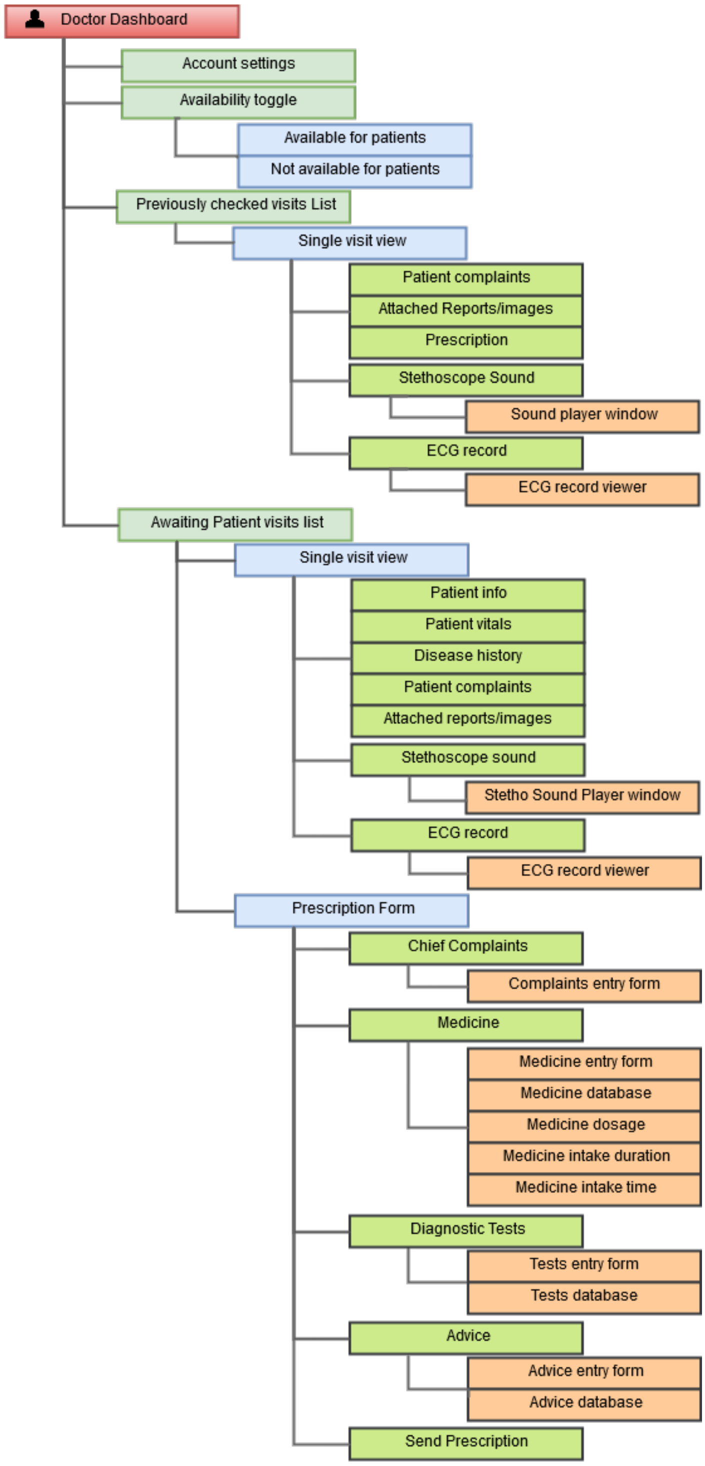


Fig. 4.10 Navigational diagram of Telemedicine Doctor's dashboard interface

Figure 4.10 shows the navigational diagram of all the functionalities accessible to a telemedicine doctor through TMS user-interface.

Doctor Panel

Figure 4.11 shows the doctor panel of the TMS available to a telemedicine doctor. The panel is featured with all the necessary functionalities required to access patient health records and issue e-prescriptions. The top of the doctor's dashboard displays tabs for two different lists, one of waiting patients and the other of previously attended patients by the same doctor. Clicking on the appropriate tab, the doctor can see either of the lists. In the list of waiting patients, each row belongs to a single

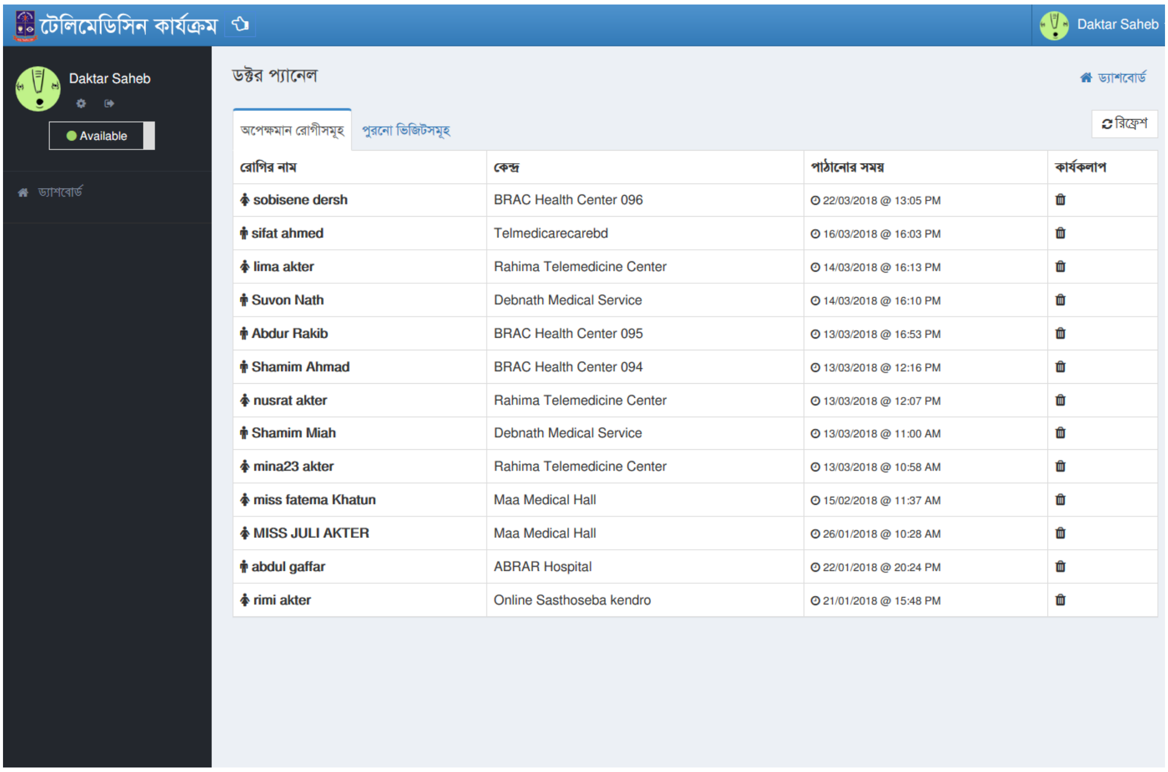


Fig. 4.11 Top level page of Telemedicine Doctor's Dashboard page

patient, displaying gender and name of that patient. The gender of the patient is indicated by a male/female icon on the left. A single row also contains the name of the centre a patient is requesting from and the submission time of the request. There is an option to delete an individual request. This option remains available till the time an e-prescription is not issued for a consultation request. Once attended,the doctor can not delete a request anymore and the request moves under the list of previously attended ones. Upon clicking on a waiting patient's name, the doctor can access the full health history of the patient including the current health problems and previous ones. The health data of the patient are displayed in an organized, concise format that helps the doctors to get an overview of the patient's health records within a short time.

The list of previously attended patients contains the same type of information as above, except the column for deleting the request and is replaced by a an option to view the prescription associated with that visit request.

The left sidebar of the dashboard interface contains a toggle button that provides option to change the availability status of the doctor. If a doctor goes "offline" by clicking on the toggle button, his/her name no longer appears on the list of available doctors. As a result, the rural operators will no longer be able to send consultation request to that doctor until he/she changes the availability status to "Online" again.

Web View : A Patient's Health Data for An Individual Consultation Request

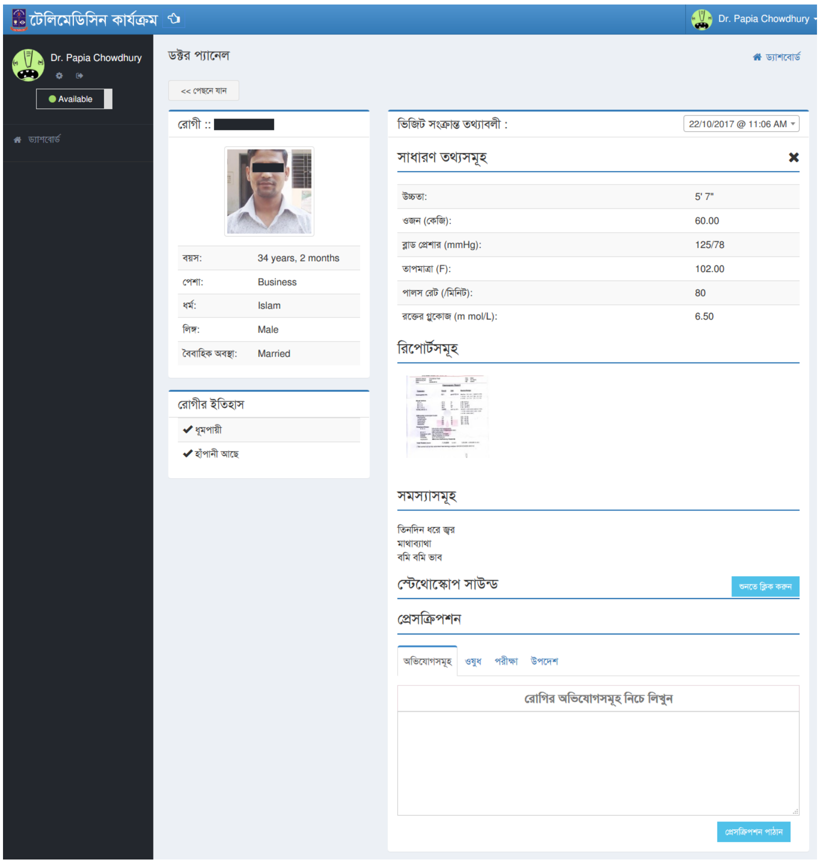


Fig. 4.12 Web view of a waiting patient's consultation page displaying relevant data within the doctor panel

A view of a waiting patient's visit data is displayed in figure 4.12. The patient's personal information taken during registration are displayed on the left along with patient's previous disease history. The top part of the right segment shows the measured value of the primary vitals and thumbnail links to attached images of paper-based health data. Next follows the current health problem description, links of stethoscope sound-viewer and ECG data-viewer respectively. Attached images, stethoscope sound and ECG data section will be visible only if the specific request contains any of these health data. A prescription writing form is located in the below-most section of the page. The prescription form includes an array of assistive tools for the doctors to prepare e-prescriptions efficiently in a short time.

Prescription Entry-Form

Prescription form consists of four tabbed editors. Each of them contains a specific type of entry option. Taking input from these different editors, final prescription for the patient against a specific visit request is created. The prescription is finally stored in the cloud. Once stored, the prescription immediately becomes available to the telemedicine operator for printing and handing it over to the patient. Each of the prescription writing editors and their features are described below with visual representation of the respective interfaces.

- **For chief complaints:** The first writing editor in the prescription form is for writing chief complaints. The doctor writes the complaints following proper clinical terms. Usually patients coming for the telemedicine service describe their health problems in a way which is informal and not suitable to be added and printed in the final prescription. The doctor writes the chief complaints after talking to the patient over video-consultation.

- **For medicine names:** The second tabbed editor provides option to write medicine names along with their dosage, application method, schedule and duration of taking drugs etc. as shown in Figure 4.13. Assistive tools for generating the medicine suggestions in conventional prescription writing format were integrated into the medicine entry-form. Use of these tools cuts down the overall time required to prepare a prescription. The text-input field for medicine names is linked to a back-end medicine database. As a result, suggestions of relevant medicine names appear below the medicine name input

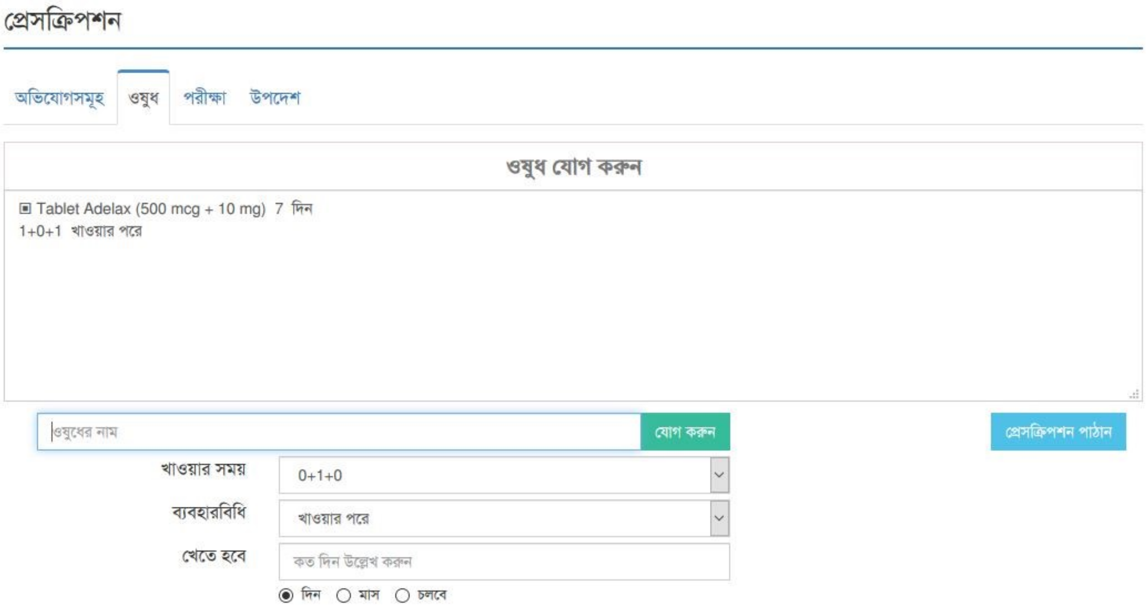


Fig. 4.13 Entry-form for medicine names

field as soon as the doctor starts typing the name (Figure 4.14). The suggestion appears for generic names of the medicine as well.

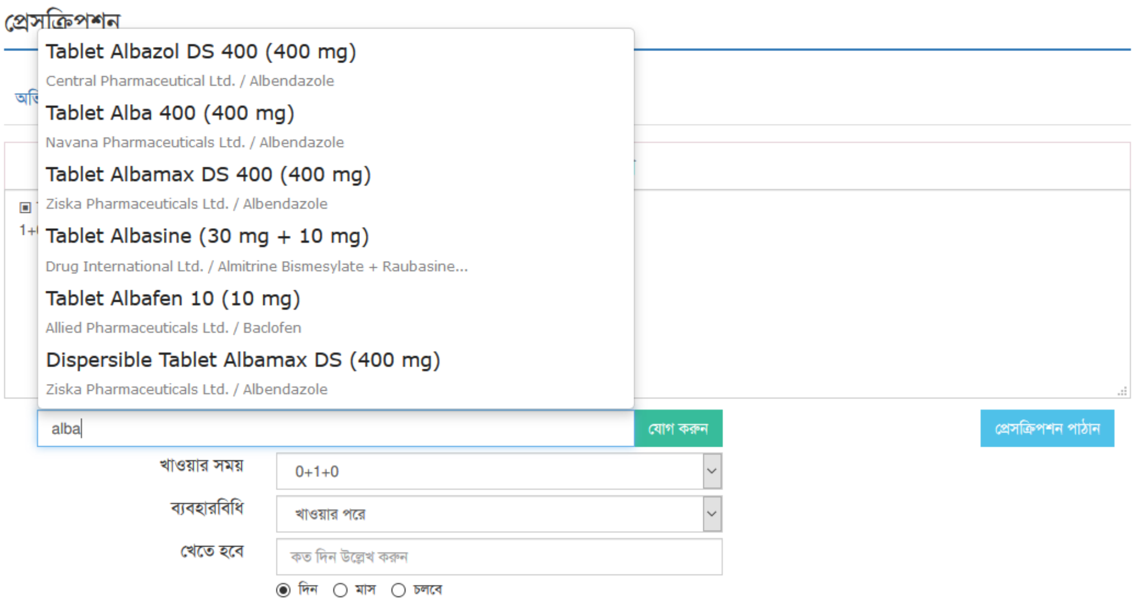


Fig. 4.14 An integrated medicine database for suggestions

- **For diagnostic tests:** Entry-form for writing the names of diagnostic tests, as shown in Figure 4.15, is used to prescribe necessary diagnostic tests to a patient. A comprehensive database of diagnostic tests was prepared and are integrated into the editor to help doctors select tests from a pre-populated lists. The suggestion also appears while the doctor starts typing a test-name in the input field. The doctor has the flexibility to either choose a test/tests from the pre-populated list, or write the names directly in editor.

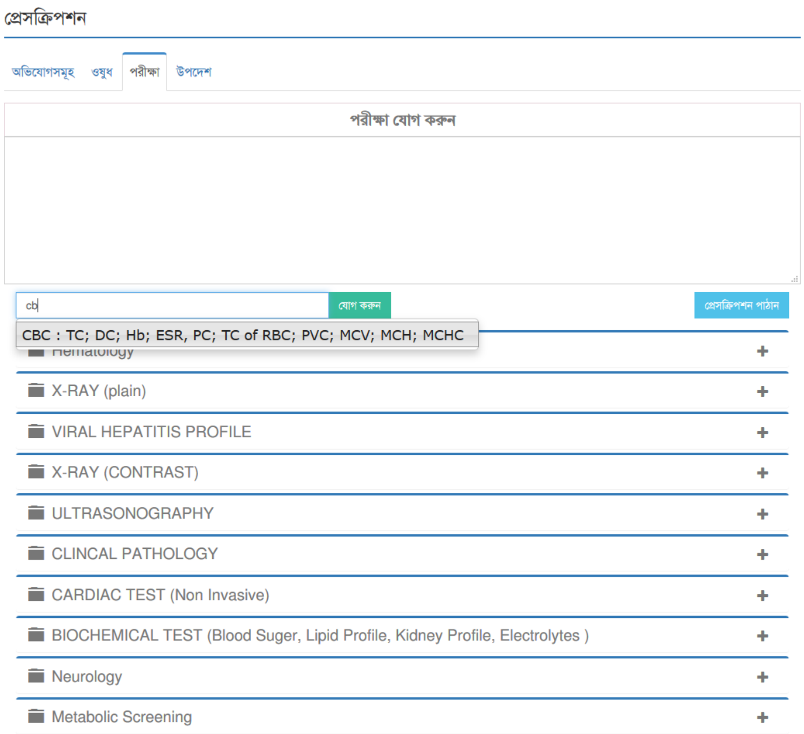


Fig. 4.15 Entry-form for diagnostic tests

- **For medical advices:**

  If the doctor wants to suggest some advices for patients to follow besides taking prescribed medicines, he/she writes them down in the advices form (shown in Figure 4.16). Clicking on to the 'advices' tab the doctor can add the desired ones in the editor box. Some commonly suggested advices are given below the advice form, which can be added to the list of suggested advices for patient by simply clicking on them and confirming their addition to the advice form.

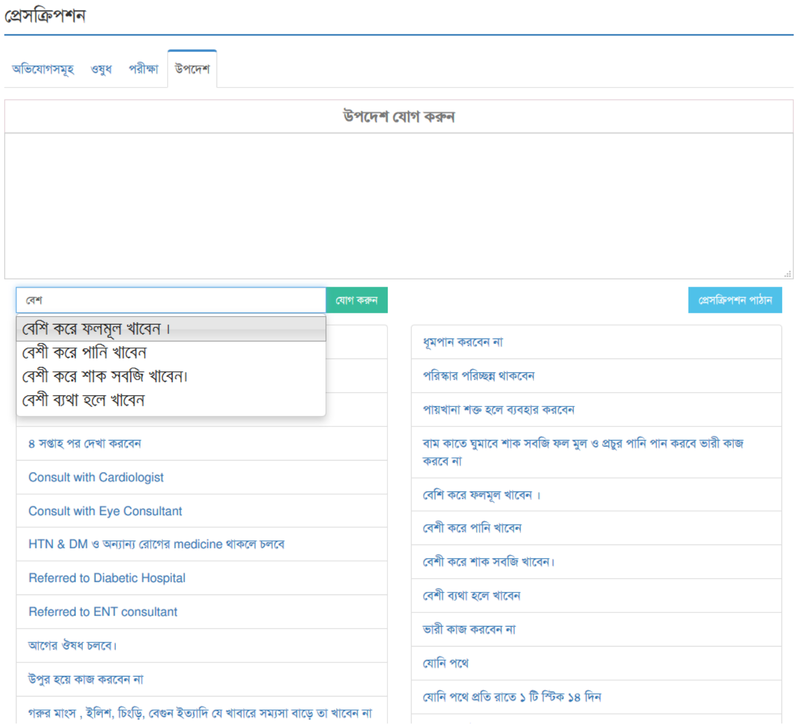


Fig. 4.16 Entry-form for suggesting advices

4.4.3 Telemedicine Administrator Dashboard

All the organisational functionalities accessible to telemedicine administrators, as shown in the navigational diagram below (Figure 4.17) , are available for the telemedicine coordinators and administrators from within the administrator dashboard interface. Access to these functionalities are defined and restricted adopting a "role-permission" bases access mechanism. A "Super Administrator" has access to all of these functionalities while a "Project Coordinator" has access to functionalities related to rural centres and patients management, but does not have permission to manage technical operations specific to the application configuration and settings. On the other hand, "Local entrepreneur" with a single telemedicine centre or "Group entrepreneur", having multiple rural telemedicine centres under their management, can access their centre/s and patient related functionalities from their respective administrator dashboard interfaces.

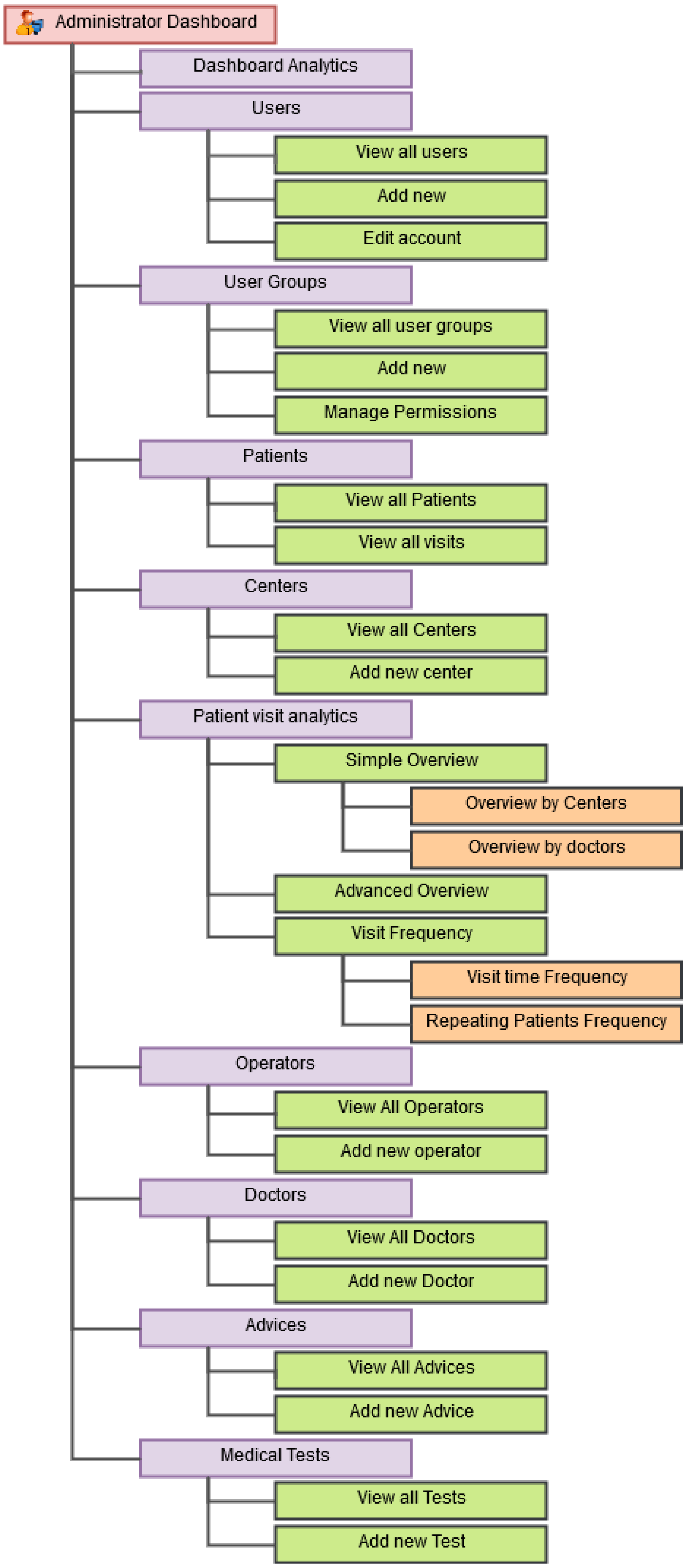


Fig. 4.17 Navigational diagram of Administrator Dashboard interface

Administrator Dashboard home

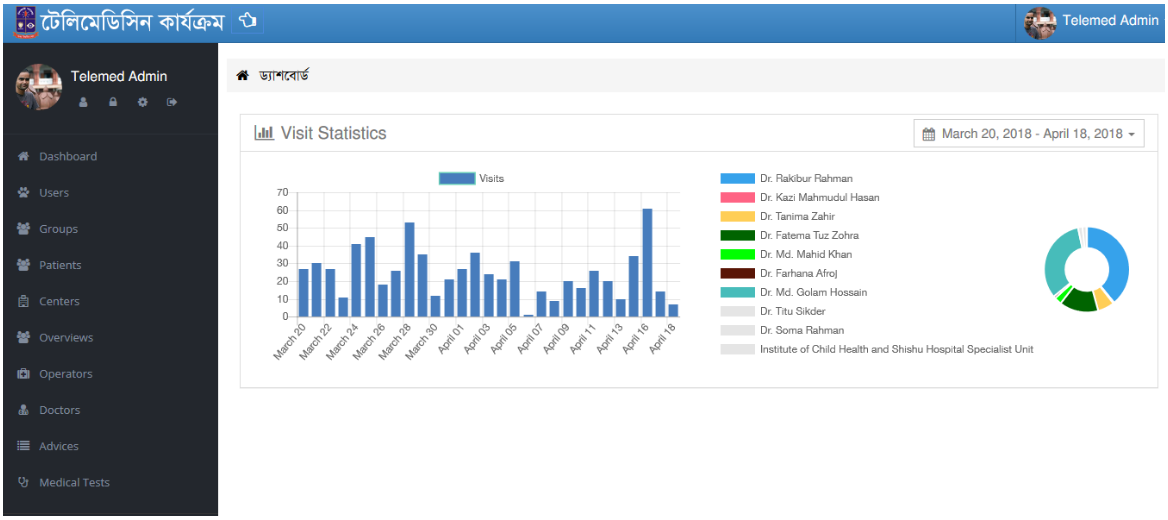
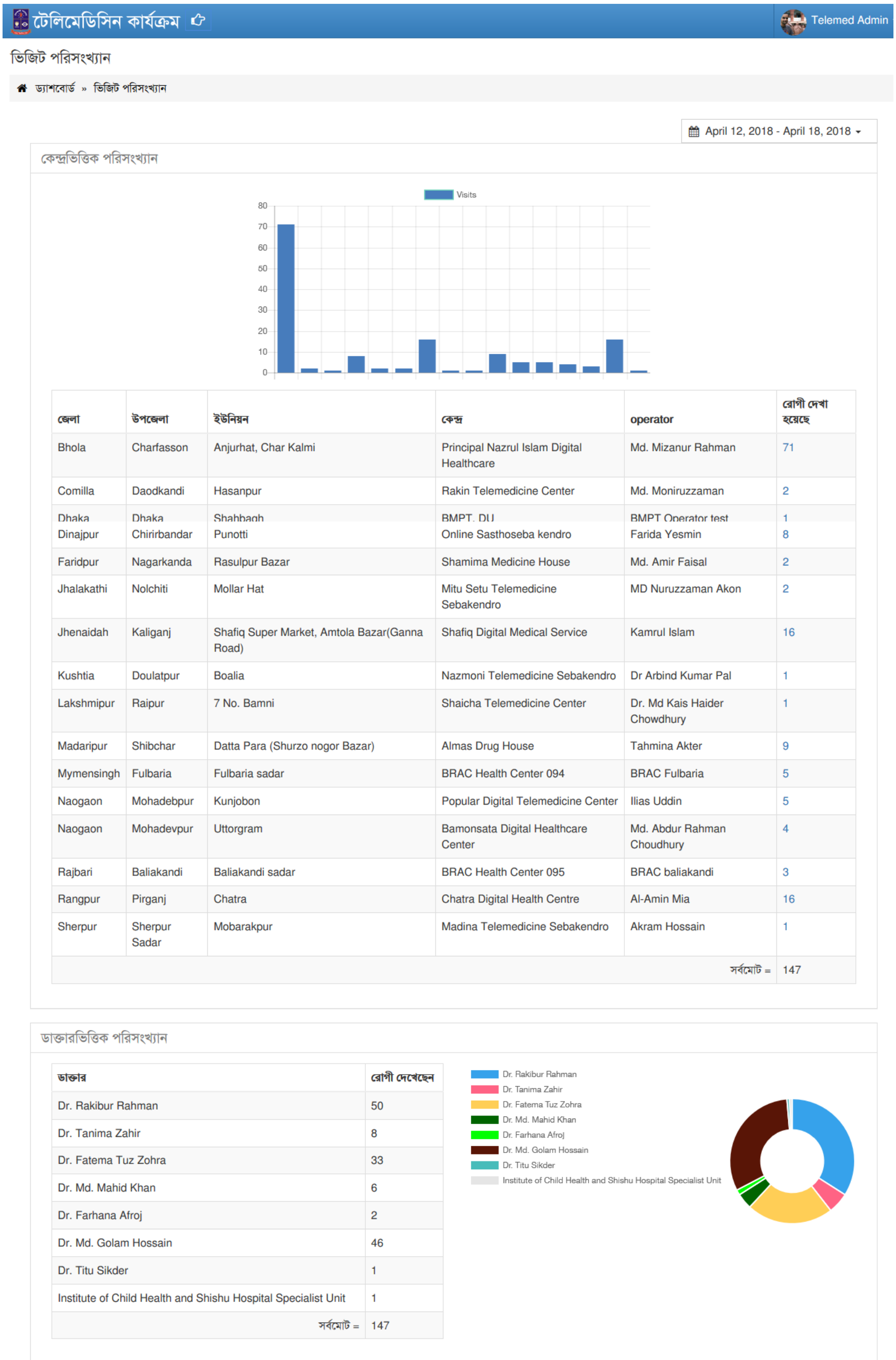


Fig. 4.18 Top level page of the Administrator Dashboard interface

The top-level page of the administrator dashboard interface (shown in Figure 4.18) displays two analytical charts, providing an overview of day-wise and doctor-wise analytics of patient visits respectively. The vertical sidebar on the left consists of all the navigational menus that direct to different interfaces for different administrative functionalities. These functionalities are briefly described with relevant visual representation of the interface below:

Patient Visit Analytics:

Patient visit analytics interface help administrators of the telemedicine system to analyse the performance of telemedicine centres quantitatively based on the number of patients served centre-wise. Telemedicine doctors' performance can also be analysed in the same fashion. Analytics data are displayed both visually using responsive charts and in data tables. Advanced analytics tool helps visualising even more detailed patient visit statistics classified by a range of parameters like demography, gender, religion, occupation, marital status, age range etc. Screen-shots of the simple and advanced patient visit analytics tool are shown below in Figure 4.19 and 4.20 respectively.

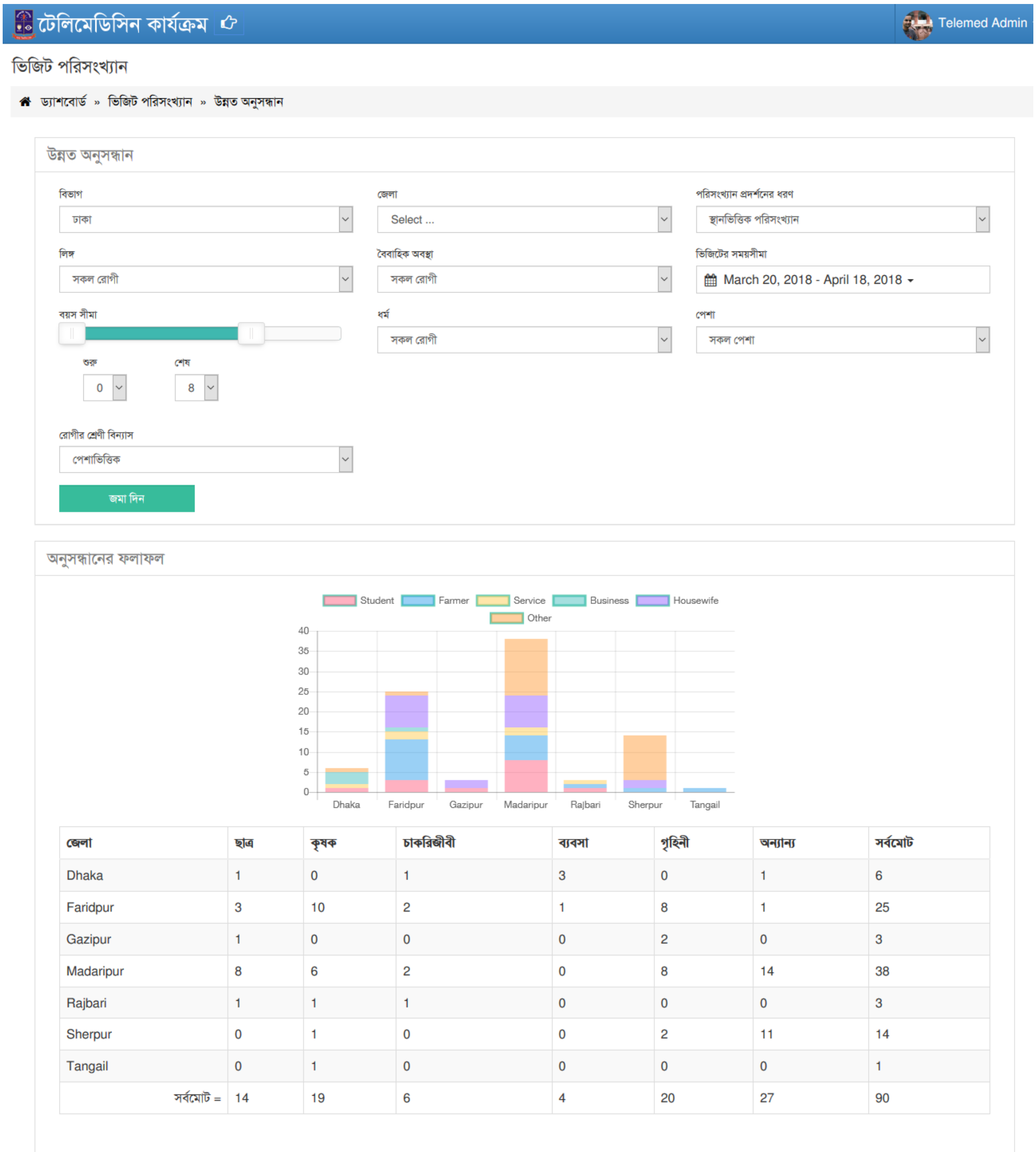


জেলা	উপজেলা	ইউনিয়ন	কেন্দ্র	operator	রোগী দেখা হয়েছে
Bhola	Charfasson	Anjurhat, Char Kalmi	Principal Nazrul Islam Digital Healthcare	Md. Mizanur Rahman	71
Comilla	Daodkandi	Hasanpur	Rakin Telemedicine Center	Md. Moniruzzaman	2
Dhaka	Dhaka	Shahbagh	BMPT, DU	BMPT Operator test	1
Dinajpur	Chirirbandar	Punotti	Online Sasthoseba kendro	Farida Yesmin	8
Faridpur	Nagarkanda	Rasulpur Bazar	Shamima Medicine House	Md. Amir Faisal	2
Jhalakathi	Nolchiti	Mollar Hat	Mitu Setu Telemedicine Sebakendro	MD Nuruzzaman Akon	2
Jhenaidah	Kaliganj	Shafiq Super Market, Amtola Bazar(Ganna Road)	Shafiq Digital Medical Service	Kamrul Islam	16
Kushtia	Doulatpur	Boalia	Nazmoni Telemedicine Sebakendro	Dr Arbind Kumar Pal	1
Lakshmipur	Raipur	7 No. Bamni	Shaicha Telemedicine Center	Dr. Md Kais Haider Chowdhury	1
Madaripur	Shibchar	Datta Para (Shurzo nogor Bazar)	Almas Drug House	Tahmina Akter	9
Mymensingh	Fulbaria	Fulbaria sadar	BRAC Health Center 094	BRAC Fulbaria	5
Naogaon	Mohadebpur	Kunjobon	Popular Digital Telemedicine Center	Ilias Uddin	5
Naogaon	Mohadevpur	Uttorgram	Bamonsata Digital Healthcare Center	Md. Abdur Rahman Choudhury	4
Rajbari	Baliakandi	Baliakandi sadar	BRAC Health Center 095	BRAC baliakandi	3
Rangpur	Pirganj	Chatra	Chatra Digital Health Centre	Al-Amin Mia	16
Sherpur	Sherpur Sadar	Mobarakpur	Madina Telemedicine Sebakendro	Akram Hossain	1
				সর্বমোট =	147

ডাক্তারভিত্তিক পরিসংখ্যান

ডাক্তার	রোগী দেখেছেন
Dr. Rakibur Rahman	50
Dr. Tanima Zahir	8
Dr. Fatema Tuz Zohra	33
Dr. Md. Mahid Khan	6
Dr. Farhana Afroj	2
Dr. Md. Golam Hossain	46
Dr. Titu Sikder	1
Institute of Child Health and Shishu Hospital Specialist Unit	1
সর্বমোট =	147

Fig. 4.19 Basic patient visit analytics



জেলা	ছাত্র	কৃষক	চাকরিজীবী	ব্যবসা	গৃহিনী	অন্যান্য	সর্বমোট
Dhaka	1	0	1	3	0	1	6
Faridpur	3	10	2	1	8	1	25
Gazipur	1	0	0	0	2	0	3
Madaripur	8	6	2	0	8	14	38
Rajbari	1	1	1	0	0	0	3
Sherpur	0	1	0	0	2	11	14
Tangail	0	1	0	0	0	0	1
সর্বমোট =	14	19	6	4	20	27	90

Fig. 4.20 Advanced patient visit analytics

Frequency of Patient Visits and Repeating Patients analytics:

Data visualisation tool has been developed to track the visit frequency of patients in different times of the day. This helps the telemedicine coordinator to manage the allotment of the doctors' time more efficiently and in a cost-effective way. In addition, another functionality module to track the number of repeating patients over the course of time were developed. It helps to understand the acceptance of telemedicine service in different telemedicine centres. These data visualisation module interface are shown in Figure 4.21. Display of these data can be filtered by a date-range specified by the administrator.

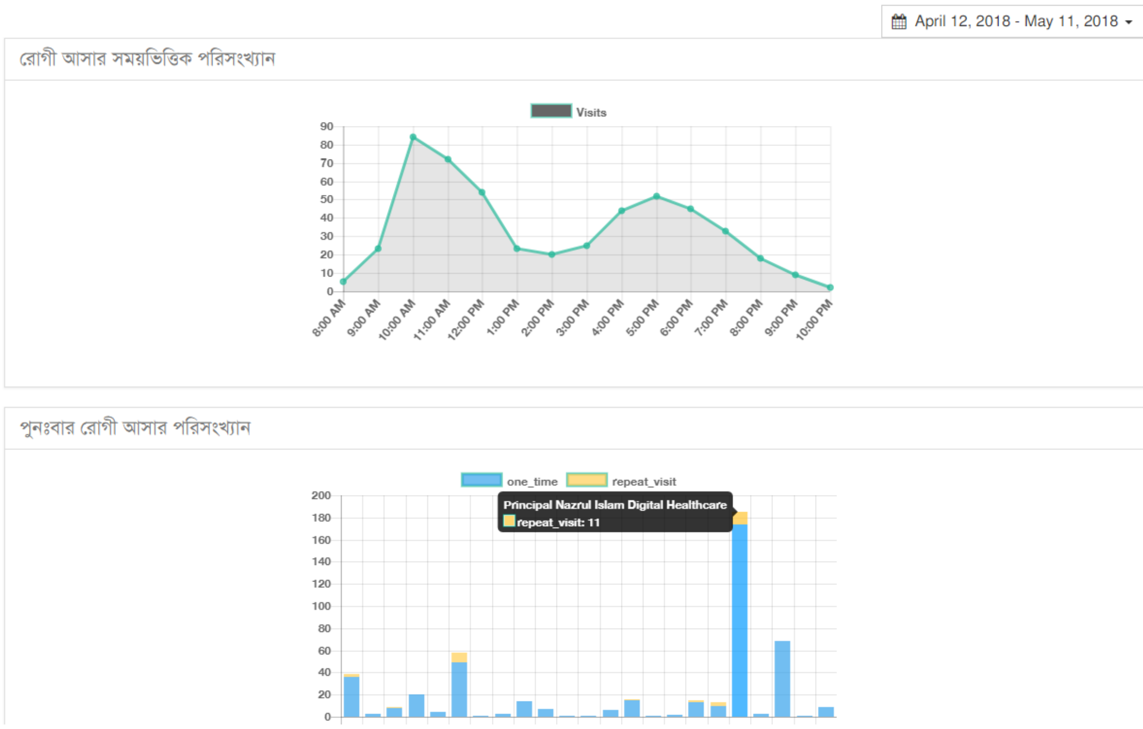


Fig. 4.21 Display of patient visit frequencies and repeating patient analytics in administrator dashboard interface.

Telemedicine Centre Management

Information of different telemedicine centres that are enrolled within the telemedicine system, are managed from the centre management interface. Centre information can be added, updated and centre operation can be allowed / suspended by telemedicine administrators within the scope of this centre management module. Some centre information such as centre address, contact details are used in the prescription.

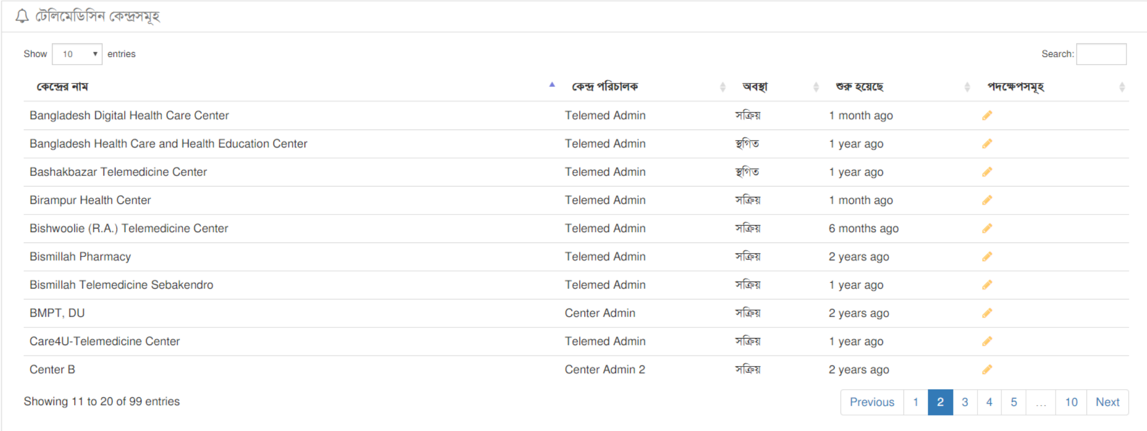


Fig. 4.22 Telemedicine centre management interface

4.5 Security

4.5.1 Connection Security:

Accessing a cloud application over a secure and encrypted http connection is crucial for the communication security. Communication between a server and a client over a secure connection prevents unwanted interception and intervention from third party. Developed TMS web application is designed to be able to exchange data between the server and the client machine over secure http (https). However, SSL certificate needs to be installed and configured properly in the cloud server. On the availability of a secure connection, all the data submitted or received by the users of the TMS are encrypted and transmitted to the remote server securely. The TMS application, currently deployed for the telemedicine project of BMPT also uses a secure connection for server-client communication.

4.5.2 Application Level Security

- **Password-based authentication for web application:** Access to all the functionality offered by TMS web application are restricted and can be accessed only after logging in to the system with valid login credentials. A valid login credential contains a combination of User ID or email and password. To start using the application, both the telemedicine operators and the telemedicine doctors need to register to the system first for obtaining their login credentials.

An operator or a doctor account remains inactive until a system administrator approves them manually. This was done to prevent spam and fake registrations to the system. Once activated, the doctor or the operator can login to the system using the approved login credentials and access their respective dashboard interfaces. The login credentials registered and stored into the TMS database are valid for both web application and API communication. For example: an operator can login to the web user-interface of the TMS as well as to the mobile interface accessed from his/her smart-phone, which exchanges data via API communication. An open source PHP authentication library called "Sentinel" [51] was used to design and develop the authentication mechanism of the TMS application.

- **Token-based authentication for API communication:** The developed web API for TMS also requires authentication from the user for any sort of information exchange through API calls. JSON Web Token (JWT) has been adopted as the authentication mechanism for all API calls made to TMS Database. An open source project called "jwt-auth" [52] was used to build the API authentication layer. Once a user is logged in to the system using a valid login credential, the TMS server returns an encrypted JWT with the login response. From then on, each subsequent request needs to include the acquired JWT and is used for data request validation. All authentication tokens issued by the TMS server comes with an expiration date for security. Once a token expires, the user needs to refresh and re-validate the authentication token by logging into the system again. The time of expiration for the JSON web tokens can be set and configured from the TMS application settings.

- **Role-permission based user-interface access:** Each user-group of the TMS application has access to a personalised user-interface tailored for his/her designated roles and responsibilities. All functionalities incorporated within the TMS user-interface are developed in a modular fashion which allows role and permission-based access or restriction to any of the modules. As a result, access to a specific functional module can be applied to or revoked from a user-group at any time. A TMS user can access only those functionalities that are permitted and available within the scope of the user-group he/she belongs to. For example, a telemedicine operator cannot access functionalities that doctors are entitled to use and vice versa. System administrators of TMS can easily control which module can be accessed by which user-group. In addition, besides default user-groups, new user-group can be created by system administrators with a customised set of roles and permissions.

- **Input-data validation:** All data input, whether submitted from TMS web application interface or through web API calls , irrespective of their types and properties, are thoroughly validated. Data are validated both in the client-side and finally in the server-side before storing them in the TMS cloud. Validation logics are set based on the type, possible minimum and maximum value and mandatory or optional nature of the input data. Submitted data will not be stored in the TMS cloud unless all validation logics are satisfied both in the client-side and in the server-side.

- **Application activity logging:** All activities within the TMS application i.e. login activity details, users' IP address, application errors etc. are logged in the server-end for troubleshooting and security purpose. Login activity and users' activity are stored in a separate table in TMS database while application errors, http requests log, API requests log are stored in the file storage of TMS cloud. Monolog, an open source logging library, was used for writing and managing these activity tracking logs.

- **Enabling login throttling:** IP address-based login throttling is set up as an added security to prevent brute-force attack and any malicious attempt to login to the system illegally. The number of failed login attempts are tracked and stored in a database table and if it crosses the specified threshold value within a specified time interval, the IP address gets banned from the system automatically for a specified period of time and no more login attempt can be made from that specific IP address within that period. Throttling threshold, time intervals and ban duration of IP addresses are configurable and can be configured from the application settings of TMS . Login throttling is enabled for all API function calls directed to the TMS database as well.

4.5.3 Clinical Data Privacy and Security

- Access to patients' registration and clinical data are maintained separately from one telemedicine centre to another. A telemedicine operator has access to the data of only those patients who have registered to that specific telemedicine centre he/she is assigned to. If a telemedicine centre has both mobile telemedicine operator and centre-based telemedicine operator, patient data of that centre will be accessible to both of the operators, irrespective of which operator registered which patients. This privacy arrangement is working quite well for now as most of the rural people are likely to get settled and stay in a specific place for long periods of time. However, there is a plan to extend this privacy in future and develop a mechanism so that a telemedicine patient, once relocated or visiting to a different place, can avail the telemedicine service from other telemedicine centres as well, without requiring him/her to register into the telemedicine system again. .

- A telemedicine doctor can view and access the data of only those patients who have sent consultation requests to the doctor via telemedicine operator. Only after receiving a consultation request from a patient, the assigned doctor can access and view the full clinical history of the patients that are stored in the TMS database. The doctor has access to prescriptions previously suggested by other doctors in the past as well. The "doctor" user-group also has access to prescriptions that he/she prepared and sent for the previously attended consultation requests.

- Once a prescription is submitted and stored in the cloud, the doctor cannot edit the prescription anymore. To prevent the accidental submission and unintentional errors, a preview of the prepared prescription is shown to the doctor before submitting it to the cloud. The doctor needs to re-confirm his/her submission in two steps before the prescription is finally submitted and stored in the cloud. This specific rule was applied in order to address and troubleshoot any possible case of inappropriate or wrong treatment suggested by any telemedicine doctor.

- Once stored in the TMS cloud database, neither a telemedicine operator nor a telemedicine doctor has permission to edit or delete a patient's clinical history or prescription data . However, a telemedicine operator can update/modify patient's registration data anytime in case of wrong data input or to update information subjected to change over the course of time i.e. patient's address, occupation, mobile number etc.

- Both version of the chief complaints are separately stored in the TMS cloud database. One complaint is described and written in patient's own words by telemedicine operators and the other one written formally using clinical terms by assigned telemedicine doctor, which he/she prepares following the tele-consultation with the patient. This measure was taken to address the claims of wrong treatments if raised by any telemedicine patient in future.

4.6 Adaptation to Slow Internet Connectivity

Slow internet connectivity has been found to be one of the major barriers in delivering telemedicine service to rural areas. Keeping that in mind, TMS web interface has been designed and tailored to be as lightweight as possible so that it takes minimum possible time to load on client-side. Among the three major user-groups of the telemedicine system, telemedicine operators living in rural areas are most likely to be affected by the poor internet connectivity constraints most. So, special emphasis was given to designing and developing the operator dashboard interface to address the limitations of low-bandwidth network. The interface was made as light as possible so that it takes up significantly less amount bandwidth to load in the browser and performs well even in a slow internet connectivity. Measures taken to address the slow internet connectivity issue in developing TMS web interface is briefly discussed below:

- **Lightweight Web Interface for Telemedicine Operator:** Within the telemedicine service workflow, rural telemedicine operators suffer the most while navigating through different sections of the web interface due to lack of access to high-speed internet connectivity . So, the regular telemedicine tasks that operators perform through developed web interface of TMS, have been tailored to be lightweight containing only the necessary contents and options. All the requests and responses, to and from the server, are handled in the background using AJAX. As a result, the operator does not need to refresh the webpage again and again, the content of the webpage gets updated dynamically with the latest response received from the server. This minimises the bandwidth consumption significantly at the client-end. Embedding of image/audio/video on the web interface has been carefully kept at minimum, as these multimedia data are usually larger in size compared to other elements present in a web interface, and requires more bandwidth to load in the client web browser. However, some static files such as CSS style sheets and JavaScript scripting files are necessary and needs to be included and loaded in the client web browser. Stylesheets contain the styling code for HTML-based web interface and ensure the display of intended representation of web interface in client browser for different screen sizes. On the other hand, scripting files containing application specific, useful JavaScript functions add interactive functionalities to the web interface that are loaded in the web browser. These static files are likely to change less frequently in the server side. Therefore, measures were taken, both in the server configuration and application code, to cache these static files locally in the client computer. This approach saves a significant amount of bandwidth, hence the loading time decreases too, preventing the download of same files from the server in every request. Below is a table that compares the data size being downloaded from the TMS server to a client web browser for the first time and then for the second time. The table includes the webpages that a telemedicine operator needs to access frequently for performing various telemedicine related tasks. All the data mentioned in the below table were analysed and captured using the network inspection feature of Firefox Developer Edition (version 60+) web-browser. The latest version of the developed TMS application are currently deployed at http://telemedbd.net and is currently being used to deliver telemedicine services in a number of rural areas within Bangladesh. This deployed version was considered for the below mentioned comparative analysis and was performed on April 20, 2018 .

Table 4.1 Comparison of bandwidth consumption for TMS application between cached and non-cached state

Web interface description	**Data downloaded from server without local caching**	**Data downloaded from server after local caching**
Home page	546 KB	4.91 KB
Login interface	356 KB	3.95 KB
Operator Dashboard interface	1.22 MB	5.68 KB
Patient Search interface	1.5 KB	1.5 KB (not cached)
Patient Profile interface	863 KB	15 KB-70KB (approx.)
Patient Visits list interface	656 KB	5 KB
New visit request submission (without stethoscope data and image attachment)	2.6 KB	2.6 KB (Not cached)
Single Prescription view	35 KB	4 KB
New patient registration	30 KB	30KB (Not cached)

Some data represented in the table do not always remain constant for relevant user-interfaces i.e. data consumption for a patient visit request, or for a new patient registration etc. and might vary a few kilobytes in different use cases as mentioned previously. But the comparison gives a clear idea about the percentage of reduction in data sizes when static files from TMS application are being cached locally in the client side.

So, there were approximately 96% reduction in data size that are transferred from the TMS server to the web browser, once all the static files are locally cached in telemedicine operator's computer. Therefore, it is only once that a new telemedicine operator will have to download a sizeable data (approximately 4 MB for all web interfaces that can be accessed by a telemedicine operator within TMS web application). When an operator logs in to the TMS web application, considering all static files are locally cached, it requires around 85 KB for repeating patient and 115 KB for new patients to complete a cycle of telemedicine visit starting from patient registration to printing prescription. Additional data will be added If any image file or stethoscope sound is captured and attached with the visit consultation request.

The cached data will remain in the local storage of the operator's web browser (i.e., inside the operator's PC) until browser cache is cleared for the TMS web

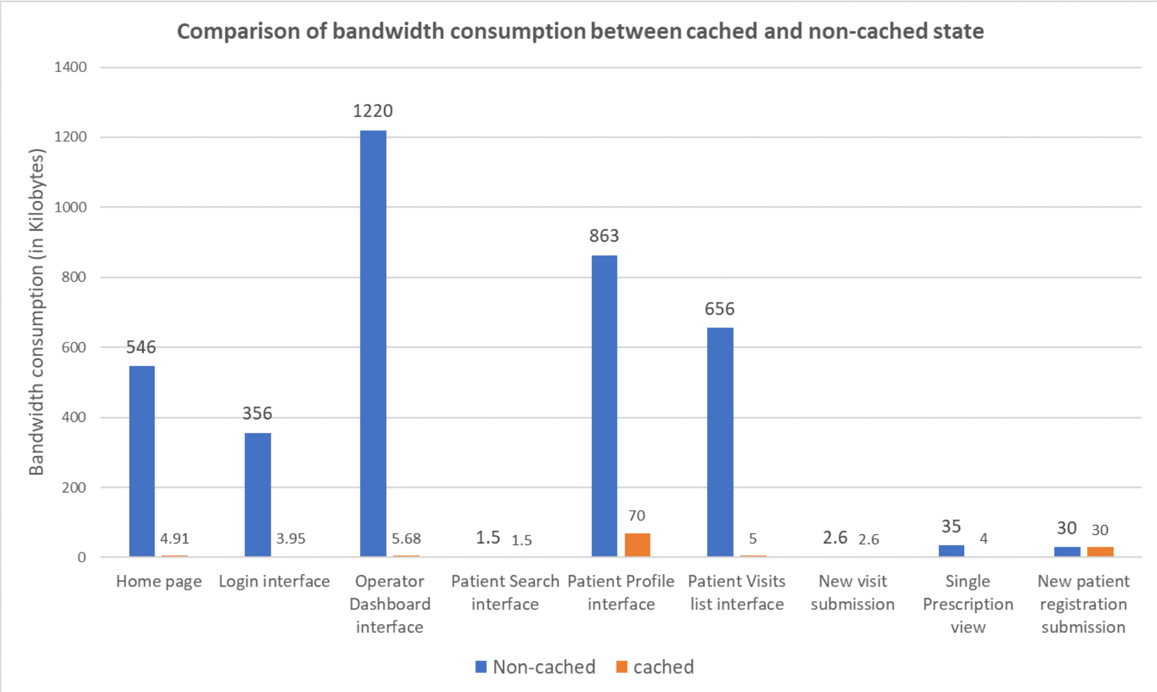


Fig. 4.23 Comparison of Bandwidth consumption for different webpages of operator dashboard between cached and non-cached state

application or any changes to any of the static files are made in the server side. However, in case of any static file being updated in the server side, only the files that have been updated or modified will be loaded and cached to the browser storage again, keeping other files already cached in the browser storage unchanged.

- **Multimedia file compression before uploading to the TMS server:** Among all of the information uploaded from a rural telemedicine centre to the TMS server, paper-based health data converted to image files and stethoscope sound file are the largest in size and takes up the maximum amount of bandwidth for uploading to the telemedicine server. In order to upload these comparatively larger files over a slower internet connection in a limited bandwidth network, compression of these images and sound files are performed on the client side before uploading them to telemedicine server. Ofcourse, the compression process is performed maintaining the quality of health data image and stethoscope sound file to an acceptable level that is required to interpret them conveniently. Paper-based health data are usually converted to digital images by taking pictures of them using mobile-phone camera or by scanning them with a digital scanner. Usually images captured by digital camera, mobile phone camera or digital scanner are larger in size and amount to a few megabytes. When a telemedicine operator selects one or multiple files with larger resolutions for uploading, these image files, irrespective of their image format, are compressed and converted to JPG format with lower resolution. That results in to smaller image file size of around a few hundred Kilobytes. Dropzone.js, an open source JavaScript library was used for the image compression in the client web browser. However, Maximum image-resolution allowed for an uploaded image and compression quality of the converted images can be configured in the settings of TMS application.

Adaptive measures taken to transfer sounds captured from digital electronic stethoscope and ECG data will be discussed and explained in detail in chapter 5.

4.7 Conclusion

This chapter highlighted the functionalities that were incorporated into the developed Telemedicine Management System (TMS). It also discussed the technical architecture of the system and adopted security measurements to safeguard data privacy and application security of the TMS. Web user-interface designed for different user-groups of the system were also introduced briefly with visual description of different components of the web interface. The chapter ends with describing the adaptive measures that were taken to make the developed system perform significantly well in a low bandwidth network. The TMS, developed in this present work, is the backbone of the telemedicine service intended to be operating in low resource settings and acts as the centre of interactions among all user-groups of the system.

Chapter 5

Medical Devices Integration and Interfacing

This chapter describes the integration of two medical diagnostic devices, a digital stethoscope and a digital ECG equipment into the Telemedicine Management System (TMS), developed as a part of this present work and described in Chapter 4. Obviously, this will involve appropriate interfacing, data acquisition, storage and transmission through internet so that the quality of the acquired data remains unaltered, as far as practicable.

Commercially available digital stethoscopes and ECG equipment from advanced countries are very expensive and do not survive long in the weather conditions and power line abnormalities encountered typically in countries like Bangladesh. Therefore, the BMPT department have developed both these instruments locally. Of course the former was an improvisation in which the sound output of a commercial good quality acoustic stethoscope is converted to an electrical output using an electret microphone through appropriate acoustic coupling and noise screening. The output is digitised using a commercial USB sound card so that together it can be named as a Digital Electronic Stethoscope. The latter, the ECG equipment was developed fully by the team of BMPT from scratch and gives digital data acquisition through the USB port. It is a single channel, 12 lead diagnostic ECG equipment, which was developed for stand-alone use, or for direct data transfer to a remote computer through the internet. However, this was developed before work for the present TMS was taken up and the protocol was not related to the requirements of the present TMS.

The present work targeted acquisition of the digital data from both the devices, which is essentially interfacing to the computer, and then integrating the resulting signals into the TMS so that the signals may be stored and transferred over internet at will.

The first section of this chapter discusses the integration and interfacing of the Digital Electronic Stethoscope to the TMS, while the second section focuses on explaining the work carried out to integrate and incorporate the 12-Lead Digital ECG into the telemedicine workflow.

5.1 Integration and Interfacing of Digital Electronic Stethoscope

5.1.1 Background

Stethoscope is the most important primary medical device used by almost every physician for audible auscultations of internal body sounds i.e. heart sounds, respiratory sounds and abdominal sounds. Therefore, incorporation of a stethoscope can improve the quality of telemedicine significantly. Obviously standard acoustic stethoscopes are not suitable for integration with a telemedicine system, what is needed is an electronic one giving an analogue electrical signal representing the audio sound patterns. Again, either within a computer or outside a computer, there has to be an analogue to digital converter and a data acquisition system to acquire the data digitally within the computer which would then be sent over the internet to the computer or the smart-phone of the receiving doctor. The digital data, picked over a certain time duration, may also be stored at the transmitting computer and sent to the receiver following 'store and forward' protocol. At the receiving end there has to be arrangements for digital to analogue conversion of data and suitable amplification and filtering to produce corresponding electrical signals of sufficient strength and quality which will then be converted to acoustic sound waves through appropriate earphones or speakers.

There are certain frequency spectrum requirements for proper reproduction of stethoscope sound. To reproduce body sounds properly one needs to have a flat gain response between 20Hz and 3kHz[53]. The lower frequencies are particularly required for reproducing heart sounds. Most standard sound transfer systems through internet focus on the reproduction of human speech, for which the lower frequencies are usually eliminated that takes out heart sounds. Therefore, this poses a formidable challenge in the transmission of diagnostic quality body sounds through internet using standard transfer software.

The research team of BMPT improvised a low-cost digital stethoscope by modifying and improvising a good quality acoustic stethoscope (Littman Classic) readily available in local market. For this the rubber tubing connected to the chest piece is cut off keeping only a short length and an electret microphone is inserted into the other end of this tubing. The coupling region is acoustically isolated from the surrounding noise as far as possible. The microphone converts the sound signal into an analogue electrical signal which is then fed to a commercial USB sound card. This card provides both amplification of the analogue signal and its digital conversion. The digital data is available to the computer from the relevant USB port.

The developed digital stethoscope costs around 125 dollars only. This is currently being used in telemedicine programme run by BMPT and has been proven to be a useful and significant addition to the telemedicine service. However, for transferring proper quality of sound an open source audio software named 'Audacity' is being used to acquire and store the sound data for a certain period of time as a digital file. It is then sent to the recipient through the internet. The recipient, usually a doctor, also uses the same 'Audacity' software to open the file and hear the sound through a good quality earphone or speakers. Obviously a live streaming of sound data through the video conferencing system used (typically, 'Skype') would be preferable. However, as mentioned before, these systems cut-off low frequency sound signals to improve speech recognition which eliminates low frequency heart sounds, and is not appropriate for telemedicine.

Therefore, integration of the stethoscope to the TMS poses several challenges which has to be tackled properly.

5.1.2 Overview of Audio Capture and Processing on the Web

5.1.2.1 Web Audio API

Capturing and processing multimedia data on the web was once a major hassle for the developers and required a significant amount of effort and support of third-party plugins/add-on i.e. 'Flash plugin'. But in recent years, with the introduction of a number of useful Web APIs including Web Audio API for web browsers, tasks like capturing audio data and processing them within the browser has been easier and hassle-free as time progressed. The Web Audio API empowers the developer with a powerful and versatile system that can be utilized for controlling the audio on the web. It allows to choose audio sources, implement effects on it, visualise the data on the web page and much more. It also allows access to the raw audio data and the liberty to process it to a great extent.

Web Audio API manages all audio operations inside an Audio Context. Audio Context represents the sound system of the computer and is the main object used for creating and managing audio. The Web Audio API has been designed in a way to support modular routing that allows linking several Audio Nodes together to form an audio routing graph. Audio Nodes are individual modules capable to perform a specific audio operation. For example, Gain Node is used to control the gain of an audio object. These audio nodes, linked to each other by their inputs and outputs, forms a chain of nodes that performs various audio operations on a single or multiple audio sources to achieve the intended outcome out of it. The modular nature of the Web Audio API makes it possible to create complex audio functions flexibly with dynamic effects.

A typical audio operation within Audio Context starts with one or more audio sources. Audio sources can come from a variety of places:

- Generated directly in JavaScript by an audio node (such as an oscillator).
- Created from raw PCM data (the audio context has methods to decode supported audio formats).
- Taken from HTML media elements (such as <video> or <audio>).

- Taken directly from a web-cam or microphone stream.

Audio samples, divided in very tiny time slices, are provided by audio sources in a large number, often tens of thousands of them per second. These audio samples then pass through a set of audio nodes linked together. Output of one node links to input of another one and streams of sound samples are mixed or modified in this fashion to finally turn these into a different audio stream. Once the sound is processed as intended, it can be linked to the input of an audio destination that delivers the processed sound to speakers of headphones. However, this last connection to audio destination needs to be performed only if the user is supposed to hear the final outcome of the audio processing.

A typical workflow of audio processing using Web Audio API follows the steps mentioned below:

1. Create an audio context.
2. Inside the context, create sources such as embedded audio on webpage, oscillator, live microphone stream etc.
3. Create effects nodes, such as Gain, Biquad filter, Analyser etc.
4. Choose final destination of audio i.e. system speakers, headphone etc.
5. Connect the sources up to the effects, and the effects to the destination.

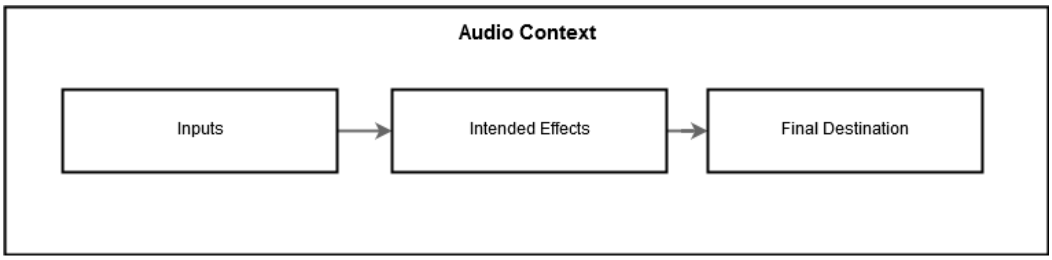


Fig. 5.1 A typical audio processing workflow within Audio Context

Within Audio context timing with high precision and low latency is maintained, which allows to create web-based audio applications by writing code that is highly responsive to events and is able to target specific audio samples, even at a greater sample rate.

Web Audio API offers a number of useful interfaces among which a few of them have been utilised to devise a solution for the problem context of this chapter. These interfaces are briefly described below:

- **AudioContext:** The AudioContext Interface is the representation of an audio graph built from the modules i.e. AudioNode linked together. An audio context controls the creation of the nodes contained within it and the execution of the audio processing tasks performed by various audio nodes.
- **AudioNode:** The AudioNode interface represents an audio-processing module, such as an audio source (e.g. an HTML <audio> or <video> element), audio destination, intermediate processing module (e.g. a filter like BiquadFilterNode, or volume control like GainNode).
- **MediaStreamAudioSourceNode:** The MediaStreamAudioSourceNode interface represents an audio source originated from a live Media Stream (such as a webcam, microphone, or a stream being sent from a remote location of the web). This, being an AudioNode itself, acts as an audio source.
- **BiquadFilterNode:** The BiquadFilterNode represents a simple low-order filter consisting of a number of filter options i.e. high pass, low pass, high shelf, lower shelf, peaking, notch etc. This is also an AudioNode which always consists of exactly one input and one output.
- **AnalyserNode:** The AnalyserNode represents an AudioNode which provides real-time frequency and time-domain analysis information. The provided information can be used for data analysis and sound visualisation.
- **ScriptProcessorNode:** The ScriptProcessorNode interface provides options to generate, process, or analyse audio data using JavaScript. This is an AudioNode acting as an audio processing module having linked to two buffers, one containing the current input, one containing the output. An event is triggered to the object each time the input buffer receives new data, and the event handler terminates when it has filled the output buffer with data.

- **GainNode:** The GainNode interface represents the change in volume. This is also an AudioNode that applies the specified gain to the input data before it finally reaches to the destination.

5.1.3 Technical Description of BMPT Digital Stethoscope

The technical specification of the developed digital stethoscope is briefly mentioned below(Figure 5.2):

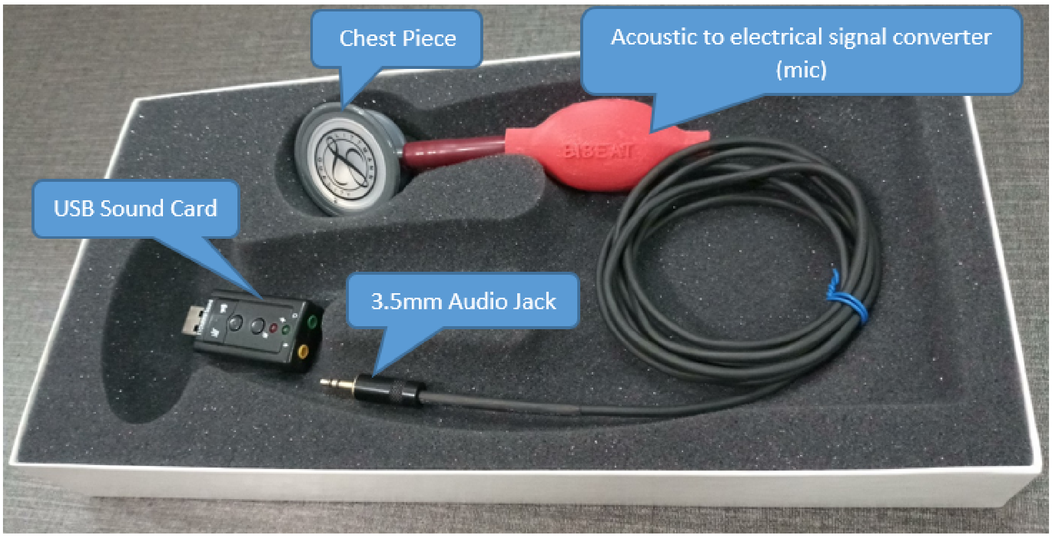


Fig. 5.2 Anatomy of locally improvised Digital Stethoscope by BMPT

- 3M Littman Classic II S.E Stethoscope chest piece.
- Condenser (electret) microphone to convert acoustic signals from the chest piece to electrical signals. The junction is acoustically shielded.
- Connects to PC / Laptop / Tablet through a USB sound card.
- Can be accessed using any sound capture software. Audacity, a free and open source audio processing software is recommended for use.
- Instant monitoring of sound is possible through earphone/headphone using appropriate software
- Sound frequency range: 20Hz to 3000 Hz. (approximately, depends on the software settings)

5.1.4 Current Usage Protocol of Digital Stethoscope for Telemedicine

The developed digital stethoscope by BMPT currently does not have its own customized software interface. However,it can be accessed and used by any audio software tool having the capability of capturing microphone sound from PC/Laptop/ Tablet. The stethoscope sound can be further recorded, played or transferred over internet once it is captured from microphone input by the appropriate software tool. After experimenting with a number of free audio software tool, Audacity, A free and open source audio processing software, was found most effective and useful for the intended purpose of capturing and recording sound from BMPT Digital Stethoscope. This software tool also supports options to record the captured data at a lower but acceptable frequency sampling rate for stethoscope sound without compromising the sound quality and information as a result which the recorded sound file becomes lightweight and can easily be transferred over internet requiring less bandwidth data usage. Currently, the steps of using BMPT stethoscope in a telemedicine workflow are as follows:

Step 1: During the conversation with the telemedicine patient over skype, if the doctor feels that he/she needs to hear the patient's heart sound, he/she instructs the operator to capture the patient's heart sound. Telemedicine operator takes instruction from the doctor over skype while trying to rightly place the chest piece of the stethoscope on patient's chest.

Step 2: Once the doctor is satisfied with the placement of the chest piece, telemedicine operator records the stethoscope sound for around 5 to 10 seconds using Audacity and exports the sound file in wav format and save it to local computer.

Step 3: Telemedicine operator sends the recorded file as an attachment through Skype chat window to the telemedicine doctor. Upon receiving the file, the doctor downloads it in his/her computer and listen to the stethoscope sound using a good quality headphone capable to play low frequency sound.

5.1.5 Limitations of Current Usage Protocol

There are a couple of major limitations that have been identified in the current usage protocol of BMPT digital stethoscope while using it for telemedicine purpose. The identified limitations are briefly discussed below:

- **Dependency on third-party software tool:** As there is no software tool specially tailored and developed for use with BMPT stethoscope currently, a user of the device always needs to rely on a third-party audio processing software for handling the digital sound produced by the stethoscope. This is inconvenient and the user needs to install yet another software tool and learn its usage procedure. Also, Audacity, the currently used software for stethoscope needs to be configured following a specific guideline to achieve the optimum performance for capturing the stethoscope sound properly.

- **Absence of a central database for recorded sounds:** The current protocol adopted within the telemedicine service provided by BMPT doesn't support any mechanism to upload and store all these recorded stethoscope sound in a central database, preferably as a health data against the individual patient health record. The recorded sound files remain in the local computers of telemedicine operators and doctors, unorganized and inaccessible for future evaluation and reference. Absence of a central database for stethoscope sound is risky from clinical perspective as well. It may compromise the safety of the patient too. Due to maintaining an unorganized, local database of stethoscope sounds in the operator or doctor's computer, there is always a possibility of mixing up stethoscope sound files of multiple users with one another that may eventually lead to wrong diagnosis and wrong suggestion of treatment by the doctors. Sending and receiving files over a third-party data transmission tool is also inconvenient and inefficient from user's point of view. In addition, the possibility of future research with the growing number of stethoscope sound files is overlooked, as they are not being stored in a central database and inaccessible to anyone except the operators sending the sound files and the doctors receiving them.

5.1.6 Present work: Web-based Stethoscope Data Acquisition and visualisation Tool

To address the limitations of using BMPT digital stethoscope in a telemedicine workflow mentioned in the previous section a web-based stethoscope sound acquisition and visualisation tool was developed. The main features of the developed software tool include the following:

- The developed tool can be accessed and used directly from web using any standard modern web browser i.e. Google chrome, Mozilla Firefox etc. and does not require any add-on or plugin to be installed in the client machine.
- It can be integrated seamlessly with minimal effort and customization within any web-based telemedicine software.
- It has two different user-interfaces for use. One is to capture and record stethoscope sound and the other is to view and hear the sound file from web. When integrating these interfaces to a telemedicine software system, the sound capture interface is integrated at the telemedicine operator's end and sound waveform visualisation and hearing interface at the doctor's end. The recording interface has options to record stethoscope sound as many times as needed until being satisfied with the quality of the recorded heart or lungs sound. Stethoscope sound viewer interface has options to view the waveform of the recorded stethoscope sound file in time domain. It also has the option to zoom the waveform to get a better view of the sound signal. The ability to view the sound waveform besides hearing the sound may assist the doctor better analyse the heart/lungs signals and take informed decision based on the evaluation of the heart or lungs sound in the future.
- Stethoscope sound data captured and recorded from the BMPT digital stethoscope is further filtered and compressed for removing unnecessary noise outside the frequency range of the heart or lungs sound making the final output file lightweight without compromising the quality of the sound. This procedure reduces bandwidth usage in case of transferring the sound file through

internet. Filtering and compression of the sound are performed in a background process (Web Worker) initiated in the web browser before uploading the final sound file to the telemedicine server.

5.1.6.1 How It Works

The Stethoscope Sound Acquisition Tool and Stethoscope Sound Viewer were developed using a set of in-built features supported within the standard web browser. Stethoscope sound acquisition, filtering and processing for eliminating higher frequencies above the frequency range of the heart sound were performed using the features and operations provided by Web Audio API. The Web Audio API provides a high-level mechanism of creating and manipulating sound directly in the browser via JavaScript. Most of the modern browsers are compatible with the Web Audio API and have built-in support for various operations of Web Audio API. The visualisation graphics of the stethoscope sound is drawn and displayed on HTML canvas element exploiting the canvas API on the web page. The sound acquisition tool and its scripting are written in JavaScript and does not require any additional plugin or add-on to work as intended.

The whole data acquisition and processing operation can be defined in three steps (with reference to Figure 5.3):

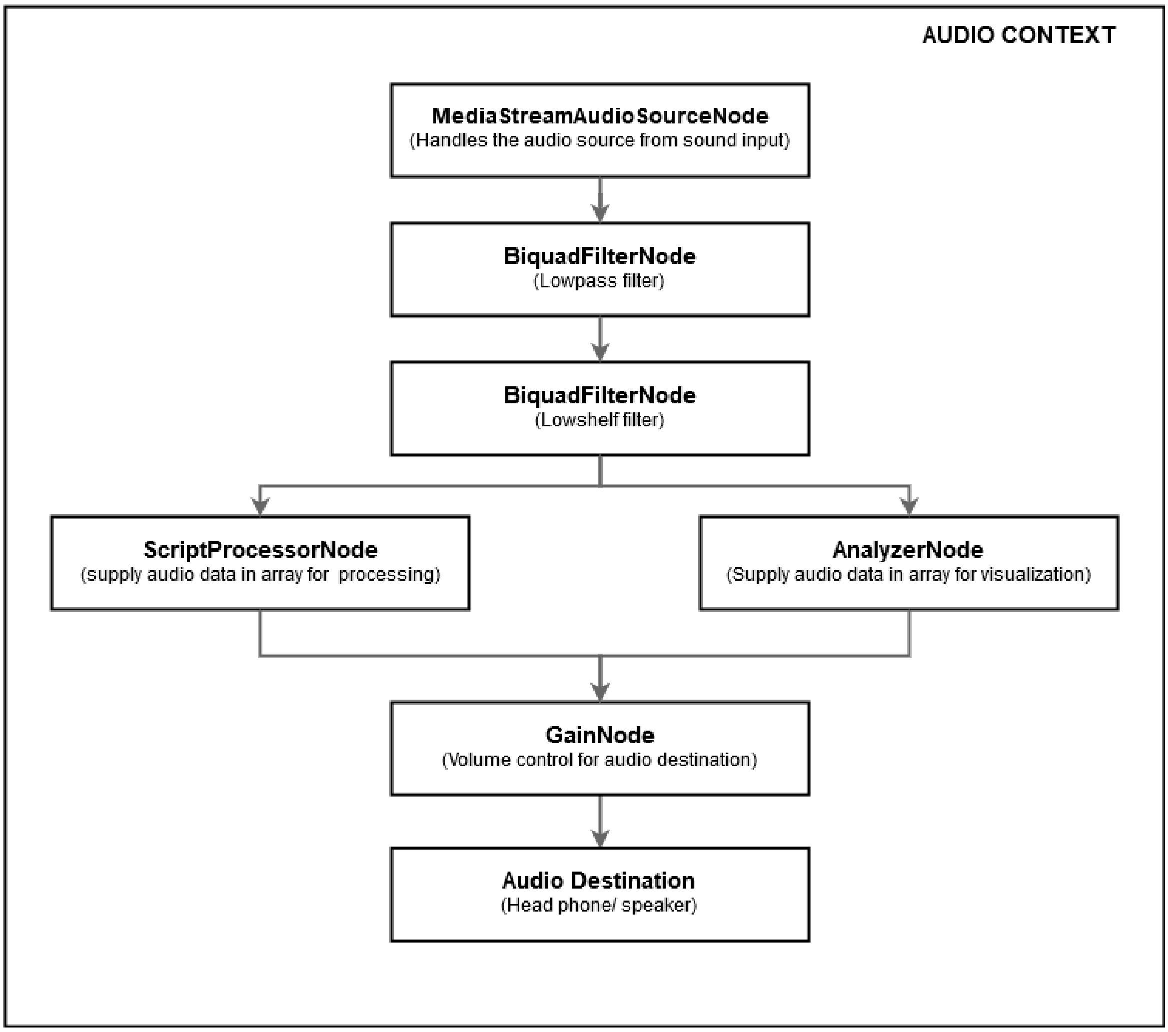


Fig. 5.3 Audio Routing Graph of Web Audio API for capturing and processing BMPT Digital Stethoscope sound

Step 1: Capture the stethoscope sound coming from sound input in local computer

When the user (transmitter of sound) clicks on the "Record" button of the stethoscope sound acquisition tool interface, a dialog window appears on the web browser asking for permission to give access to microphone to the sound acquisition tool. Once the user gives the permission, Media Stream Object containing the microphone input is obtained that gives access to the media stream coming from microphone input in real-time. After the successful acquisition of media stream access of the user microphone, an Audio Context is created in the background process of the browser by passing the Media Stream Object to it. Following the creation of audio context, audio operations, which are defined within the audio context, start capturing and processing the audio source that is coming from digital stethoscope via microphone input in real time.

Step 2: Process the captured sound in real time for visualisation and output to computer sound system

Once the permission to access microphone input is obtained within the Audio Context via MediaStreamAudioSourceNode, audio samples of stethoscope sound coming in tiny slices from the audio source are passed through a number of audio nodes connected to each other in a modular fashion in real-time. Firstly, the audio is passed through a BiquadFilterNode that applies a low pass filter on the incoming audio and filters out the frequencies higher than the range of heart sound (3000 Hz). The output of BiquadFilterNode is then supplied to another BiquadFilterNode as input where the audio goes through a low shelf filter, which applies a specified amount of gain to amplify the heart sound frequencies. Heart sound is very feeble in nature and is usually very difficult to hear without appropriate amount of gain applied to it. Low shelf filter allows all frequencies through but amplifies frequencies by applying predefined amount of gain that falls below the upper limit set during the initialization of BiquadFilterNode. The abovementioned processing can also be performed for lungs sound as well if required. Once the stethoscope audio is passed through the low shelf filter, the output audio is handed over to two different nodes as input to simultaneously perform two different operations on it. The analyserNode processes the filtered sound and generates an array of sound data that can be plotted on HTML5 canvas to visualise the sound. At the same time, the filtered audio is also passed to ScriptProcessorNode, which allows access to the raw sound data whenever new data are available in the ScriptProcessorNode buffer in real-time. This buffer data can be accessed from a JavaScript event call whenever new audio samples arrive and further actions defined in a JavaScript function can be performed on the data. In this specific case, whenever new data are available in the ScriptProcessorNode buffer, a JavaScript function is called which grabs the newly available audio samples, puts them in an array and passes the data to WAV encoder for encoding the raw binary sound data in WAV audio format. An open source JavaScript WAV encoding library has been used to encode the binary audio data to WAV format. While a JavaScript function keeps visualising the stethoscope audio in the front-end, binary sound data obtained from ScriptProcessorNode are encoded in the back-end simultaneously. Finally, the data coming out from both the analyserNode and ScriptProcessorNode are passed to the audio destination via a GainNode. The audio destination is the output system of the computer i.e. speaker or headphone and the intermediate GainNode is used to mute/unmute the volume of amplified stethoscope sound that reaches the audio destination after passing through a number of AudioNodes. When unmuted, the computer user can hear the filtered, amplified heart sound in his/her headphone or computer speaker at the time of capturing data from stethoscope in real-time.

Step 3: Process and prepare the captured sound for transmission over low bandwidth network

Once the user clicks on "Stop" button (located inside the sound acquisition tool interface) to terminate the operation of stethoscope sound recording, the process for preparing the uncompressed binary sound data captured from the stethoscope for transmission over low bandwidth network gets triggered as a background process. The binary data is first stored in WAV audio format and then handed over to FLAC encoder for further compressing the file by encoding it into FLAC audio format. FLAC audio format is a lossless audio compression commonly popular in the audio industry for its comparatively lightweight file generation while retaining the full audio quality. This conversion process is entirely performed in the client-end using open source FLAC encoding library and takes less than a couple of seconds to complete the whole conversion process. Before choosing FLAC as the compression format for reducing the sound file, a comparative analysis between WAV, MP3 and FLAC audio format for a sample stethoscope audio was performed and FLAC was found to be the better choice for our specific purpose. The experimental findings of this comparative analysis are given in detail in section 5.1.10 of this chapter.

5.1.6.2 Implementation Constraints

The stethoscope sound acquisition and viewing tool were designed and developed utilizing some in-built features of modern web browser such as HTML5 and Web Audio API. These features are readily available in almost all standard web browser such as Google Chrome, Firefox, Safari, Opera etc. in their latest versions. The developed tool and related interface only works in web browsers that are compatible with the aforementioned Web APIs and features. The web browser in use also needs to have JavaScript enabled in order to make the tool work as expected.

5.1.6.3 Integration and Interface within TMS

The developed stethoscope sound acquisition and viewing tool has been integrated into the TMS to overcome the limitations identified in the earlier section. The proposed solution overcomes the limitations of installing a separate, third-party software or plugin of any kind to use the BMPT digital stethoscope to capture and send stethoscope sound file over the internet. Stethoscope sound recorder interface has been integrated within the new consultation request form of TMS from where operator can directly capture and send stethoscope sound and send it to telemedicine doctor along with other primary vitals and health data input. Operator can record multiple times unless he/she is satisfied with the outcome of the sound. Sound files are stored in the TMS server cloud and treated as another health data recorded against patient's individual consultation information. Doctors can also view and hear the stored stethoscope sound from TMS doctor panel directly without requiring any third-party tools like Audacity.

5.1.6.4 User Interface

In order to integrate and incorporate the digital stethoscope of BMPT for capturing heart sound locally and sending it to the doctor over internet within the developed Telemedicine Management System (TMS) described in Chapter 4, two separate user-interfaces have been developed and incorporated into the TMS user-interface. One has been designed and developed for stethoscope sound acquisition directly from the webpage and another for viewing, hearing and analysing the captured heart sound uploaded in the telemedicine cloud server from the webpage as well. While the former is accessible by telemedicine operator for acquiring stethoscope sound from within the TMS user interface, the latter is intended to be used by telemedicine doctor to view, play and hear the heart sound stored in the cloud and sent by telemedicine operator for evaluation.

Stethoscope Sound Acquisition Interface:

Stethoscope sound acquisition interface is integrated within the new visit form that is being used to send patient's primary vitals, chief complaints, report images etc. and submit the data to the cloud server making it immediately available to the designated doctor. Like entering other primary vitals, the operator can easily capture, play and send the stethoscope data of 10 seconds using this user interface and store the sound in the cloud along with other clinical information of the patient. Once a 10-second data is captured, the recorder immediately stops and present the captured sound in playable format. If the operator does not get satisfied with the heart sound quality, he/she can discard the sound and take heart sound again following the same procedure. This way the operator can capture data, as much time as he/she wants and finally choose the sound file he/she gets satisfied with. The sound data can also be downloaded and stored locally in the operator's computer.

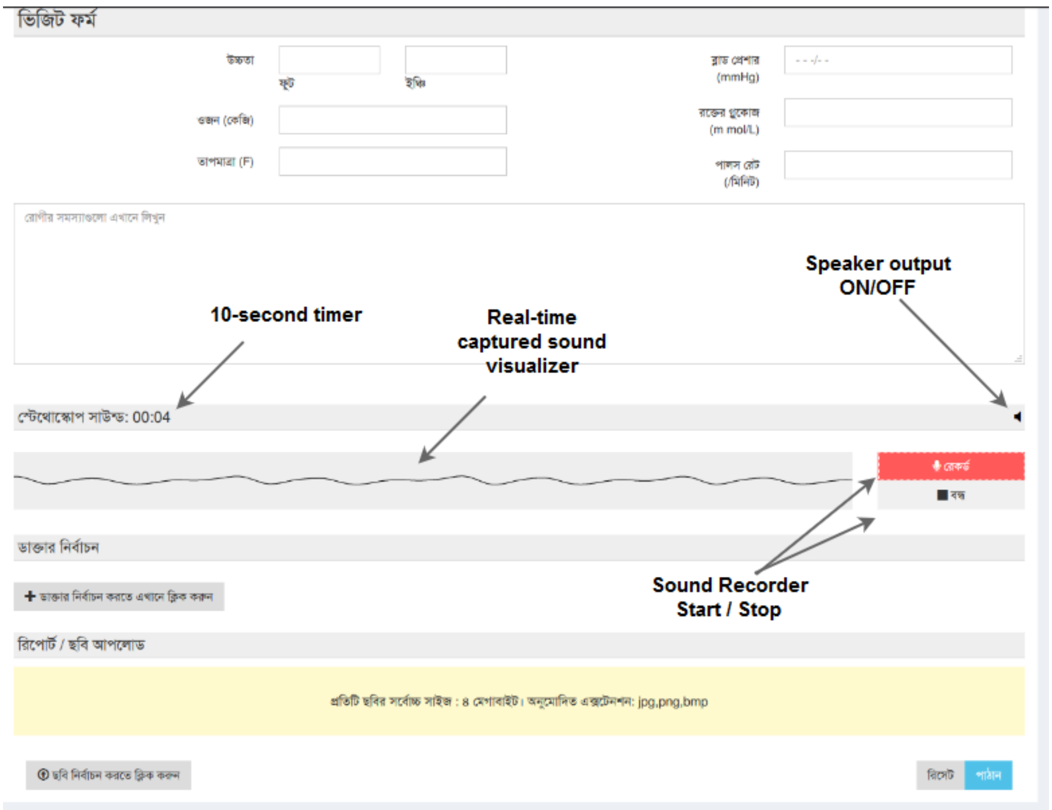


Fig. 5.4 Web-based Digital Stethoscope Data Acquisition interface integrated within Telemedicine Management System (TMS) interface

Stethoscope Sound Viewer and Player Interface:

Fig. 5.5 Web-based Digital Stethoscope and Sound Viewer and Player interface

To address the slow internet connectivity constraints at the Telemedicine Operator's end from where the patient's stethoscope sound will be uploaded to the telemedicine cloud server, acquired stethoscope sound has been further compressed to reduce the file size before uploading it to the server. Digital stethoscope sound captured using the developed sound acquisition tool are initially stored as uncompressed WAV files in the local computer. Usually a 10-second heart sound data is captured by the operator for storing in the cloud, which takes around two-megabyte size after being captured from the web-based data acquisition tool. Uploading uncompressed WAV files over the Internet requires more bandwidth data and is encountered with more difficulties when the internet connection is slow. Reducing the file size while retaining the quality of the captured sound to an extent necessary for clinical evaluation would appropriately address both extra bandwidth data usage and slow internet connectivity issue. For this, an appropriate audio file format needs to be chosen with the right compression that will serve the purpose. There are three major groups of audio file formats: uncompressed audio format such as WAV, formats with lossy compression and formats with lossless compression.

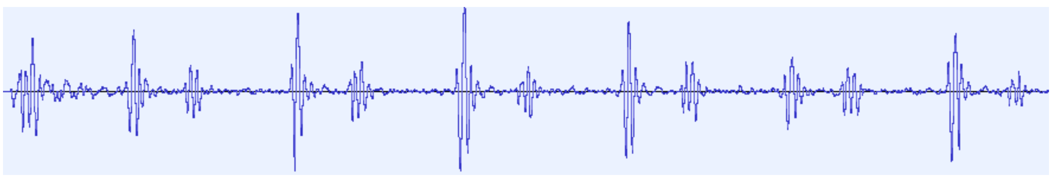


Fig. 5.6 Sample Heart Sound signals of 5 seconds captured from BMPT Digital Stethoscope using developed web-based data acquisition tool for BMPT digital stethoscope

An experiment was carried out to find out how the audio quality and file size of stethoscope sound varies after compressing it from uncompressed WAV format to a suitable audio compression format. MP3 and FLAC, a lossy and a lossless compression respectively, were chosen. MP3 format, a lossy audio compression format, is widely used for storing music audio as because the audio file gets reduced to a smaller size at the cost of losing some sound information. On the other hand, FLAC audio format is gaining popularity among lossless audio formats for the same reason as mp3 but with more advantage as no data is lost during the audio compression process.

To carry out the experiment, a 10 second stethoscope sound data captured from the developed stethoscope data acquisition tool, was taken as a sample. The sample audio file was then compressed to FLAC format and mp3 format respectively using Audacity software. FFT was then performed on all three audio samples using Hanning Window Function and the data were analysed by spectrum plotting using the same configuration for all three samples.

Figure 5.6 shows the frequency signal for heart sound captured using digital stethoscope of BMPT from a 26 years old, Male subject's body. 5 seconds of data out of captured 10 seconds has been shown in the figure for better viewing.

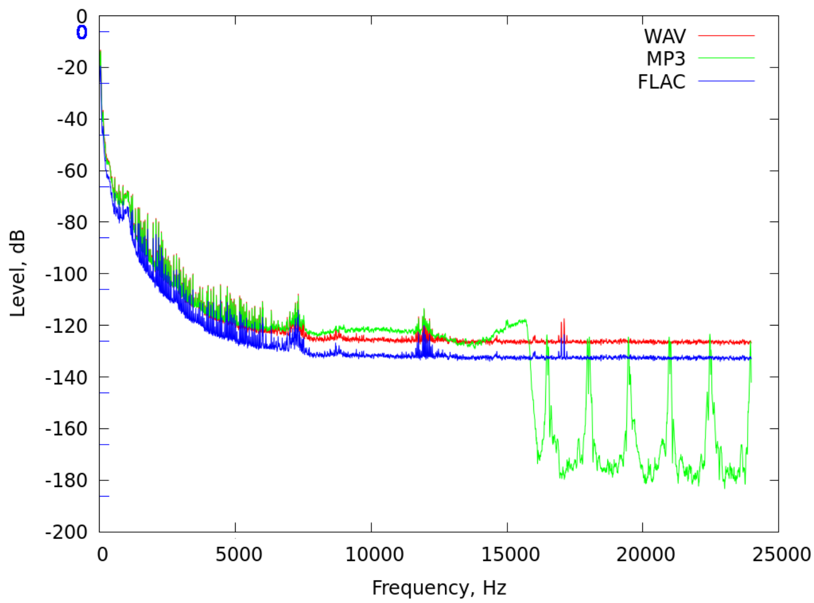


Fig. 5.7 Frequency analysis comparison between WAV, MP3, FLAC for heart sound captured using digital stethoscope of BMPT

Figure 5.7 shows the comparison of FFT analysis among the three uncompressed and compressed file formats. In this experiment frequency graph of WAV and FLAC has been found

identical and no visible variation were observed, which is of course expected, as FLAC is a lossless compression audio format that stores data in less space without losing any information. As the frequency graphs of WAV and FLAC were perfectly identical, overlaying the one on another seemed like a single frequency graph. So, to better understand the similarity between two, FLAC graph was shifted slightly lower compared to the other two graphs in the plotted graph shown in Figure 5.7. On the other hand, MP3 compression of stethoscope sound showed a little deviation from the uncompressed audio data and the deviation increased significantly above 15kHz. However, this is beyond most of the audio signals of interest and the deviation is very less and might be neglected for stethoscope sounds. Therefore, it may be said that for the capture of stethoscope sounds from the human body, all the three types of audio files essentially give the same output. However, when the file sizes of three sound file formats were compared, it was found that both FLAC and MP3 compressions reduce the file size significantly compared to the raw WAV format, and that FLAC file size is marginally smaller than the MP3 file size. For the example of the heart sound used in this study, the uncompressed heart sound audio file in WAV format was 1.82 MB in size. After MP3 compression with a bit rate of 112Kbps the file size became 137KB while the file size in FLAC format was 131KB, even with a slightly greater bitrate of 120Kbps.

The comparison above clearly shows that FLAC is the best choice out of the two methods (FLAC and MP3) for compressing the captured stethoscope sound that reduces the file size by about 93% without losing any sound information. So, FLAC was chosen for compressing the stethoscope sound captured from the BMPT digital stethoscope.

5.2 Integration of 12-lead Digital ECG

5.2.1 Background

Electrocardiography can be defined as the process of recording the electrical activity of the heart as waveforms over a certain period of time using a number of electrodes placed on body skin. The graph of the waveforms of the electrical activity is known as Electrocardiogram (ECG). Electrocardiogram is a non-invasive yet considered as one of the most valuable diagnostic tools in the clinical field. Correct interpretation of ECG signals captured using Electrocardiography helps detect and monitor a variety of heart conditions. Though the invention of first practical Electrocardiography machine dates back to more than hundred years ago, the benefits of one of the finest inventions of the last century are still out of reach for the majority of the world population, especially in the developing countries. With a vision to expand the benefits of ECG among third world countries, researchers at BMPT has designed and developed a low-cost computerised single channel, 12-lead digital ECG machine. Both the hardware and software application of the ECG device were developed locally from scratch by the BMPT team. Besides functioning as a standard 12-lead diagnostic ECG, it also has software functionality to transmit ECG signal over the internet in near real-time. The overall cost of BMPT ECG equipment is very low compared to other digital ECG devices available in the market that have the capability to transmit captured ECG data remotely over internet. The capability of transmitting ECG signal data remotely makes it eligible for telemedicine use as well. BMPT ECG device has been tested and used for telemedicine to record and transmit ECG signal from rural telemedicine center to urban doctors for interpretation and evaluation. However, some limitations and constraints of using BMPT ECG for telemedicine purpose have been observed during the field trial of telemedicine programme run by BMPT.

As part of the present work, the protocol of using BMPT ECG for telemedicine has been carefully observed and analysed. Current limitations and future scope of improvements for better integrating the device into the telemedicine software platform has been identified and a solution in the light of identified problem context has been proposed. The following sections of this chapter provides a brief technical description of the BMPT ECG followed by describing the approach to solve the current issues and limitations of the device for telemedicine delivery.

5.2.2 Technical Description of BMPT 12-lead Digital ECG

Fig. 5.8 12 lead digital ECG developed by BMPT

Some key features and specifications of BMPT 12-lead Digital ECG are as follows:

1. Single Channel, 12 lead ECG, selectable using Graphical User Interface and mouse click.
2. Connects to PC/Laptop/Tablet through USB Port.
3. Runs on Windows XP or later versions.
4. Basic patient entry.
5. Displays ECG trace and heartbeat rate on computer monitor.
6. Displays the above in a remote computer through internet (the software should be run in both computer).

7. Prints ECG traces on ordinary paper using any computer printer (color printer preferred).

8. Saves data on hard disc for future use.

9. Operates on power from USB port of the connected computer.

5.2.3 Current Usage Protocol

Unlike measuring primary vitals of a patient for sending to telemedicine doctor before a teleconsultation, recording ECG is not always necessary and is only provided to the doctor on demand. Typically, doctor requests for ECG only when s/he feels it necessary after studying the basic patient information and consulting the patient's problem and health condition over video conference. Once requested by the telemedicine doctor, telemedicine operator records the ECG data of the patient and sends it to the doctor for further evaluation of patient's heart condition. In the current mode of operation, recorded ECG data from BMPT Digital ECG can be sent to doctor in two ways, 'store and forward' or transmitting the ECG data through internet in near real-time.

- **Store and Forward:** In this mode of sending ECG data to doctor, operator takes the ECG signal from patient's body following the recommended procedure of ECG data collection. Every telemedicine operator is required to complete a short training on how to operate diagnostic devices including digital ECG yet the operator may take instructions from the doctor over video communication on placing the electrodes correctly on patient body to minimize data collection errors. Operator can directly view the ECG signals coming from different electrodes on his/her computer monitor using the ECG software. Once the operator is done recording ECG signals for all leads, the software combining all the inputs from different leads generates a final, printable version of ECG graph. The generated ECG graph then can be printed or exported in either xml or pdf format to send it over internet. The operator prints a copy for the patient and sends the pdf or xml version of the ECG graph to telemedicine doctor for evaluation and interpretation. In case of receiving xml data, doctor needs to open the xml file using ECG software to view the graph.

- **Semi real-time data transmission:** In this mode, doctor at the remote end can view the ECG data recorded from patient's body in near real-time. The ECG software needs to be opened in both the operator and doctor's end. After successfully connecting to the ECG server, the ECG data is transmitted and displayed on doctor's monitor through ECG software. The data sent to the ECG viewer interface at the remote end gets refreshed in every four seconds enabling the doctor to monitor and direct the operator accordingly in case of incorrect data recording or wrong placement of any of the leads. The doctor can also generate PDF version of the remote patient's ECG graph or print it if needed.

5.2.4 Limitations in Current Usage Protocol

Though current usage protocol of BMPT ECG device is working well in the context of rural telemedicine application , there are some specific areas identified in the process of evaluating its workflow that can be further improved to deliver better telemedicine service in terms of sending and receiving ECG data between doctor and rural telemedicine center. Identified areas of concern are briefly discussed below:

- **No central storage of ECG data:** Currently ECG data that are being recorded and sent to the doctor for interpretation are not being stored centrally. All the data either are kept locally in telemedicine operator or in the doctor's computer. The current protocol adopted within the telemedicine service provided by BMPT does not support any mechanism to upload and store all these recorded ECG data in any kind of central database, preferably as a health data against the individual patient health record. The recorded ECG data remain in the local computers of telemedicine operators and telemedicine doctors, unorganized and inaccessible for future evaluation and interpretation. Absence of a central database for storing these health data is also risky from clinical perspective as well. It may compromise the safety of the patient too. Due to maintaining an unorganized, local database of ECG data in operator or doctor's computer, there is always a possibility of mixing up ECG files of multiple users with one another that may eventually lead to wrong interpretation of the problem and wrong suggestion of treatment by the telemedicine doctors. In the 'store and forward' mode sending and receiving ECG files over a third-party email server or Skype is also inconvenient and inefficient in terms of user friendliness and ease of access. In addition, the possibility of future research with the growing number of ECG data is lost as they are not being stored in a central database and are inaccessible to anyone except the individual telemedicine operator and doctors who are storing these files locally.

- **Separate user interface for viewing ECG data:** In current mode of operation, the doctor needs to open and use ECG software for viewing ECG graph in near real time, or if the operator sends the data in xml format. Though xml file is lighter in size compared to the pdf version, it adds an extra step to read the file in proper format. In case of pdf version also, a pdf-reading software needs to be installed in the computer, which is yet another dependency that needs to be satisfied.

- **Unavailability of access to telemedicine patient information within ECG software:** Current ECG software in use has a few input fields related to the patient's personal data that includes patient name, age, gender and Patient ID. Operator is required to input this data manually matching the data of the same patient already stored in the telemedicine database. Data entry following this manual procedure leaves room for error in case of the operator entering wrong patient ID or any other personal information incorrectly.

- **Size of exported file for sending over internet:** In 'Store and forward' mode of ECG file transfer, telemedicine operator usually sends the file to the doctor in PDF format. PDF files are comparatively larger in size and takes up around 4 to 5 MB bandwidth data to attach and forward to the doctor via email or skype chat. Sending a file this size may not be a problem for high bandwidth network but operators operating under a low bandwidth network with limited data usage may experience difficulties sending it over to doctor.

5.2.5 Present work: Web-based ECG Monitoring System (ECGMS)

A web-based ECG monitoring system was developed to address the issues identified in the earlier section. The developed ECG monitoring system connects the Digital ECG developed by BMPT to a central ECG data server and provides provision to access the data in near real-time from the web. The web-based ECG monitoring system has the following features that successfully addressed the limitations of current usage protocol of BMPT Digital ECG mentioned in section 5.2.4 within the current telemedicine workflow adopted by BMPT.

- The web-based ECG monitoring system has a back-end ECG cloud database that stores all the ECG data of patients coming from an online BMPT ECG connected to the telemedicine server. The previous ECG software developed by BMPT has been improved and updated to make it compatible for the developed web-based ECG monitoring system and to upload the lead data from the ECG software to the cloud database server directly.

- Web interface has been developed to monitor and view the ECG data acquired by BMPT ECG device from the web. Previously, for viewing the exported data generated from BMPT ECG or monitoring the data remotely required BMPT ECG software to be installed in the local computer of both ECG data sender and receiver. The developed monitoring system does not require any dependency or software to be installed in the ECG data receiver's end and the receiver can view the ECG data being uploaded from the sender's end to ECG cloud server from any web browser. It also allows monitoring of ECG signal coming from an online ECG device in near real-time from the web as well. In case of real time monitoring, the data is refreshed in the web interface in every 4 seconds.

- The developed ECG monitoring system also addressed the issue of transferring large pdf file over internet for doctor's evaluation. A telemedicine operator no longer needs to send the PDF file, which usually would require 3 to 4 Megabytes of data to send via SKYPE or E-mail.

5.2.5.1 Integration with Telemedicine Management System (TMS)

The developed web-based ECG Monitoring System was successfully integrated into the telemedicine system adopting an easier and more efficient workflow for capturing, storing and viewing ECG data. The underlying design of the system and its adopted workflow within the telemedicine system are described in the following two sections.

5.2.5.2 System Design Overview

The developed ECGMS is designed and built on top of the Application layer earlier developed for the Telemedicine Management System (TMS) as described in Chapter 4.

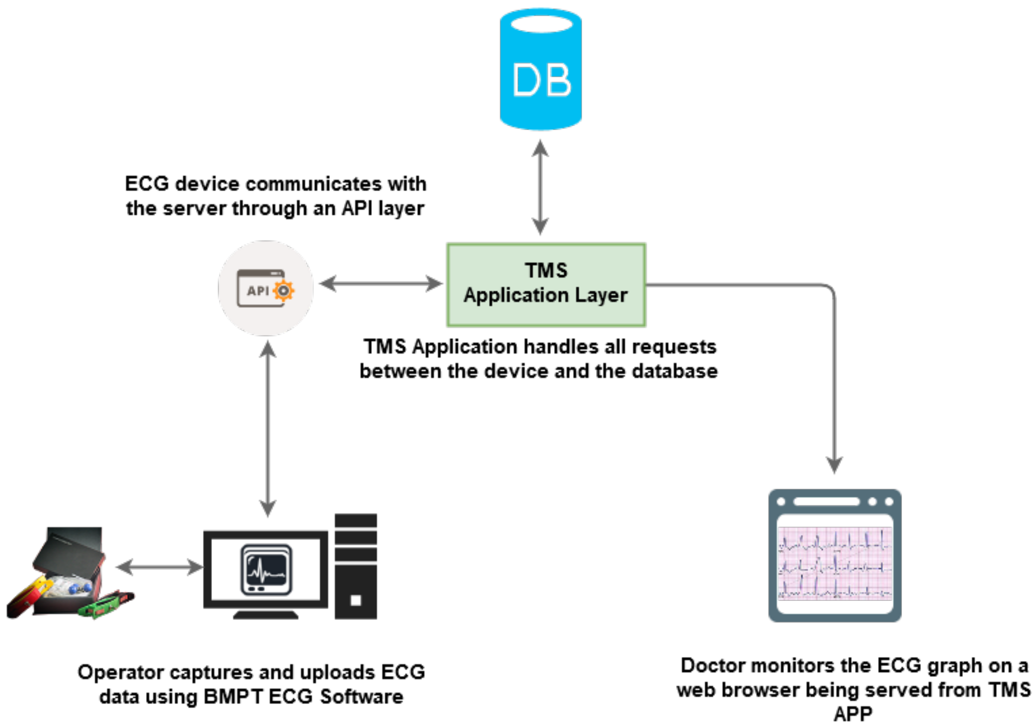


Fig. 5.9 System design architecture of the Web-based ECG monitoring system

The implemented system design of the ECGMS is shown in figure 5.9 depicting the major components of the system. The JAVA based ECG desktop software interface that was developed earlier as a part of another research work, has been heavily modified and updated for the present work to make the software compatible with the developed ECGMS. The ECG software connects to the cloud server through a set of API functions and perform operations such as retrieving the patient information from patient database and uploading ECG data to the cloud database. The viewer can access the ECG data of 12leads on a webpage served from telemedicine application server in a properly formatted manner. In case of semi real-time monitoring, which updates the ECG data in every 4 seconds on the receiver's end, refreshes the webpage with client-side JavaScript function calls.

5.2.5.3 Operational Workflow

Usually a doctor requests ECG data only when he/she feels it necessary for better evaluating the patient's condition besides examining other primary vitals measurement and talking to the patient over video conference. The new and improved workflow of capturing, uploading and viewing ECG data obtained from BMPT ECG is described in steps below:

"Store and Forward" Workflow:

1. **At the operator's end:** After being instructed from the doctor to record ECG data for the patient, the operator prepares the patient for ECG data collection by placing the electrodes at the right places of the body followed by other relevant procedures. The operator then opens the BMPT ECG software and connects to the telemedicine server providing the same login credentials that he/she uses for accessing the Telemedicine Management System for usual telemedicine operations. Once connected successfully to the server, the operator can access the patient information from telemedicine server and fill up the information fields of patients in the BMPT ECG software interface such as patient ID, name, age, sex etc. Patient information can be searched and retrieved from within the ECG software interface by patient ID. After filling up the information fields with appropriate patient information retrieved from the server, the operator then starts recording ECG signal from different leads sequentially from the BMPT ECG software interface. Once data collection from all of the 12 leads are completed, the operator clicks on the relevant option to upload the data to the server. Before uploading the data a list of recent visits of the patient selected

at the initial step of the procedure, appears in a dialog box from which the operator selects the visit against which he/she wants the ECG data to be stored in the cloud. Once the upload of recorded data is completed, a confirmation message is displayed in the ECG software interface.

2. **At the doctor's end:** Once the operator confirms the submission of ECG data for a specific patient visit, the data gets immediately available at the doctor's panel. Then the doctor checks back the visit information of that patient for whom he/she requested the ECG signal and can view the data online plotted on the web interface that displays the 12-lead ECG signal in clinical format.

Semi Real-Time Monitoring Workflow:

A provision for monitoring ECG data in semi-real time was also developed which allows the doctor to view the captured ECG data remotely on a web interface that is updated in every 4 seconds with the new set of recorded ECG data. This option helps the doctor to guide the operator to properly collect all the lead data in case of one or more lead data are not captured correctly due to the wrong placement of ECG electrodes. The workflow for semi real-time monitoring is same as the "store and forward" method explained above except all the lead data is being uploaded to the cloud individually at the time of recording in every 4 seconds. The web ECG viewer in the doctor's end is updated too upon receiving every new set of recorded ECG data fetched on AJAX call from the server. In this mode of operation, the doctor may keep contact with the operator over video conference during the whole procedure for guiding the operator to acquire patient's ECG information correctly.

5.2.5.4 User Interface

User interface for ECG Monitoring system combines a computer-based software interface for capturing and uploading the data to cloud server and a web interface to view the ECG data online from a web page. Two interfaces involved with the system are briefly described below:

Computer-Based Software Interface

A JAVA based computer software interface is used to acquire and send ECG data to the cloud server. The software interface provides the user with necessary options to collect and forward

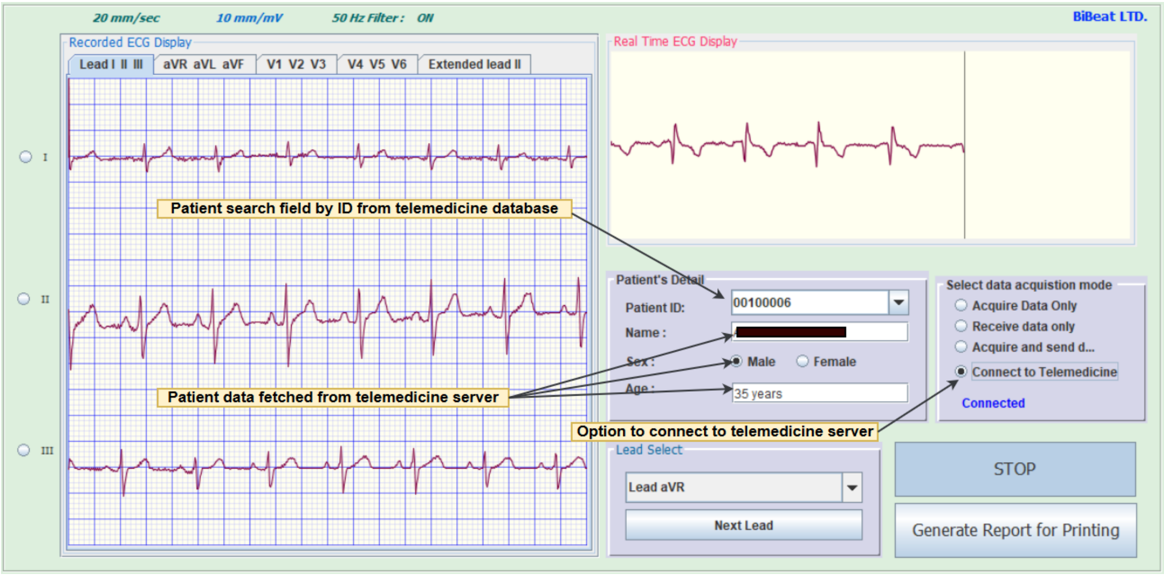


Fig. 5.10 Computer based ECG user interface integrating to telemedicine server

the data to the ECG data receiver's end. The software interface was modified and re-arranged in order to extend its telemedicine capabilities integrating the software with the developed Telemedicine Management System. Figure 5.10 shows the desktop-based ECG user interface that has been modified and extended for telemedicine use. After connecting to the telemedicine server successfully, patient information can be retrieved from within the software interface. Patient information can be searched by last four digits of the patient ID, mobile number or patient name registered within the TMS. In case of multiple suggestions retrieved from the database, suggestion lists are shown below the search field providing option to choose the right patient. Once clicked on the appropriate patient id from the drop-down list, patient information field i.e. name, sex and age below the patient ID are updated accordingly with the information fetched from the telemedicine server.

Web Interface

ECG web interface consists of data captured from 12-leads of the BMPT digital ECG displaying them in a proper clinical format. The information of the related patient are also shown along with the data. All the data are plotted on the webpage inside a HTML5 canvas using JavaScript. In case of semi-real time monitoring, the webpage updates the data of the relevant lead in every 4 seconds.

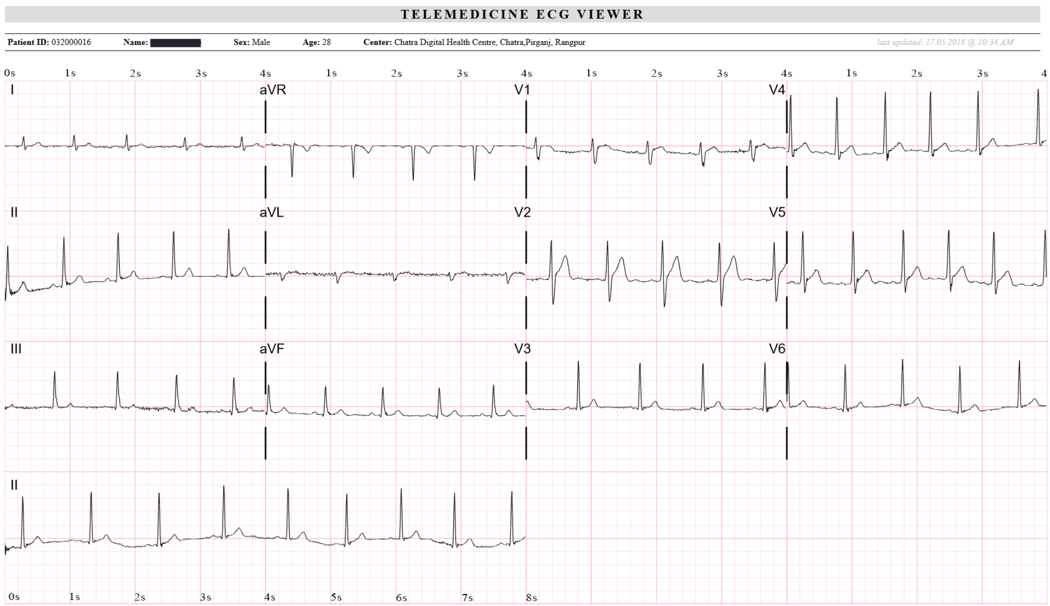


Fig. 5.11 Web interface for viewing ECG data online in Web-based ECG monitoring system

Fig 5.11 shown above displays the web page for viewing and monitoring ECG data acquired and uploaded to the server from BMPT ECG device. In case of semi real-time monitoring the relevant lead data is updated accordingly.

5.2.5.5 Adaptation to Slow Internet Connectivity

The developed ECG monitoring system requires only a few kilobytes to transmit the ECG data from the client computer of rural telemedicine center to the cloud database for uploading and storing. For a single “store and forward” protocol the data containing information of the 12-lead ECG signal together amounts to around 20 kilobytes, which are required to be transmitted from the client machine to the server for storing them in the ECG database making the system very adaptive to the network environment that suffers from slow internet connection and bandwidth limitation.

5.2.6 Conclusion

This chapter introduces the two medical devices improvised and developed by BMPT specially for telemedicine use and describes the adopted mechanisms that the present work demonstrated to integrate these two devices with the developed Telemedicine Management System (TMS) discussed in section 4. Integration of these two devices with the web-based telemedicine system also took care of the concerns that may arise while operating in a low bandwidth network and addressed the issues effectively by optimizing the bandwidth data usage to a minimum level.

Chapter 6

Integrated Real-time Multimedia Communication for Slow Internet Connectivity

6.1 Introduction

A meaningful and uninterrupted consultation between a doctor and a patient is one of the crucial requirements in any sort of clinical service including telemedicine. However, telemedicine projects targeting rural communities for healthcare delivery very often find it difficult to host stable and consistent multimedia tele-consultations over internet. A multimedia consultation including the transmission of both voice and visual data requires a significant amount of bandwidth and a reliable,high-speed internet connection for uninterrupted communication which is very often absent in the rural areas. Poor internet connectivity is prevalent in the rural areas of all developing countries including Bangladesh. Therefore, telemedicine projects eyeing to operate in those areas face challenges in regards to arranging stable tele-consultation over slow internet connection. Most of the existing telemedicine projects operating in Bangladesh seem to rely on third-party multimedia communication tool like Skype for the tele-consultation. The present system of DUTP also uses Skype for the purpose. In the present operation protocol of DUTP, the user needs to switch between Skype and TMS application frequently, which is inconvenient and inefficient as far as the user-experience is concerned. Hence, an integrated, web-based solution would be desired for greater user-friendliness. To address the above-mentioned issues, a web-based real-time communication user-interface was developed, especially giving priority on holding tele-consultations in a low-bandwidth environment. This chapter reports the experimental results that were obtained from a comparative analysis of bandwidth consumption between Skype and the developed tool at varying internet speeds.

6.2 Overview for Real-Time Multimedia Communication on the Web

6.2.1 WebRTC

WebRTC stands for Web Real-Time Communications. WebRTC is a free, open source project that offers web browsers, mobile applications and IoT (Internet of Things) devices options to integrate Real-Time Communications (RTC) capabilities via simple APIs (Application Program Interface). Since its announcement in 2011, the technology has steadily grown in popularity and adoption. The technology has been widely adopted by most of the modern browsers that allows developers to build browser-based application with voices and video communication functionality with the capability to work inside web pages. Previously, achieving the same functionality with web browsers would require external plugins to be installed in the local computer or devices. In addition, it would require long development cycles and higher development costs for developing a basic multimedia communication tools with the same capability as is offered by WebRTC. The following section gives a brief overview on how WebRTC works and implemented into a web browser.

Architecture

Web browser makers, through implementing a set of C/C++ APIs, incorporate WebRTC technology into a web browser. The capability to interact with the WebRTC is exposed via a set of WebAPIs for building voice and video communication application. These JavaScript WebAPIs interact with the underlying C/C++ APIs for performing all WebRTC related actions inside the browser. A WebRTC-based application is developed on top these WebAPIs. Figure 6.1 shows a high-level diagram of how the communication occurs from browser to the web in a typical WebRTC-based voice and video application.

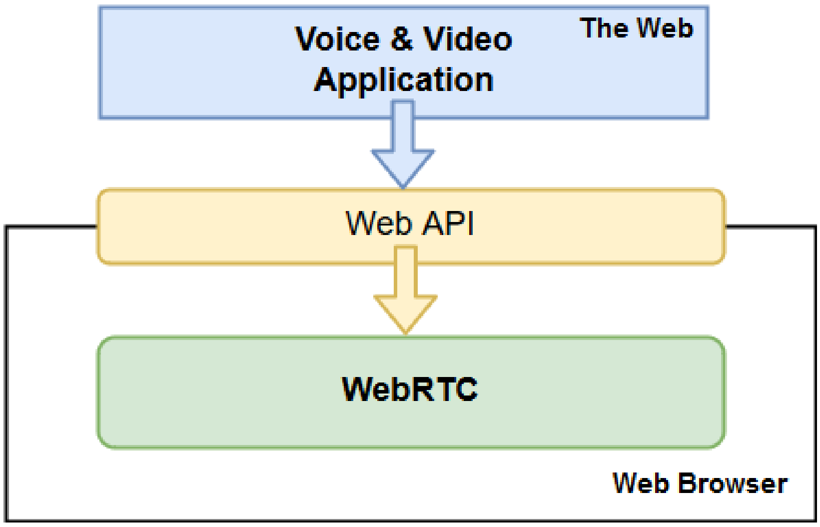


Fig. 6.1 High-level diagram of WebRTC architecture

Peer-To-Peer Communication Using WebRTC:

WebRTC enables users to communicate from browser to browser with real-time audio and video transmission. In order to do that, each user's web browser must agree to begin communication followed by exchanging each other's information i.e. IP address, port number etc. However, in real world it is not as easy as it may seem. One of the major challenges in browser-based peer-to-peer communication is to know how to locate and establish network socket connection between two web browsers in order to transmit multimedia data bidirectionally. Most of the computer system connected to the web are assigned to private IP addresses and typically sit behind a firewall and Network Access Translation (NAT) Device. These NAT devices translate private IP addresses from inside a firewall to public-facing IP Addresses enabling the computer systems to interact on the web. WebRTC cannot interpret these public-facing IP addresses and exchange related information between the browsers itself. It requires a signaling server to exchange this information between two peers. The signaling server utilizes STUN (Session Traversal Utilities for NAT) and TURN (Traversal Using Relays around NAT) server to interpret the public IP addresses of the browsers trying to communicate with each other. The information required to initiate the connection are exchanged between two browsers in a specific format called "Session Description". Once the two browsers receive Session Description of each other via a signaling server, WebRTC starts to transmit multimedia data between two peers from their respective web browsers. The whole process of P2P communication using WebRTC is illustrated in Figure 6.2.

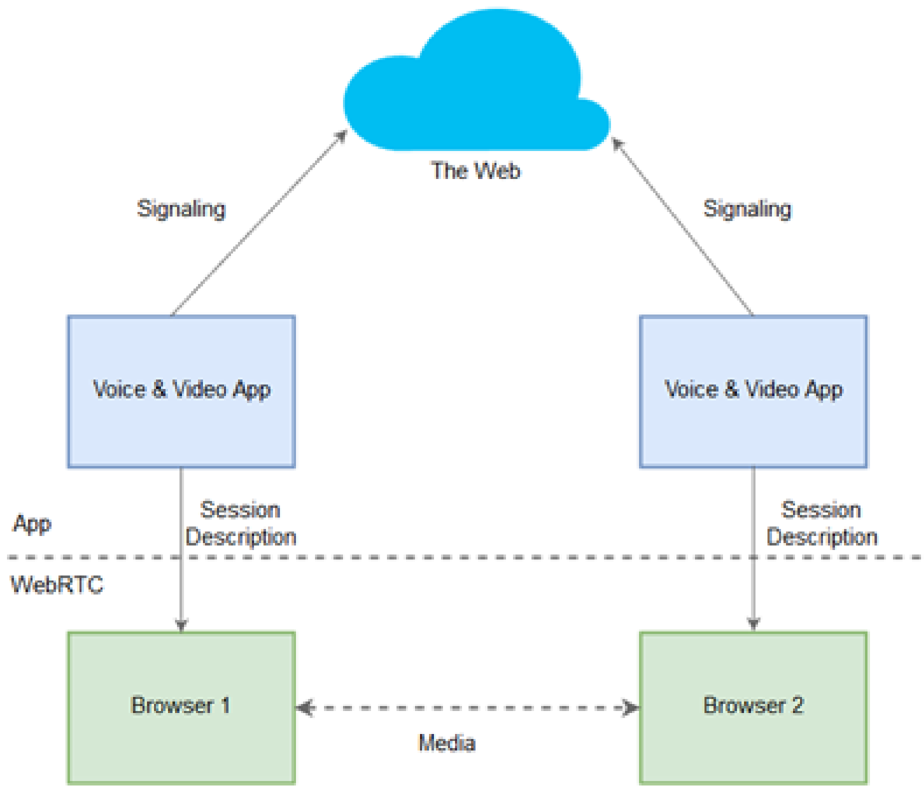


Fig. 6.2 High-level diagram of how WebRTC P2P connection works

However, in real-world scenario, it does not always become possible to identify the public IP address of the peers due to strict firewall settings and NAT related issues. In that case, a TURN server is used for relaying the multimedia data between two peers and each peer no longer needs to know the details of each other. Instead, they communicate via the TURN server to send and receive real-time multimedia data during a communication session.

Security

A real-time communication application or a plugin might compromise security of the computer system in many ways. For example:

- Exchanged media or data might be intercepted between browsers or browser-to-server communication over an unencrypted connection.
- An application may capture and distribute multimedia data without a user's permission.
- The plugin may be infected with malware or viruses installed alongside.

WebRTC has several mechanism to address these specific security issues. They are briefly mentioned below:

- It is mandatory to use secure encryption for all communications that take place through WebRTC including signaling mechanisms.
- WebRTC is not a plugin. All its components are in-built within a web browser requiring no separate installation. WebRTC is updated whenever the related browser is updated.
- WebRTC requires the application to ask for permission explicitly for accessing camera and microphone within the browser. The browser interface shows indicator whenever the camera or microphone are running. This prevents unwanted use of these input devices in the background.

6.3 Problem Context

In a telemedicine Programme, doctor-patient teleconsultation is crucial to delivering quality telemedicine service. Besides communicating over mobile phone conversation, a number of telemedicine programmes operating in developing countries rely on online voice and video communication services like Skype for over-the-web consultation. However, in developing countries, due to the poor and unreliable nature of internet connectivity, telemedicine providers very often experience issues in managing consistent voice and video conference for a long period. In addition, relying on a separate software tool for consultation and another for the the clinical data management are inconvenient for the relevant users. An integrated telemedicine software platform incorporating all the facilities including tele-consultation functionality from the same web platform would most likely benefit the users of the system in a positive way. That would result in to efficient management of telemedicine operations and greater user-friendliness of the system. In a preliminary study conducted among the existing telemedicine projects operating in Bangladesh, it was observed that a number of projects adopted third-party voice and video communication services such as Skype for tele-consultation. The present system of BMPT telemedicine programme, which is currently running using the Telemedicine Management System (TMS) developed under the present work, also uses Skype for tele-consultation. During the first field-test of the programme and also in the present system, a number of rural operators and doctors reported their dissatisfaction regarding the use of Skype for tele-consultation. To better evaluate their issues and concerns, a structured survey was conducted among the operators and the doctors, by asking a set of questions relevant to their experience with Skype. 16 operators and 5 doctors, who are currently involved with the present telemedicine operation of DUTP and regularly use Skype, participated. The common concerns and opinions collected from the survey are briefly discussed below:

- 11 operators reported that a Skype conversation between a doctor and a patient usually lasts for 3 to 6 minutes during a tele-consultation. 4 doctors reported the same. 4 operators mentioned that it usually lasts for 6 to 10 minutes and one operator and one doctor reported that the consultation time usually lasts from 10 to 15 minutes.

- 13 telemedicine operators reported that they often experienced issues with both audio and video quality of the tele-consultation over Skype while the other 3 reported of experiencing intermittent call drops during Skype conversations. On the other hand, 3 out of 5 doctors reported that they could not hear the audio sound properly. Two doctors reported that they experienced issues with both audio and video call quality of Skype.

- All the participants agreed to the fact that it would be better if they could initiate the voice and video communication from within TMS user-interface instead of using a separately installed communication software.

In addition, it is worth to mention that relying solely on a third-party voice and video communication service may raise issues if the service experiences a region-specific restriction. The DUTP had to endure one such incident when the government imposed a nation-wide restriction over the use of Skype in Bangladesh for few weeks. Telemedicine operators living in rural areas are most likely to use internet package of limited bandwidth that are offered by different mobile operators of the country. Therefore, it is also crucial to keep the data consumption for multimedia communication at a minimum level. Services like Skype are highly optimized for operating even in a low-bandwidth environment. Therefore, if it is possible to develop and integrate a real-time multimedia communication tool that consumes less or almost same amount of bandwidth as Skype does, it would be considered as a viable alternative for the former service. In addition to that, an integrated, web-based solution capable to host doctor-patient consultation even in a low-bandwidth network environment would be desired for greater efficiency and improved user experience for the users of a rural telemedicine service.

6.4 Present Work: Integrated Real-Time Multimedia Communication User-Interface

To address the issues and concerns discussed in the previous section, a web-based prototype for real-time voice and video communication was developed. The prototype was developed on top of a WebRTC-based open source framework, "EasyRTC". The prototype allows to initiate real-time communication from the web browser directly and do not require any other plugin or software to be installed in the computer.

A comparative analysis was performed between Skype and the developed prototype to observe the bandwidth consumption and the minimum speed requirements for each of the solutions. Following are the discussions of the experiment details

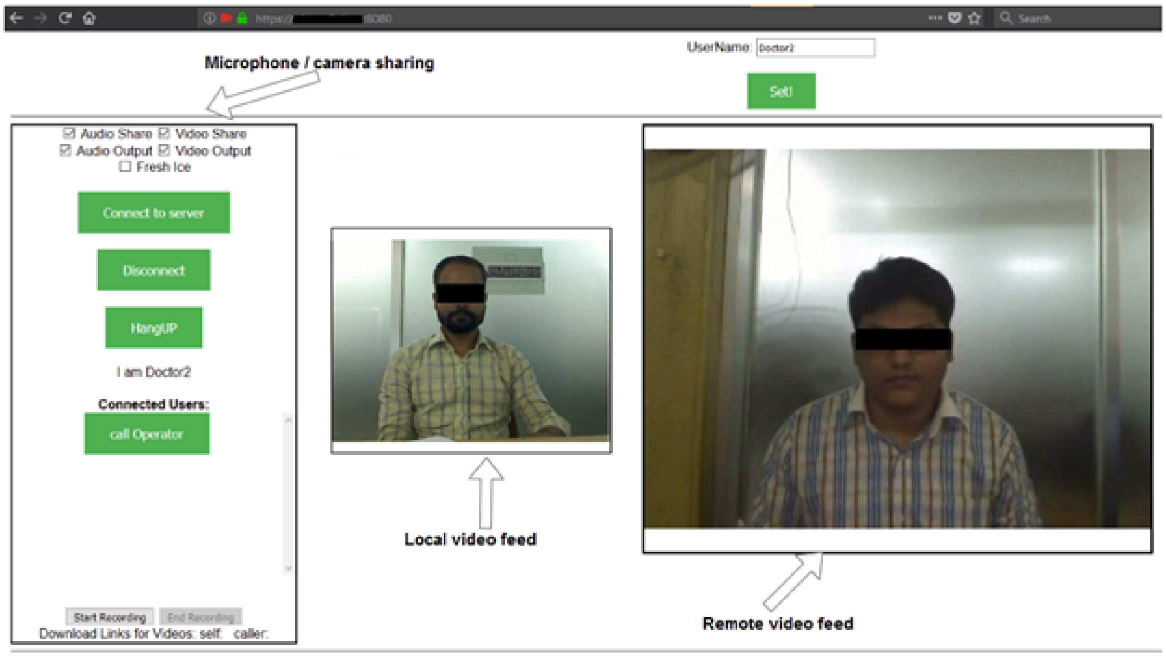


Fig. 6.3 Web-based real-time multimedia communication user-interface integrated into the TMS

including results and observation.

Experimental Setup

Below are the experimental setup constraints specific to the experiment carried out between Skype and the developed prototype.

Client Computers:

- **Webcam:** Logitech webcam pro 9000 v-u0009 on both computers.
- **Computer:** A Windows-based desktop computer to act as the operator's computer and a laptop for the doctor's side. The operator side had Processor: Intel Core i7-7400 CPU @ 3.0 GHz, Memory: 8192 MB and OS: Windows 10 Education Edition 64bit. The doctor side had processor: Intel Core i5 @ 2.53 GHz, Memory: 3 GB and OS: Windows 7 Professional
- **Internet Connection**: : A 4 Mbps broadband connection at the doctor's computer and a 3G mobile internet connection at the operator's end.

- **Web Browser:** Google Chrome version 66.0+ at both ends were used for conducting the experimental multimedia call using the developed prototype.
- **Speed Control:** : Net Limiter version 4 was used to limit the speed in each of the computers to a predefined speed category in order to simulate the internet connection environment of the operator and the doctor′s end respectively.

Server Environment For the Developed Prototype:

The server environment for the developed WebRTC-based multimedia communication prototype are mentioned below:

- **Host server:** Ubuntu 14.04 with 4GB memory was deployed in a commercial grade cloud server with 40 Gbps Network Input and 1000 Mbps Network Output connection. The scripts of the developed tool were hosted in this server.
- **STUN Server:** RFC 5766 STUN server was deployed in the above mentioned host server. All the communication via the STUN server was performed through UDP port.
- **TURN Server:** RFC 5766 TURN server was deployed in the above mentioned host server and was used for relaying voice and video stream in case of the STUN server failing to resolve the network address of the caller and the called. All the communication to the TURN server was performed through UDP port.

Experiment Constraints:

Below are the experiment constraints for the WebRTC-based developed prototype. On the other hand, skype does not allow any modifications on its audio or video transmission configuration, hence was used as it is for this experiment.

- **Video resolutions :** For the current experiment, video resolutions for the video transmission through the developed prototype was set to 640 X 480 and 320 X 240 respectively in two different set of experiments.

- **Video frame rates:** For the current experiment, varying video framerates were used for different speed categories. Those were mentioned accordingly in the discussion of the relevant experiment results.

- **Audio bitrate:** No constraints were applied on the bitrate of the voice sound transmitted through the developed prototype.

Experiment Procedure:

The experimental environment was set up in such a way that it simulates the real-life application scenario of voice and video consultation over the internet between a doctor living in the urban areas and a patient sitting in a rural telemedicine centre. A desktop computer was set up with appropriate tools and configurations mentioned above, which acted as the workstation of a rural telemedicine operator and a laptop computer for a doctor located in the urban areas. Skype is a third-party closed source application offering free multimedia conference service and does not allow controlling or applying any of the constraints i.e. audio bitrate, video resolution, video frame rate etc. to its service. So, to compare between skype and the developed prototype, bandwidth consumption during a multimedia call for a certain period of time were adopted as the quantitative measures for comparison. Netlimiter4 was used to calculate the amount of bandwidth data consumed during a multimedia call in Skype. On the other hand, data consumption of the WebRTC-based prototype were calculated from the WebRTC dump file generated during each of the calls. For experiments involving audio-only communications that were carried out at 64Kbps and 92 Kbps, a qualitative approach was followed to determine the minimum connection speed required for holding a decent audio-only communication via the developed prototype. Once connected to an audio call, the caller, acting as a telemedicine operator read aloud the digits counting from 1 to 100 while the receiver took note of how many digits he couldn't hear. Experiments were performed 5 times for both of the speed category. For multimedia communication experiments involving both audio and video, every call performed in either Skype or in the developed prototype was recorded for five minutes feeding same audio and video input from both the operator and the doctor's computer. Two computers were set up side by side and webcams of both the computers were placed closely one above another so that each of the cameras captures the same video feed as identical as possible. The background of the place captured in webcams was kept identical for all the calls to minimize the video input data variation for each calls. Excerpt from a book were read aloud in front of the microphones for five minutes in a calm and quiet room to make sure the audio input remains same for all experiments. Moreover, data were collected five times from five consecutive calls for all the internet speed categories. The average of the five data for each internet speed category were then calculated and taken into consideration for the comparison.

6.5 Results and Observations

The experiment results and observations classified by the relevant speed category are discussed below. Two speed categories, 64Kbps and 96Kbps, were primarily considered for the experiment of determining of audio-only conversation quality of the WebRTC-based call.

6.5.1 Audio-Only Communication Experiment

64 Kbps:

At this speed category, audio-only communication was carried out five times to see if audio conversation with consistent voice quality can be maintained at a speed as low as 64 Kbps. The audio data transmitted via the WebRTC-based tool seemed to suffer significantly and the listener could not hear a number of digits ranging from 30 to 50 digits during the 5 experiments carried out for this speed category. Hence, it was decided that audio quality at 64 Kbps was not enough to rely on for clinical tele-consultation.

96 Kbps:

At 96 Kbps, audio transmission via the developed prototype worked significantly better and no jittering or loss of communication were observed during the experimental calls performed via the developed communication tool. The listener could hear all the digits from 1 to 100 except missing a few (1 to 5 digits) in two occasions.

6.5.2 Audio and Video Communication Experiments

128 Kbps:

At 128 Kbps, the WebRTC-based tool was configured to transmit video at 10 frames per second with a resolution of 320X240. At this speed category, all five consecutive calls made from either Skype or the WebRTC-based tool, performed poorly. Voice and video quality were found to be very low and video frames were freezing quite frequently with high amount of jittering. Therefore, at 128Kbps, both the tools were found to be unsuitable for conducting doctor-patient consultation in a rural telemedicine service.

256 Kbps:

At 256 Kbps, the WebRTC-based tool was initially configured to transmit video at 15 frames per second with a resolution of 640X480. Adopting this configuration, the WebRTC tool consumed around 12.43 MB of bandwidth for uploads and downloads combined, which was 4.6 MB more compared to the average upload and download bandwidth consumed by Skype calls. Therefore, the bandwidth data consumption was found to be significantly greater with the developed prototype . Hence, another five set of data were collected for WebRTC calls at an even lower resolution (320X240 pixels) with 10 FPS. This time, data consumption during WebRTC calls were found to be reduced significantly, than the amount it consumed with the initial configuration. The amount of data consumed were almost similar to those of Skype. Figure 6.3 shows the comparison between the amounts of data uploaded and downloaded during calls in two different set of configurations of WebRTC at 256 Kbps. The two columns at the right side of the graph denote the average FPS for two different constraints adopted for the experiments respectively.

Figure 6.4 shows the comparison between WebRTC and Skype calls in regards to uploaded and downloaded data transmission during voice and video calls. Average

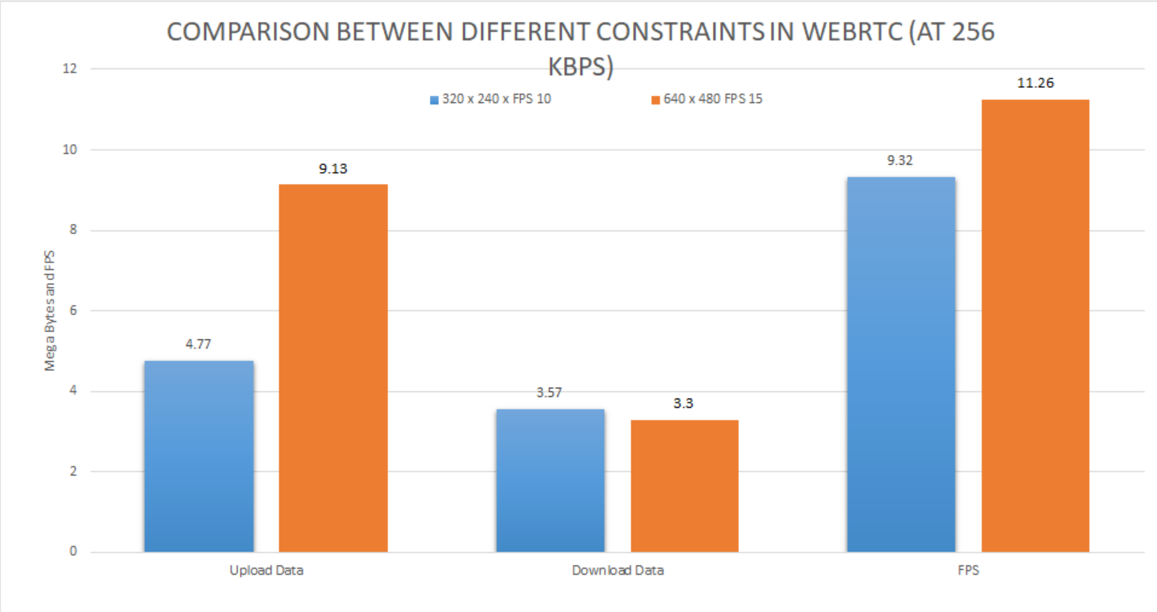


Fig. 6.4 Comparison of bandwidth consumption for WebRTC-based real-time multimedia communication tool adopting two different set of constraints at 256 Kbps

data consumption for five calls by WebRTC was around 8.34 MB while Skype consumed 7.83 MB at 256 Kbps.

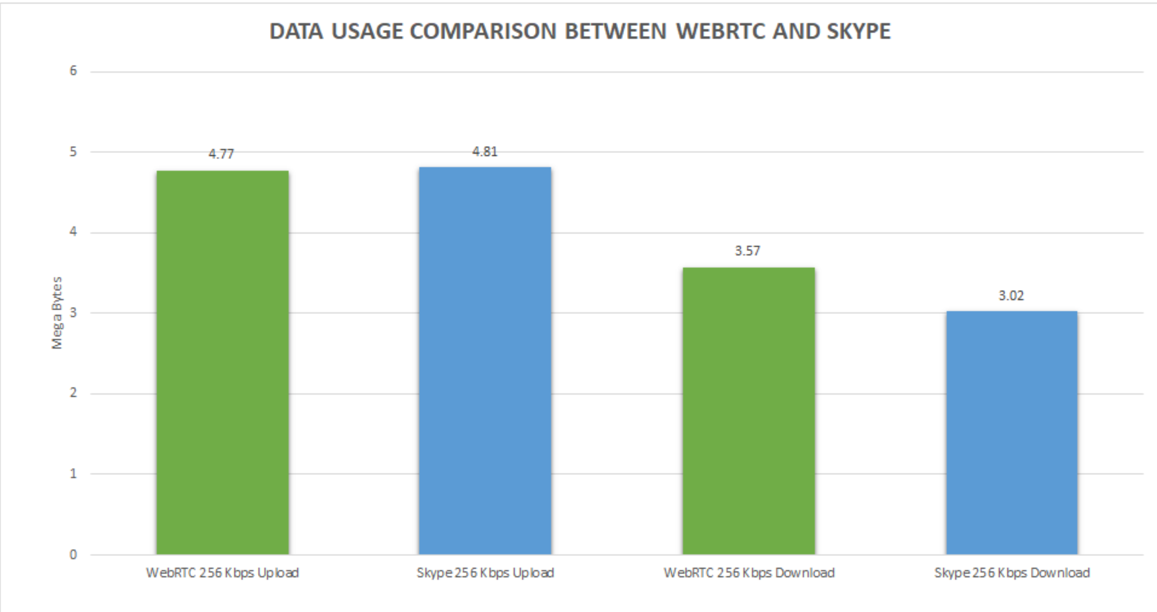


Fig. 6.5 Comparison of bandwidth data consumption between Skype and WebRTC-based real-time multimedia communication tool at 256 Kbps

At this speed category, calls placed through WebRTC performed fairly well with an average of 9.32 FPS. The clarity of voice sound and quality of video feed were found to be sufficient for teleconsultation at this speed category. There were some jitters observed intermittently during both video and audio transmission but most of the times it was limited to negligible interruptions. Therefore, at this speed category of 256 Kbps, the developed WebRTC-based tool performed well enough to consider it for teleconsultation.

384 Kbps:

At 384 Kbps, Skype performed significantly better than the WebRTC-based tool, especially in uploading data during the multimedia transmission. The average bandwidth consumption by Skype for data uploads was 5.29 MB, which was 1.86 MB less than that of the developed tool. However, in case of data downloads bandwidth consumption for Skype and WebRTC was almost same, 5.04 MB and 5.01 MB respectively. Figure 6.5 shows the comparison between bandwidth consumptions for two different set of WebRTC constraints (320X240 resolution at 10 FPS and 640 X 480 resolution at 10 FPS).

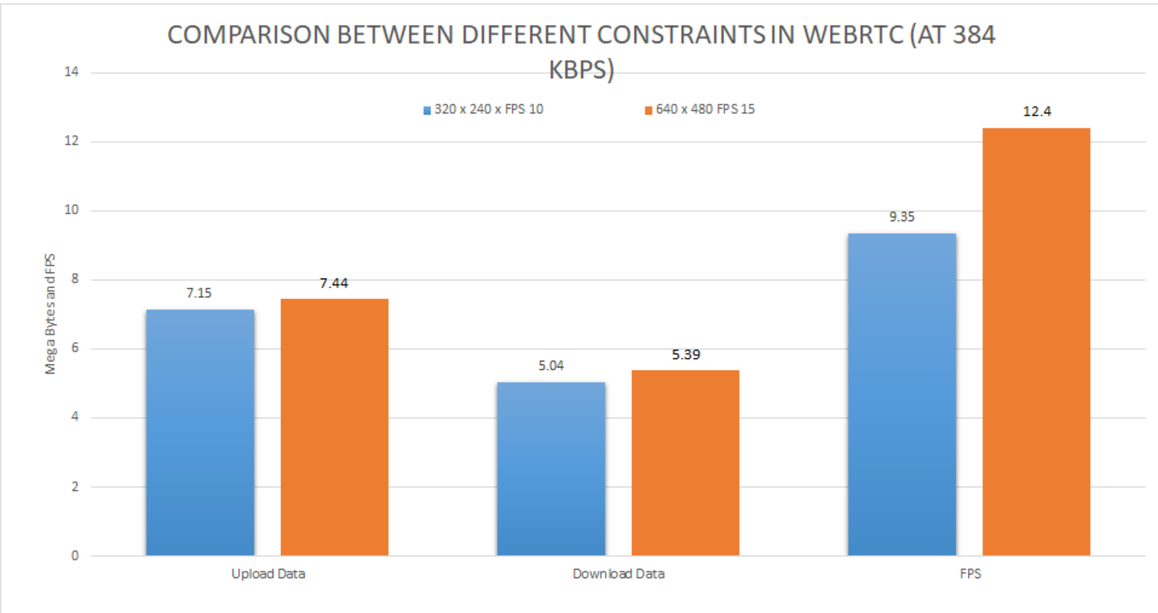


Fig. 6.6 Comparison of bandwidth consumption with two different sets of constraints in WebRTC-based real-time multimedia communication tool at 384 Kbps.

Figure 6.6 compares the bandwidth consumption between Skype and the developed tool at a resolution of 320X240 pixel with a frame rate of 10 FPS.

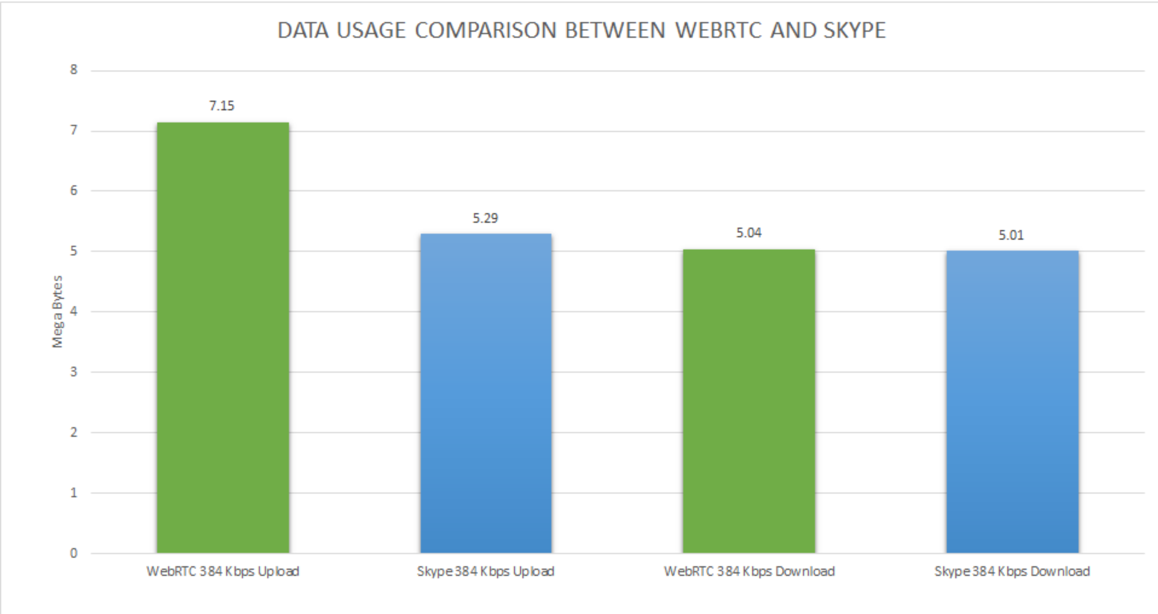


Fig. 6.7 Comparison of bandwidth data consumption between Skype and WebRTC-based real-time multimedia communication tool at 384 Kbps

512 Kbps:

While experimenting with this speed category, no constraints were applied to WebRTC in order to observe how WebRTC performs with default settings. At 512 Kbps, both Skype and the developed tool performed fairly similar in terms of data consumption, 15.38 MB and 15.73MB respectively. It was observed that Skype consumed more data in uploading than that of WebRTC-based tool while the bandwidth consumption for downloads was 2.63 MB less compared to the download data consumed by the developed tool. At this speed category, both Skype and the developed tool maintained fairly better quality with no visible jitters or interruption during the audio and video data transmission.

6.6 Conclusion

Skype is a highly optimized multimedia communication service that scales gracefully in slower connection speeds. It is difficult to match the optimized quality of Skype in varying speeds considering the efforts and resources invested in implementing the service. However, the WebRTC-based communication interface developed as a part of this present work performed fairly well and the bandwidth

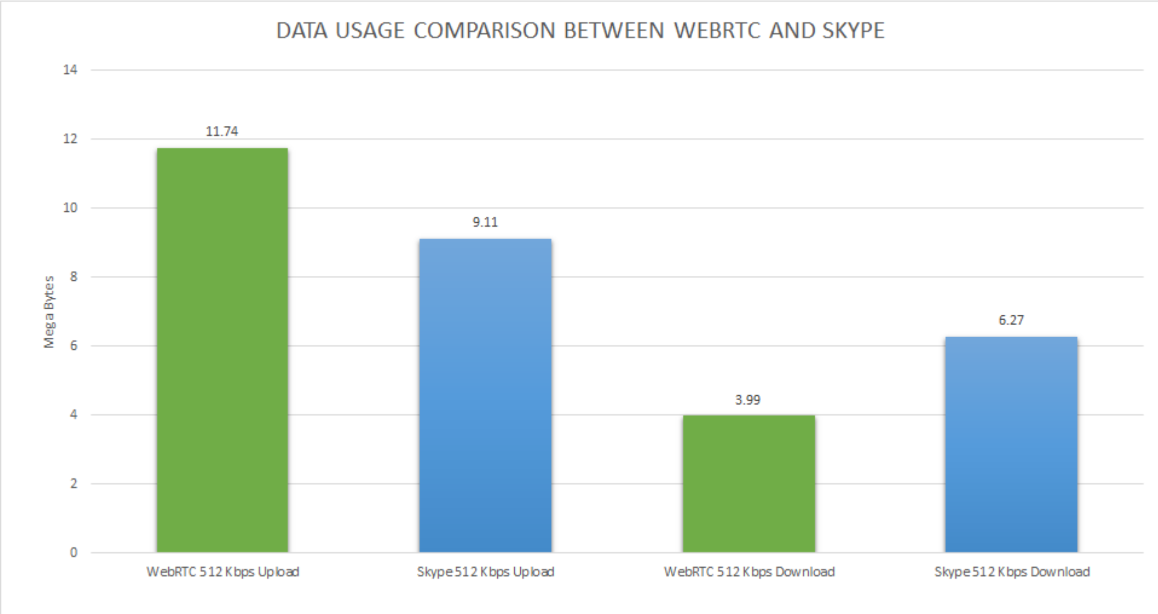


Fig. 6.8 Comparison of bandwidth data consumption between Skype and WebRTC-based real-time multimedia communication tool at 512 Kbps

consumption was more or less similar to the amount consumed by Skype in most of the cases. But the main advantage the interface offers compared to Skype was that it could easily be integrated within the Web-based Telemedicine Management System discussed earlier in chapter 4, which would be a big leap towards developing a more user-friendly software system having all the necessary requirements translated and integrated into one single platform. WebRTC is revolutionizing the way we communicate over internet and it can be effectively used to develop self-managed multimedia telemedicine consultation platform too.

Chapter 7

Implementation

7.1 Introduction

It has been mentioned earlier, that the telemedicine system implemented by the Department of Biomedical Physics and Technology in its trial phase between 2013 and 2015 used a software developed by Khan [23], in which the present author also contributed. Based on this experience, the present author completely redesigned the system and developed the initial form of the software that was implemented under the Dhaka University Telemedicine Programme in November 2015.

The feedback received from the users of the programme that was running concurrently with the present work for last two and half years since November 2015, were the guides for further improvement of the system software. This also influenced the addition of capabilities, requirements of which arose as the implementation continued. Working closely with the implementation group, this software has taken a shape, which appears to have assumed a considerable height in quality and functionality for a telemedicine system that actually works as intended in low resource settings prevalent in developing countries like Bangladesh. This chapter discusses the implementation process.

In the final section of this chapter, results of a qualitative assessment are discussed that were conducted among the user groups of the DUTP to evaluate the Telemedicine Management System (TMS) as earlier discussed in chapter 4. Certainly, the whole service depends on a number of factors such as the delivery model, management, doctor's quality, patient satisfaction and many more. However, TMS, or the software is a major part of the overall system. Therefore, a successful result also relates to the success of the software developed and also presented in this thesis.

7.2 Background

One factor that makes the present work significant is that the outcome of the research carried out within the scope of this research, was directly being implemented on the field level for "Dhaka University Telemedicine Programme" (DUTP), an ongoing telemedicine project run by BMPT. The research group at BMPT started working on designing and developing a telemedicine service for the unreached population living in remote areas of Bangladesh in 2011. Two research groups of BMPT, specialized in hardware and software development, were closely working together to materialize a full-fledged telemedicine system. The aim was to address all the requirements and challenges to operate a sustainable remote healthcare service model in low resource settings typically observed in developing countries like Bangladesh. After a couple of years of research, a working prototype of the telemedicine system including a few online diagnostic devices were developed. The system was taken to the field and went for its first field trial in June 2013. This field trial went on for two years with the on-field support from a local NGO, Sadharan Manusher Majhe (SAMAMA). There were five rural telemedicine centres spread across Faridpur and Madaripur Upazila in Bangladesh and a total of 1576 patient consultations were provided using the telemedicine platform developed by BMPT. Together with another researcher, the author of the present work was involved in the development of the necessary software for computer interface of diagnostic devices such as Digital ECG, designed and developed locally by BMPT and the telemedicine software system being used in the trial period of the project. The invaluable knowledge and experiences gathered from this involvement relevant to telemedicine service delivery and the overall working system environment of the project helped the whole telemedicine team at BMPT in improving and reshaping the mode of delivery and the requirements to make a sustainable telemedicine delivery model. Towards the end of 2015 the BMPT team took up the full R&D and implementation in their own hands. The author also worked as an active member of the team and had to undertake the responsibility of developing the system software, which is also presented here in this thesis.

As the implementation continued, the decisions taken at the organisational level also affected the telemedicine system requirements, resulting in requirements to changes to software functionalities of the system as well. Summarizing the experiences of the two year-long field trial, it was soon realised that a holistic approach to designing and developing the web-based telemedicine system addressing local needs and existing constraints of the system environment is critical to the overall success of the programme. The web-based system deployed and used in the trial run of the programme was elementary and with limitations of different magnitudes as discussed briefly in chapter 2 while describing the preliminary initiatives of DUTP. Therefore, a decision was made to re-design and re-develop a web-based telemedicine system from the scratch taking into account the lessons learnt from the field trial. This is where the present work took over the responsibilities of designing, developing and finally implementing a web-based telemedicine system suited for the local needs considering the socio-technical context of the rural Bangladesh.

The present work began with developing a prototype adopting the workflow of BMPT telemedicine programme. The understanding and insights attained from the prior association with the field trial developing the first version of telemedicine system formed the foundation of the present work. However, the new prototype was developed from scratch, adopting the latest technology and tools of the web development. The initial prototype was developed within a couple of months, which went operational on the field level as soon as the Dhaka University Telemedicine Programme resumed its operation in November 2015.

Since the first deployment of the present work, a user-centric development approach was followed that helped resolving the current issues at hand. It also helped in translating the requirements that surfaced as the operations continued into relevant functionalities.

The strategies in different parts and stages of the present work varied slightly from one to another based on many different conditions. Variables like involvement of multiple parties, time constraints, various social, cultural, behavioral and organisational aspects etc. as discussed in chapter three influenced the possibilities to pick the appropriate direction and methodology.

In addition, the scope of engagement in the present work wasn't confined within the software development only, rather the level of involvement went beyond the mere development of the telemedicine solution. For instance, the involvement extended to responsibilities ranging from attending phone calls from rural telemedicine operators reporting various issues regarding the developed system to training the new batch of operators on how to use the developed system effectively and efficiently. Countless hours were invested in developing and nurturing collaborative relationships with the system users to develop and implement a suitable solution. A wide range of activities took place throughout the life span of the present work including Focus Group Discussion, interviews with key stakeholders, bi-annual round table discussion with the rural operators, doctors and system administrators, etc., that acted as the major sources of information and feedback collection for developing the final solution. Active involvement in every stages of "development to deployment" cycle offered a unique opportunity to understand the real needs of the system users first-hand and act accordingly that resulted in to the development of a user-friendly telemedicine system with high usability and efficiency.

7.3 Evaluation of the Service Given by Dhaka University Telemedicine Programme

Starting with 5 rural telemedicine centres the outcome of the present work has been successfully integrated into many centres operating under the Dhaka University Telemedicine Programme. This is being used at present as the core platform for connecting the rural people at these centres in Bangladesh to deliver better primary and secondary healthcare for more than two and half years. As of June 1, 2018, there are 31 telemedicine centres and more to join in the near future. The software has the ability to cover thousands of centres. The data and a number of charts reported in the following sections were directly generated using the user-friendly analytics tool developed for the TMS as a part of this present work.

7.3.1 Yearly Patient Visits Statistics of DUTP

The table below (Table 7.1) shows the yearly reports of patients served under the telemedicine service provided by Dhaka University Telemedicine Programme.

Year	Months in operation	Active centres	Total patients served	Average monthly patients
2015	2	7	219	109
2016	12	19	3512	293
2017	12	31	4665	389
2018	5 (till June)	37	3058	611
Total patients served till			11,454	

Table 7.1 Yearly reports of patients served by DUTP from November,2015 to June 1, 2018

7.3.2 Average monthly patients of DUTP

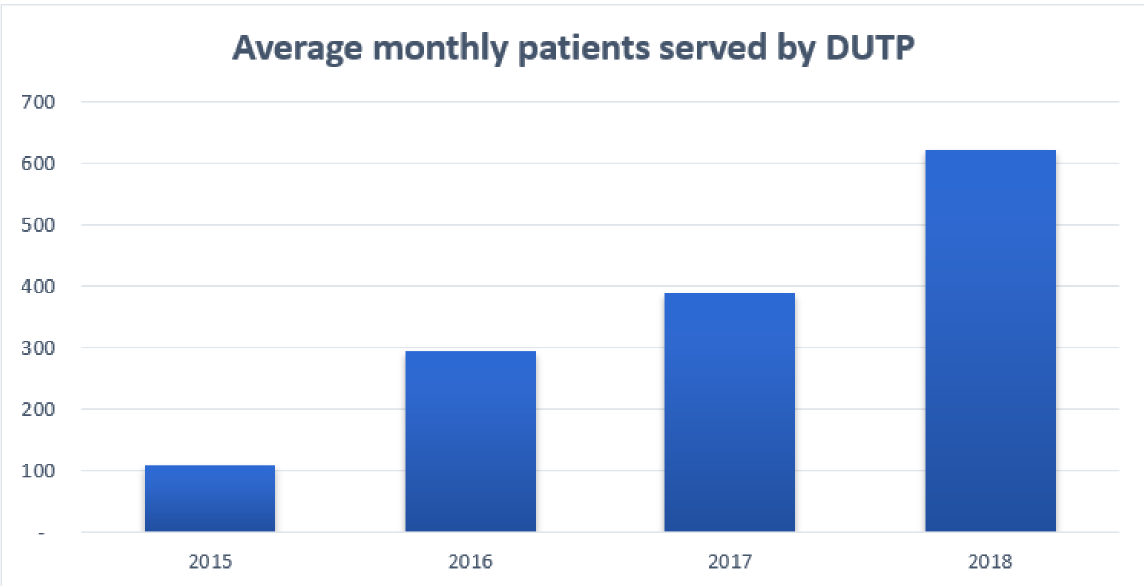


Fig. 7.1 Average monthly patients served through the telemedicine programme provided by DUTP

The figure 7.1 shows the growth rate of patients coming to different rural telemedicine centres of DUTP. In 2015 the average monthly patient visits were 109 in five telemedicine centres. Within less than three years the average patient visits reached to an average of 611 monthly patient visits in thirty-one centres.

7.3.3 Repeating patients

The data visualization tool developed as part of the present work shows that 13% patients have come to rural telemedicine centres twice or more to receive the telemedicine service of DUTP. Fig 7.2 shows the distribution of patients visiting one time and patients who visited twice or multiple times in different rural centres for medical treatment since DUTP started its operation in November 2015. This analysis is useful for the administration to assess if the service is gaining confidence among the patients.

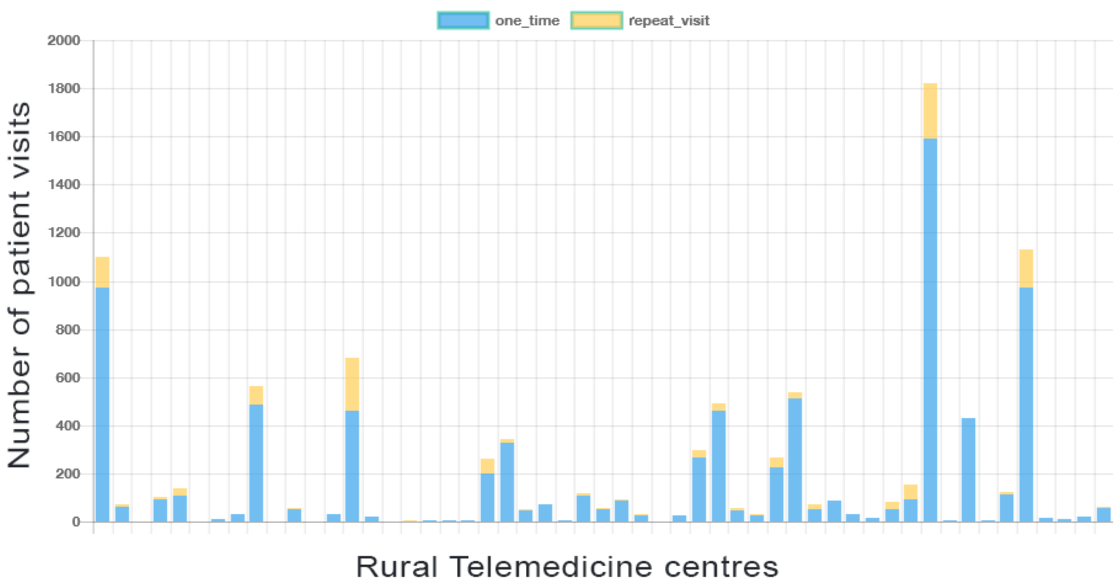


Fig. 7.2 Number of patients coming to different rural telemedicine centres of DUTP

7.3.4 Frequency of patient visits in different times of the day

The visit time frequency visualization tool developed as part the present work shows that rural people came to different telemedicine centres of DUTP during 11AM to 12 PM for most of the times (1926 visits). 10AM to 11PM is the second busiest hours with 1676 patients visiting during this time of the day. The frequency of patient visit decreases gradually after the peak hour of 11AM to 12PM and comes to a low in the noon during 2PM to 3PM. The frequency of visit increases gradually again with 4 PM to 5 PM becoming the busiest hour in the afternoon (1334 visits).

There is another interesting fact we observed from the visit frequency chart shown in figure 7.3 is that a number of people came to consult doctors deep into the night, even at 11pm or 12am. Due to the flexibility of working from home or any place in the model adopted by DUTP, doctors have been able to see patients even at these difficult hours.

Fig. 7.3 patients' visit time to different rural telemedicine centres of DUTP

The developed tool also helped the DUTP administrators to allocate the doctors' time more efficiently based on the frequency of visits of patients during different times of the day.

7.3.5 Average Time To Completion (TTC) for Patient Visits

Figure 7.4 shows the monthly average Time To Completion (TTC) for a single visit from November 2015 to May, 2018. A single patient visit cycle starts from submitting a visit consultaion request by a telemedicine operator to a doctor responding to the request submitting the prescription once done talking to the patient and analysing the received primary vitals and health information from the operator′s end. The time to completion has been calculated by the time difference between submission of visit request by telemedicine operators to submission of prescriptions by doctors responding to visit requests. The graph shows that more or less a steady TTC was maintained since the beginning of DUTP operating on the field. The TTC remained within 13 to 16 minutes for most of the lifespan of the project except observing a high of 22 minutes in the beginning month and a minimum of 10 minutes in the third month of its operation. It can easily be visualised that in the beginning people need to adopt to any system which caused this high or low values.

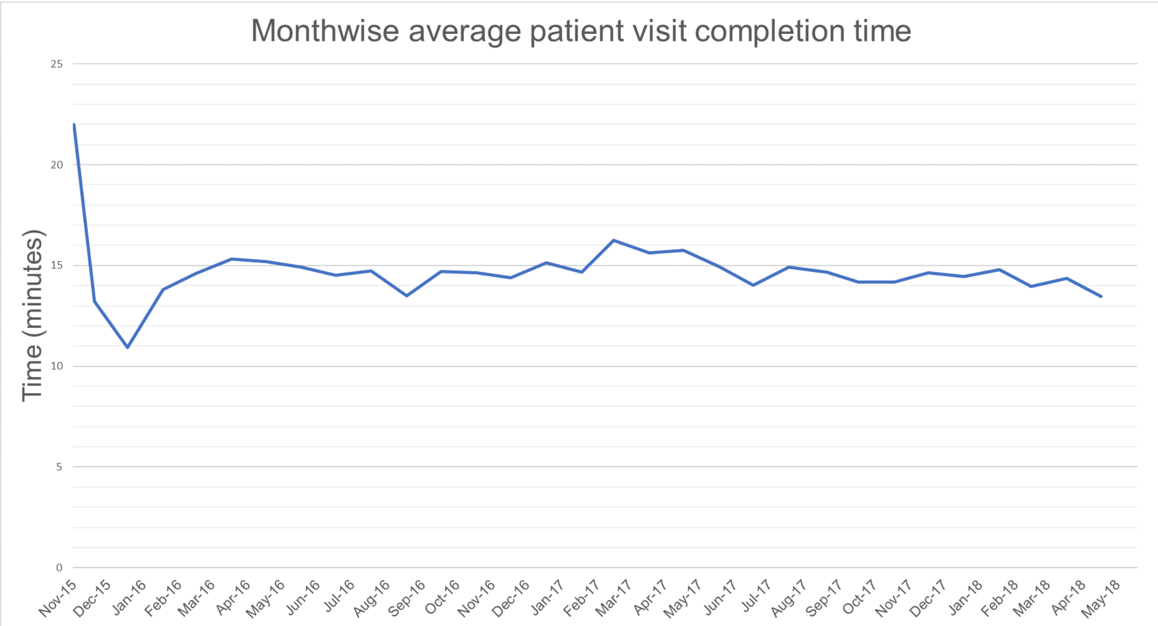


Fig. 7.4 A month wise representation of average Time to Completion (TTC) for patient visits

7.4 Users' Assessment of the System

To evaluate the developed Telemedicine Management System (TMS) described in chapter 4, which is currently deployed to deliver telemedicine service run by BMPT, a qualitative assessment among the key user groups of the system, Telemedicine Operator, Doctor and System Administrator, were conducted. This assessment used a set of questionnaires regarding slow internet connectivity, time required to perform the prime tasks and user friendliness in using the system. Total sixteen telemedicine operators, five doctors and two project administrators of Dhaka University Telemedicine Programme (DUTP) participated in the assessment survey. Users involved with the DUTP having experience of using the TMS at least for one month were considered eligible for the survey conducted. The results of the survey are briefly described with visual charts below:

7.4.1 Telemedicine Operators (16 participants)

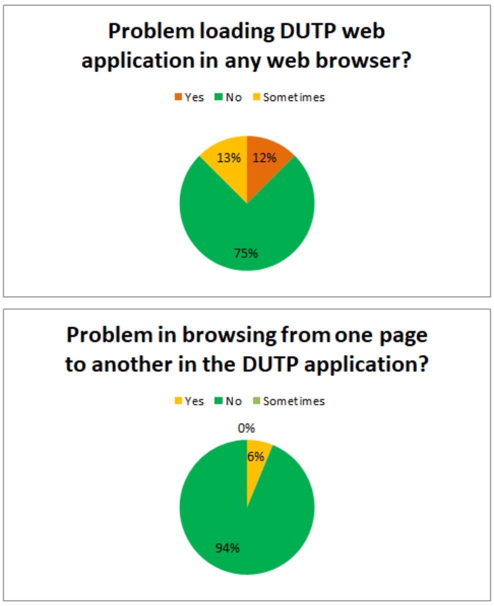


Fig. 7.5 Telemedicine Operators' assessment of the TMS regarding slow internet connectivity

Among 16 telemedicine operators, 15 reported that they use mobile internet and one operator uses a broadband connection. The internet speed varies from 50 kbps to 1.5 Mbps, according to the speed test tool (http://speedof.me) they were provided to check their own internet connection. Questions were asked to find out whether they experienced any issue loading the TMS application in slow connection.

As shown in figure 7.5, 12 out of 16 operators said that they don't face any issue loading the TMS web application in any web browser while accessing from their current internet connection. Two operators said sometimes and another two said they experienced issues loading the application using their current internet connection.

Answering the question of whether they faced any problem browsing from one webpage to another within the application, 15 out of 16 operators responded that they did not.

As shown in figure 7.6, 14 operators reported that they take around 3 to 5 minutes to register a new patient while 1 operator said 5 to 10 minutes and the other operator said 10 to 15 minutes.

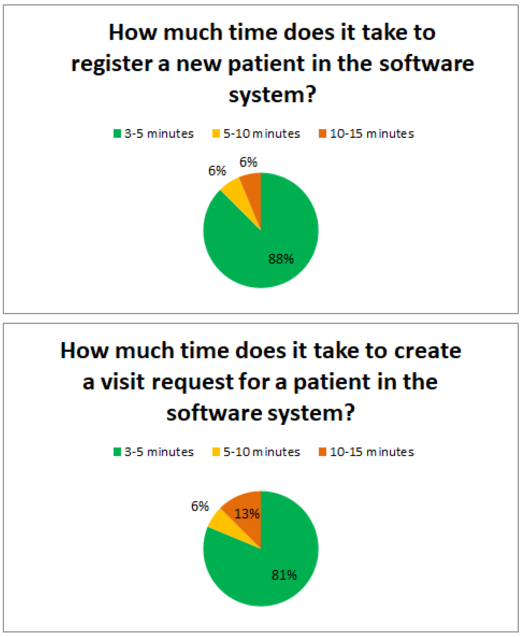


Fig. 7.6 Telemedicine operators' assessment on the time required to register or create visit request for a patient

In case of creating a new visit request for a patient, 13 operators said they require 3 to 5 minutes to fill up and send a visit request to a doctor. On the other hand, 2 operators said they usually need 10 to 15 minutes and one operator said about 5 to 10 minutes.

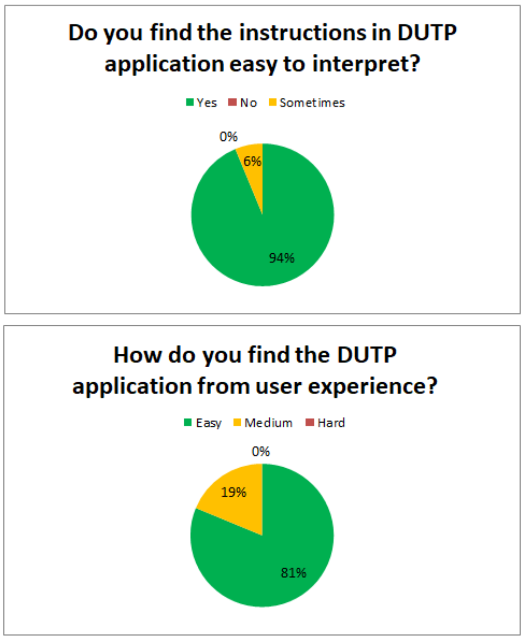


Fig. 7.7 Telemedicine operators' assessment on user-friendliness of the TMS

As shown in figure 7.7, among 16 operators 15 of them said that they found the instructions of the TMS useful and easy to interpret while 1 operator said sometimes he found it difficult to follow the instructions.

13 operators said that they found the TMS application easy to use and interact to perform their task while delivering telemedicine service to patients, whereas 3 operators said that interacting with the TMS application is moderately easy.

7.4.2 Doctors (5 Participants)

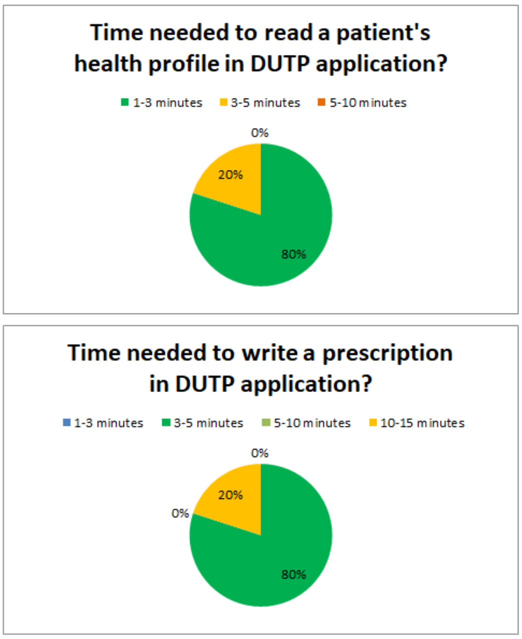


Fig. 7.8 Doctors' response on time required to reading a patient's health profile and writing prescription

As shown in figure 7.8, 4 out of 5 doctors reported that they usually require 1 to 3 minutes to read a patient's health profile while the other doctor said he/she requires about 3 to 5 minutes.

4 doctors said they usually take 3 to 5 minutes writing a prescription while the other doctor said about 10 to 15 minutes.

As shown in figure 7.9, 4 doctors said that they found the instructions of the doctor panel easy to interpret and follow while the other doctor said he/she sometimes experienced difficulties interpreting the instructions given within the doctor panel user interface.

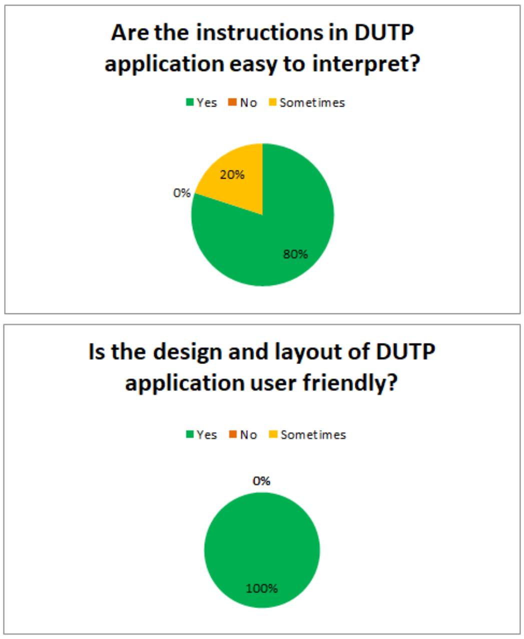


Fig. 7.9 Doctors' assessment on the usefulness and user-friendliness of the TMS

5 out of 5 doctors reported that they found it easy to use and interact with the doctor panel that they access within the TMS.

7.4.3 Telemedicine Administrators (2 Participants)

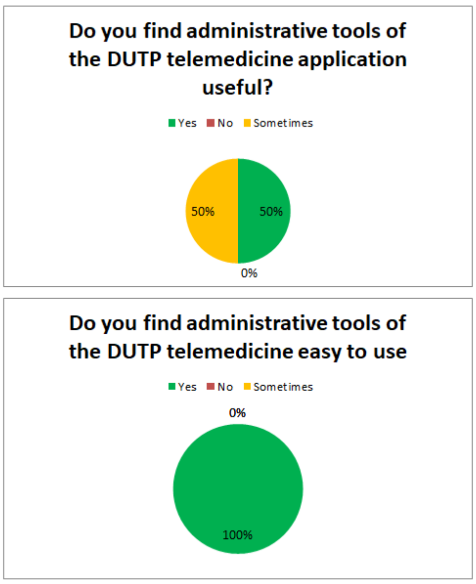


Fig. 7.10 Telemedicine administrators' assessment on the usefulness of the administrative tools incorporated into the TMS

As shown in figure 7.10, one of the two administrators found the administrative tools developed for helping in various administrative tasks useful while the other said he found those useful sometimes. In addition, both of the administrators found the administrative tools easy to use.

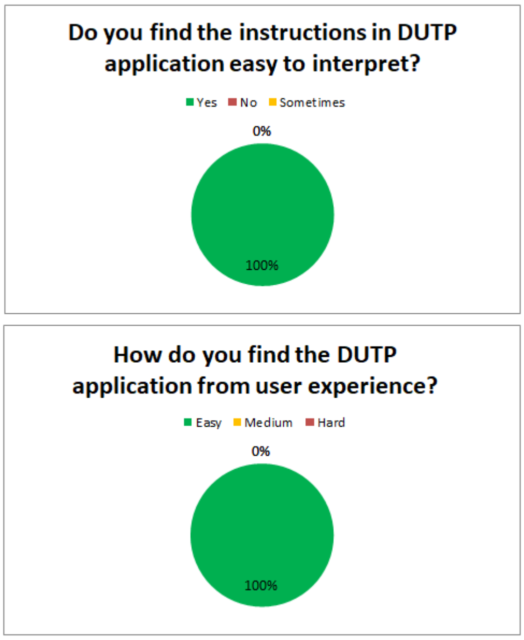


Fig. 7.11 Telemedicine administrators' assessment on user-friendliness of the administrator dashboard incorporated into the TMS

As shown in figure 7.11, both of the administrators reported that they found the instructions used throughout the TMS application useful. Both of the administrators also expressed their satisfaction in regards to overall user experience as a user of the developed TMS application. Both of them reported that, they found the application easy to use.

7.4.4 Remarks:

The survey results reported above clearly indicates that the developed TMS application was found to be useful and easy to use for most of the users of the system.

Most of the telemedicine operators could use the system for registering patients and sending visit request to doctors within very minimal time. Besides, they could access the application even from low bandwidth network without facing any major issues. Their overall satisfaction in using the system also reflected on their responses to how convenient they found the system to be useful with easy-to-follow instructions throughout the workflow of the system.

Doctors also found the design and layout of the doctor panel with assistive features concise and simple to interact with. It helped them to view patients' health profile conveniently and write prescription faster.

Since the existing TMS still uses Skype and Audacity – two third-party software, this possibly caused some reduced satisfaction among doctors. Once the Stethoscope, ECG and the video conferencing starts using the integrated software developed in the present work, this satisfaction score will hopefully increase.

System administrators also expressed their satisfaction in managing the telemedicine programme through using the developed web application. Like other two user groups of the system, they also reported that the TMS application helped them oversee the programme efficiently.

7.5 Conclusion

This chapter discussed the implementation aspects of the present work and reported about Dhaka University Telemedicine Programme that is currently operational in thirty-one rural unions/villages spread all around Bangladesh using the system developed as the outcome of this research. This chapter also reported the results of a qualitative assessment that were conducted among 16 rural telemedicine operators, 5 doctors and 2 telemedicine administrators of DUTP to assess the usability and efficiency of the developed system in regards to operating in low resource settings.

The feedback suggests that the TMS developed in the present work is highly successful in achieving its prime target, and makes the effort worthwhile.

Chapter 8

Discussion

We are living in a time when the world is getting smaller and more accessible to everyone with the help of continuously advancing Information and Communication Technology. Despite this fact, more than half of the world population still do not have access to elementary living requirements like essential healthcare. Developing countries like Bangladesh suffer the most due to the dearth of proper health services, especially in distant rural areas where majority of the population reside. These people remain out of the healthcare coverage for a number of reasons, and the shortage of skilled physicians is the most pivotal of those reasons. In a technology-driven era, ICT-based innovation like telemedicine can be a viable solution to address the shortage of doctors in needy areas to provide healthcare services for the unreached communities. However, developing countries, including Bangladesh, are yet to adopt this promising technology to its full potential due to lack of awareness and introduction to proper telemedicine service addressing the local context and requirements. A number of initiatives were taken since the inauguration of the first one by CRP in 1999, but only a few could sustain in the end. In addition, considering the scope and potential to alleviate the current crisis of physicians, the country needs more likewise initiatives. Hence comes the necessity of a sustainable delivery model and appropriate technology solution to instantiate them on-field. Absence of proper telemedicine research was strongly felt during all these years that are necessary to fill the voids unattended by existing telemedicine delivery models of Bangladesh. Most of the telemedicine researches that are conducted in the developed countries are used to resolve their national needs which mostly revolve around the delivery of secondary and tertiary care. However, for developing countries like Bangladesh, the needs are different, hence, so are the research approaches. One needs to understand the social, cultural, economic and technical factors first, which are unique to developing countries' socio-technical environment. These understandings are crucial to the success and sustainability of a telemedicine service model in a developing country setting. A number of groups in the developed countries are conducting research to further telemedicine solutions for the Third World. However, less familiarity with the target environment and failure to realise these socio-technical factors eventually made those solutions futile. Many of these initiatives often include diagnostic devices that are primary developed targeting the application environment of the developed countries. As a result, these devices are very often deemed unsuitable for implementing in developing countries. The durability suffers greatly when they are imparted in an environment alien to these devices. And of course, the expense of the imported devices and solutions is also a major barrier to adopt the solution in large scale. As a result, many of these initiatives eventually fail to come up with a context-appropriate solution that is likely to sustain and be replicable in similar working environments typically observed in the developing countries.

On the other hand, research groups in the developing countries are mostly focusing on software-based telemedicine solutions due to lack of expertise in developing hardware for medical devices. As a result, they still need to rely on the foreign solutions for diagnostic devices that are necessary for delivering proper telemedicine service. Therefore, the concerns regarding the durability of the devices and sustainability of the telemedicine initiatives in general remains unattended, as stated above.

Therefore, there is an obvious demand for adopting a holistic approach to telemedicine system development, requiring expertise in both software and hardware design and development, and taking into account the socio-technical context of the application. The research group at BMPT has a unique combination of these two capabilities that gave them an edge to address the limitations of telemedicine research conducted in the specified context. Applying these skill-sets effectively, the group has materialized a solution, which demonstrated an impressive outcome during its first formal field-test. Again, BMPT themselves is deploying the technology using their own innovative model. This has been instrumental in getting a comprehensive effort involving technology development and dissemination. Several programmes in Bangladesh stopped because very few doctors were interested to participate. The BMPT model encapsulated flexibility and sparked a sense of motivation and self-esteem in everyone to do something for the betterment of the society. Hence, with a much smaller funding compared to other efforts, BMPT model has sustained a long time, to date.

The present work was initiated as a part of the comprehensive telemedicine research that BMPT started back in 2011. The first field-test of BMPT telemedicine system continued over a span of two years. After its completion in June 2015, the present work took the responsibility of developing an integrated technological solution for a rural telemedicine service reflecting the challenges and necessities realised from the experience of two years of field trial. The research group at BMPT believes in the philosophy of implementation-oriented research that would directly affect the lives of millions in regards to healthcare delivery. Therefore, the present work also adopted the same development methodology from the very beginning. Throughout the lifespan of the present work, requirements and necessities felt by the relevant stakeholders of the BMPT telemedicine project dominated the course of the research, and not the other way around.

The present work began with an extensive preliminary research to understand the application environment and pinpoint the needs of the relevant stakeholders from a socio-technical perspective. Involvement with similar initiatives taken earlier by BMPT helped the author realise the bigger picture of the application context and decide the next steps of the research that followed. After identifying and sorting out the requirements on a priority basis, a basic telemedicine system prototype was developed within a very short period with minimal functionalities required to start operating on the field immediately. On top of this prototype, a full-fledged telemedicine management system was developed, with gradual and evolutionary improvements, addressing the requirements coming from the on-field users on a day-to-day basis. The developed Telemedicine Management System is equipped with all the essential functionalities like clinical, organisational, etc. that are crucial to conduct an operational telemedicine service, especially for rural telemedicine delivery. The present work specifically addressed the slow internet connectivity issues prevalent in the rural areas and made the developed system compatible to work even in a low-bandwidth network.

The present work also includes the integration of clinical diagnostic devices like digital electronic stethoscope and 12-lead digital ECG machine. Mechanisms were developed to integrate these two clinically useful devices into the developed TMS, as discussed in chapter 4. The present work targeted acquisition of the digital data from both the devices, which is essentially interfacing to the computer, and then integrating the resulting signals into the TMS so that the signals may be stored and transferred over internet at will.

The present work also developed a prototype for web-based real-time communication. A WebRTC-based open source framework was used as a starting point of the development. Some experiments were carried out to test its adaptability with slow internet connectivity. A comparative analysis was performed between Skype and the developed prototype in regards to bandwidth consumption at varying internet speeds. In the experiment, the developed WebRTC-based prototype performed fairly well. The voice communication worked consistently even at a speed as low as 96 Kbps. 256 Kbps was found to be the minimum internet speed requirement for consistent audio-video communication. A common tendency among the telemedicine services operating in low resource settings is to rely on third-party multimedia communication tools like Skype, which can perform the intended task but demonstrates limitations in terms of user experience, as the system users frequently need to switch between the telemedicine software system and the third-party communication tool for over-the-web communication. The developed prototype addressed these limitations successfully by providing an option to incorporate the web-based real-time communication mechanism into the developed Telemedicine Management System. Also, the solution does not require any plugin/software to be installed in the computer. This integrated solution can potentially save a lot of time that would otherwise be needed in troubleshooting for the users as well as from the system administrators' end.

Finally, the most significant trait of the present work is its adaptation to the real-world environment solving real problems. The developed Telemedicine Management System was implemented on-field from the very beginning, as the core platform of the telemedicine project coordinated by Dhaka University Telemedicine Programme and is in use to date. Currently, there are 30+ rural telemedicine centres spread across the country, helping the rural people receive quality health service from urban doctors through this telemedicine programme. The extent of the telemedicine services is likely to expand even more in the coming days.

The learning curve associated with the use of the developed system was also found to be minimal. Usually in a three-day mandatory training for the rural telemedicine operators of DUTP, only two hours are allocated for the software training, leaving the rest of the training for diagnostic devices and certification examination. From the experience of conducting such trainings a number of times in last two and a half years, the author found that, the operators, even with a minimal technical literacy, could easily learn the usage procedure of the TMS within the allocated two hours. This undoubtedly demonstrates the simplicity and ease of use of the developed solution deployed in a real work environment. Being used as the core platform for a telemedicine programme that served 11500+ patients in last two and a half years, the developed telemedicine system also shows the potential and maturity as an effective and efficient technical solution in delivering essential health services to the deprived population. Internationally acclaimed NGO like BRAC has recently joined the initiative of DUTP and is currently using the developed system to deliver health services to a number of rural areas in Bangladesh. CRP will follow it soon and will use the telemedicine platform of DUTP for one of their own telemedicine programmes. The collaboration will provide therapeutic assistance to the physically challenged patients, who otherwise would need to come to the divisional facilities of CRP for follow-up visit from distant upazilas and unions of Bangladesh.

Therefore, considering the impactful adoption of the present work and positive feedbacks received from the active users of the developed system, it can be said that the work has been highly successful in achieving its prime target, and it makes the effort worthwhile. Moreover, the author strongly believes that the present work can also contribute to serving the unreached population not only in Bangladesh but also in any country with similar socio-technical context that are common to developing countries around the globe. However, like any other software development project, there will always remain scopes for further improvement. Nonetheless, it can be said that the present work has built a solid foundation based on which the future initiatives can achieve even higher goals. The future direction of the work would be to incorporate more functionalities that would come along the way, as the adoption of the developed solution will likely to expand in the coming days. For the Telemedicine Management System, the next priority would be to incorporate financial functionalities to automate the monetary operations that are currently being managed manually by the project coordinators. Another priority would be to extend the currently adopted centre-based service delivery to an individual level so that anyone with access to internet, either living in villages or in cities, can avail the telemedicine service using the developed telemedicine platform. For the web-based real-time communication solution, the direction of research would be to optimize it even further for slow internet connections and integrate provisions for digital stethoscope sound transmission so that the doctor can remotely hear the heart sound of the patients in real-time. Another priority would be to develop a mechanism for the transmission of ultrasound video in real-time utilising the developed real-time communication interface. To reach the deprived majority of the world population with essential health services, the effective use of Information and Communication technology, like introducing telemedicine, can certainly play an instrumental role. However, telemedicine is still at its infancy, not only in the developing countries, but also in the developed countries. More research should be done in the quest of finding the most effective mechanism to reach the unreached with proper medical care and that too should be tried with local initiatives and appropriate technology.

In the long journey of achieving the much longed-for "Health for all", together we still have miles to go. The present work, as the author likes to believe, is a humble effort to shorten the distance a little more.

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