# Smartphone-based Real-time Patient Monitoring and Decision Support System

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# List of Abbreviations

| | |
|---|---|
| API | Application Programming Interface |
| BP | Blood Pressure |
| BT | Bluetooth |
| CDSS | Clinical Decision Support System |
| Dia | Diastolic Blood Pressure |
| EBR | Evidence Based Reasoning |
| ECG | Electrocardiography |
| EWS | Early Warning Score |
| GPRS | General Packet Radio Service |
| GPS | Global Positioning System |
| GSM | Global System for Mobile |
| GUI | Graphical User Interface |
| EHR | Electronic Health Record |
| HFRM-II | Hendrich Falls Risk Model II |
| HMS | Health Monitoring System |
| HR | Heart Rate |
| I/O | Input/ Output |
| $ICO_2$ | Inspired (inhaled) Carbon-Dioxide |
| ICU | Intensive Care Unit |
| IDE | Integrated Development Environment |

| | |
|---|---|
| J2ME | Java Platform, Micro Edition |
| MFS | Morse Fall Scale |
| MHMS | Mobile Health Monitoring System |
| mmHg | Millimetres of mercury |
| OS | Operating System |
| OT | Operating Theatre |
| P | Pulse |
| Pleth | Plethysmography |
| PMS | Patient Monitoring System |
| PPG | Photoplethysmography |
| RFID | Radio Frequency Identification |
| RHMS | Remote Health Monitoring System |
| RR | Respiratory Rate |
| SD | Standard Deviation |
| SDK | Software Development Kit |
| SHMS | Smart Health Monitoring System |
| SpO2 | Oxygen Saturation |
| Sys | Systolic Blood Pressure |
| Temp. or T | Tympanic Ear Temperature |
| WMS | Wearable Monitoring System |

# Attestation of Authorship

“I hereby declare that this submission is my own work and that, to the best of my knowledge and belief, it contains no material previously published or written by another person (except where explicitly defined in the acknowledgements), nor material which to a substantial extent has been submitted for the award of any other degree or diploma of a university or other institution of higher learning. It contains results of my investigation, except where otherwise stated. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.”

Signed: ………………..

Date: …………………..

# List of Publications

## Peer Reviewed Journals

- Baig, M. M., GholamHosseini, H., **Moqeem, A. A.**, Farhaan, M. & Lindén, M. (2017). Clinical Decision Support Systems in Hospital Care using Ubiquitous Devices – Current Issues and Challenges (under review), 2017.

- Baig, M. M., GholamHosseini, H., **Moqeem, A. A.**, Farhaan, M. & Lindén, M. (2017). A Systematic Review of Wearable Patient Monitoring Systems – Current Challenges and Opportunities for Clinical Adoption, (accepted, in press) Journal of Medical Systems, 2017.

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- **Moqeem A. A.**, Baig, M. M., GholamHosseini, H., and Farhaan, M. (2017). Bed-side Vital Signs Monitoring Application with Real-time Clinical Decision Support (Submitted, under review), 2017

## Thesis

- **Moqeem, A. A.** (2009). Enterprise Trouble Shooting Management System. Bachelors Thesis, Osmania University, India.

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# Abstract

Patient monitoring systems have evolved over the past decade as an important first-line monitoring and warning tool. The healthcare delivery is moderately shifting from the traditional manual process to computer-based electronic healthcare system, supported by advanced tools and technologies. Mobile healthcare applications are now increasingly integrating into the healthcare mainstream to provide mobility with patient's electronic health record. However, the use of mobile raises the challenge of accuracy, stability, security and dependency of such applications in clinical care settings. In particular, lack of clinician engagement, poor user experience, and no clinical decision support are posing some serious issues on the acceptability of smartphone applications in clinical settings.

The main aim of this research project was to develop a vital signs monitoring and decision support application for the clinician-as-a-user. An Android-based smartphone application has been developed to monitor vital signs on a mobile device in real-time and to provide rich decision support to the clinicians. The application is fully integrated with wireless medical devices for real-time vital signs monitoring and decision support backed by the six screens (6S) user experience framework for the smartphone applications in healthcare settings.

The unique features and contributions that this research project provides are: (1) The ability to access, share, monitor, contact and stay-connected with patient's data anywhere; (2) Hospital-grade medical device connectivity using the standard Bluetooth protocol; (3) Rich clinical decision support in real-time based on the patient's recent vital signs (health data); (4) The '6S' framework developed for clinician-centered mobile user experience by adapting the international standards and protocols.

The proposed application has been evaluated using the best-practice guidelines for a successful mobile healthcare application. The criteria include review of the market available applications, literature review of best-practice guidelines, user engagement, privacy and security and standard design architecture for medical device integration. The proposed application demonstrates the easy to use screens and unique functionality including; patient list with search options, real-time viewing of vital signs, integrated medical devices, structured data entry, historic data, evidence-based knowledgebase search, clinical notes and clinical decision support via clinical risk assessments tools, scales and scores.

The proposed smartphone-based clinical decision support application could be seen as a potential standard/ best-practice tool that will help the clinicians to deliver better and timely outcomes. The functional design and implementation required rigorous and systematic workflow methodologies to be acceptable in the clinical care settings. The patient-orientated workflow and the available automated clinical assessment tools and calculators can assist researchers with collecting data that can help clinicians in future decision making.

# CHAPTER 1 Introduction

## 1.1 Overview of Remote Vital Signs Monitoring System

The need for continuous and real-time patient monitoring has increased with the increase in the chronic care conditions, ageing population and healthcare costs [1]. Patient monitoring and decision support systems have great potential to play a significant role in reducing; hospitalisation, clinician's workload, treatment time and overall healthcare related costs. The patient monitoring systems are classified into two categories, remote and mobile patient monitoring systems. Mostly, such applications send patient data to or from a remote location, ranges from single to multiple parameters, cover a variety of symptoms and can be accessed by an individual from home, rest home or hospital.

Mobile health (mHealth) monitoring systems refer to mobile phones, personal digital assistants (PDA), pocket personal computer (PC) based applications, which are used as the data collector, data transmitter or in some cases used as a main data source. These systems are considered to be more convenient and cost effective than traditional or institutional care, since they enable patients to remain in their usual environment whilst receiving professional healthcare [2, 3]. Mobile health monitoring system/ application is a promising tool for engaging patients in their own healthcare because most people own and regularly use a mobile phone and mHealth can be an appropriate medium for delivering health information. Given the great potential of mHealth, it is not surprising that current estimates suggest that there are more than 40,000 mHealth applications (apps) available on the market [4, 5].

Vital signs are considered as the key measurements of the body's most basic functions. The common vital signs (physiological parameters) regularly measured by the health professionals are body temperature (Temp.), pulse rate (PR), respiration rate (i.e. rate of breathing) (RR) and blood pressure (BP) (blood pressure is not considered a vital sign, but is often measured along with the vital signs) [4, 5].

## 1.2 Motivation

This research is motivated by the worldwide rising of healthcare costs, growing older adult population, increase in the chronic conditions and availability of advanced technologies and tools to address those current healthcare challenges. Key motivating factors are given below:

### 1.2.1 Rising Worldwide Healthcare Costs

According to US Bureau of the Census [6], within the next decade, annual U.S. expenditure on healthcare is projected to reach $4 trillion/year, or 20% of the gross domestic product [7]. During this period, all United States healthcare spending is projected to grow at an annual average rate of 5.8%, 1.1 percentage points faster than expected growth in Gross Domestic Product (GDP). By 2020, healthcare spending is projected to be 19.8% of GDP, increasing from 17.6% in 2010. All healthcare spending will reach $4.64 trillion in 2020 [8, 9]. Health monitoring systems can play a significant role in reducing hospitalization, the burden on medical staff, consultation time, waiting time and overall healthcare costs.

### 1.2.2 Growing Older Adult Population and Expenditure on the Chronic Diseases

In the last two decades, the rapid increase in the older adult population (those aged 65 years and over) has proved to be a major challenge in healthcare. The number of patients now requiring continuous monitoring has risen proportionally with this increase in population and, by 2025, this (65+) group will number approximately 1.2 billion. By 2050, there will be 2 billion in this age group, with 80% in developing countries [10]. Recent estimates for the amount spent annually on long-term care services in the US are between $210.9 billion and $306 billion [11]. For the UK, nearly 29% of the total population now lives with a long-term medical condition, while as much as 80% of the healthcare budget is spent on the management of chronic diseases [12, 13]. People with long-term conditions are accounted for 50% of the GP appointments and 70% of all inpatient bed days [14] and around 70% of the total health budget is spent on the care of people with long-term conditions in the UK [15]. In Canada, 10.7% of the total healthcare spending, expected to reach $219.1 billion or $6105 per Canadian as of 2015 [16]. New Zealand's total health and disability spending is about $18 billion, or about 9.5 percent of gross domestic product (GDP) and recent New Zealand health strategy for 2020 focuses on the long-term and chronic condition management, treatment, prevention and early detection [17].

### 1.2.3 Uptake of Ubiquitous Devices

One of the rapidly growing area of smartphone apps is the healthcare, including health and wellbeing, fitness, activity, monitoring and decision support. The smartphones available on the market gives the user all the required computational power, sophisticated sensors, fast connectivity and integration with the 3rd party applications. These features put the smartphone apps as the potential go-to tool for healthcare solutions. The current rate of adoption of mobile health apps in the clinical care settings suggests positive growth for mHealth researchers, developers and healthcare IT vendors [18].

### 1.2.4 Rich User Interfaces and Availability of Patient's Medical Data

Majority of healthcare applications have been developed without considering the user experience, user engagement and usability. Clinician and end-user engagement and consideration from the initial stages of the application design and development is often ignored or overlooked. Emphasising, it is essential for application developers to design and develop a user-friendly application with high user engagement. It is found that in the early stages of system development, a theoretical framework should be set in combination with data (simulated or trial) to manage physiological parameters. At each stage of the development, the feedback of medical professionals should also be considered and discussed in every possible aspect regarding the end user (patient) engagement.

## 1.3 Research Contributions

The objective of this research is to develop a real-time vital signs monitoring application with clinical decision support capabilities. The work has been carried out with the following approaches:

### 1.3.1 Smartphone-based Vital Signs Monitoring Application

An Android-based smartphone application has been developed, focused on clinician-as-a-user and to be used in the acute care settings. The developed application is designed and built using the standard best-practice healthcare application framework and guidelines for future scalability. One of the aims of this project is to make any other 3rd party system integration easy and smooth. The application is developed for clinician-as-a-user for inpatient (acute) care settings.

### 1.3.2 6S Framework for best User Experience

The '6S' refers to the *Six Screens* approach for a mobile healthcare application to provide smooth user experience. This research investigated and explored hundreds of medical applications available in the app stores for clinicians. The proposed six screens '6S' framework, addresses the current gaps in mobile healthcare applications, such as; lack of user engagement and user experience. The proposed framework aims to serve as the best-practice guideline to overcome the current challenges related to the user engagement and user experience.

### 1.3.3 Medical Device Connectivity and Interoperability

A key portion of the work involved design and development of an integrated smartphone application. This was achieved by assembling necessary components required for monitoring a hospitalised patient, in a way it is integrated into a single healthcare application. The application allowed features such as: recording physical observation, vital signs monitoring, decision support and wireless device connectivity. The developed application is capable of surfacing real-time vital signs from the wirelessly connected medical devices and provide clinical decision support based on the collected information via early warning score, Morse falls score, body mass index (BMI), clinical notes, data trends, statistical analysis, historical trends and medical knowledge-base.

### 1.3.4 Clinical Decision Support

The proposed application is currently capable of identifying several clinical risk scores, scales and assessments that is used in the acute care. There are few monitoring systems available (non-mobile) based on set threshold setting for generating warnings and alarms. The proposed application is superior to other systems due to the fact that it is used for individualised monitoring, evidence-based reasoning and provides real-time decision support on a smartphone.

## 1.4 Structure of the Thesis

**Chapter 2: Background and Literature Review**

This chapter presents an overview of the state-of-the-art patient monitoring applications, vital signs monitoring, decision support applications and issues and challenges. The research gaps in vital sign monitoring and its associated research problems related to the clinical decision support capability are investigated by the literature review.

**Chapter 3: Patient Monitoring Application Design and Development**

This chapter presents the design approach used for the proposed application as the six screens (6S) framework, application design using the standard approaches and functional design of the proposed application.

**Chapter 4: Application Functionality with Vital Signs and Clinical Decision Support**

This chapter presents the proposed application workflow, vital signs monitoring and clinical decision support functionality and capability of the smartphone monitoring application and its use case for the clinician to make better and informed decision.

**Chapter 5: Discussion and Conclusions**

This chapter concludes by discussing the key outcomes, measures and approaches adopted in this research and its implementation path in the wider clinical context. This chapter discusses the future development and its impact on the acute care settings.

# CHAPTER 2 Background and Literature Review

## 2.1 Introduction

This chapter distributes the patient monitoring application literature into: (1) wearable, remote and wireless vital signs monitoring applications; (2) mobile patient monitoring applications; and (3) clinical decision support. The current issues and challenges are also discussed which highlights the current research and its related areas.

## 2.2 Classification of Vital Signs Monitoring Applications

Advanced vital signs monitoring systems are foreseen to play an important role in early detection and early warning in case of health deteriorations. Medical professionals can further follow up the outcome. A study found that more than half of 3160 admissions to five acute hospitals had at least one recording of an early sign of critical illness (e.g. SpO2 < 95%) [19]. A recent review recommended that every patient should have a documented plan for vital signs monitoring that includes; physiological parameters to assess, time and duration [20]. More frequent vital signs monitoring in clinical settings can better identify acutely ill patients for earlier intervention and reducing grave consequences.

A usual example of using vital signs monitoring for early warning generation is a widely-adopted scoring mechanism called 'Early Warning Score'. The score can be calculated from common physiological parameters described in this paper. Derangement in any of the parameters is assigned a number and the sum of these numbers is used to calculate an overall early warning score [21, 22]. It has also been reported that self-monitoring of health indicators has a positive impact on the health of users [23]. There has been rapid growth in techniques and methods to assist healthcare professionals in achieving better healthcare delivery for older adults [24] and people with disabilities

[25]. Since there are no restrictions to such applications, they can also be used in hospital [26, 27], home [24, 28] as well as outdoor [29]. Figure 2.2-1, shows the current trend and architecture of the vital signs monitoring applications including types of application, wireless connectivity, categories and places. These monitoring applications are usually connected and synchronised with online dashboards.

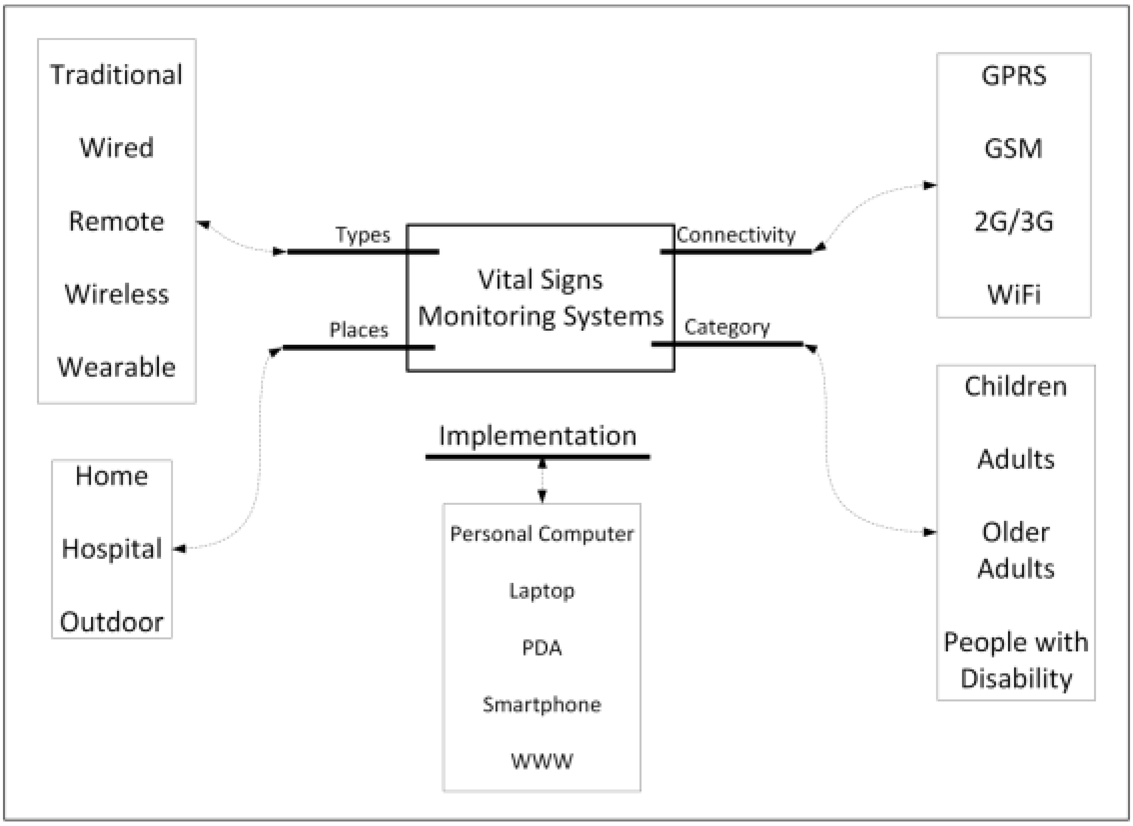



**Figure 2.2-1 The current trend of vital signs monitoring applications**

### 2.2.1 Wearable Patient Monitoring Applications

Wearable systems/ sensors and wireless medical devices are used to collect individual's personal health data [30]. The wearable monitoring applications use the advanced communication protocols and sophisticated sensors to capture the health data continuously. The collected data then used for processing and interpretation [30]. Wearable sensor technology seamlessly integrated into the standardised clinical data sets are few examples of the impact and potential of wearable monitoring on wider healthcare systems especially patient monitoring, decision support, self-management of long-term and multiple conditions management [31].

The chronic and progressive nature of an individual's health condition often time-boxed and fluctuate rapidly, require a flexible monitoring model and technology that consider the timely nature and precise support [32]. Wearable monitoring applications are deployed into the community care to examine the gait, activity of daily life and data trends [33]. The increase of wearable monitoring systems will lead to huge streams of new data which will amplify the database and, therefore, complement and improve the accuracy of its predictive models [34].

Majority of wearable technology is distributed into, *biopotential sensors*, such as electrocardiography (ECG), electromyography (EMG) and electroencephalography (EEG) sensors. Secondly, *motion sensor units*, such as accelerometers and gyroscopes. Finally, *environmental sensor units* such as video cameras, vital signs monitors (such as heart rate, pulse rate and temperature) and pressure sensors [35].

Some studies suggested that the three-dimensional (3-D) printing technology may play an important role in this concept [36]. This technology has shown the potential of allowing any person equipped with a 3-D printer to fabricate their own 3D model/objects and if this technology is combined with a seamless integrated wearable sensor then this combination can produce some thoughtful outcomes for the healthcare delivery. We believe this will change the way healthcare is being managed today and healthcare information exchange will be much more easy for any service provider to access the relevant information and provide better care [37].

### 2.2.2 Remote Patient Monitoring Applications

Remote monitoring applications are based on the integrated network using internet as a connectivity channel to transmit the data, including, vital signs, video data, ECG recordings, etc. to support the healthcare delivery when distance separates the clinicians and patients. Remote monitoring applications is often a combination of mobile communication-based systems and wearable monitoring technology. With its many advantages, this technology has provided innovative solutions to deliver healthcare by remotely monitoring a patient. Some of these applications are still in the development stage, and others have already been implemented in the medical environment.

An advanced wearable application has been developed using the sensor's energy to communicate and transmit the data in real-time [26]. In [38] the researchers have developed a mobile ECG monitoring application backed by the RFID to transmit data continuously to the local server. The system is depended on the battery life of mobile and RFID tags. Another application, Prognosis [39], based on the fuzzy logic, mapped to the various signs, symptoms and disorders for identification of the health conditions. Such applications are heavily depended on the specific use-case and limited in the saleability to incorporate the wider disease and conditions. Mostly due to the limit of data collection using the sensors, accuracy of the wearable body sensors and transmission protocols [40].

Such applications aim to surface key physiological parameters or conditions for viewing the information in real-time. The data collector application then transmits the data in the cloud for complex processing which require high computational powers. The processed data will be available on the web for viewing and the alert or warning will be pushed back to the mobile application for timely actions. This communication poses serious security and privacy threat to the health data. Security and privacy are considered one of the most important issues and challenge when using such application in clinical care settings. Table 2.2-1 summaries the selected wearable systems.

### 2.2.3 Wireless Medical Devices

The market available medical devices are suitable for integrating with any 3rd party application and based on; wireless feature, accuracy, affordability, availability and performance. The selected devices with wireless functionality and standard Bluetooth transfer protocol and internal storage are listed below:

1. Boso-medicus prestige blood pressure monitor [41] is a wireless Bluetooth device. It measures blood pressure (systolic and diastolic) and pulse rate. Records at user defined time intervals and it's easy to operate.

2. Nonin's Onyx II finger clip oximeter [42] is a wireless Bluetooth device which records oxygen saturation and heart rate continuously.

3. Accu-Chek Compact plus blood glucose meter [43] is wireless infrared connected device which records the blood glucose level.

4. Omron's instant ear thermometer [44] is an accurate and fast ear temperature measurement device.

5. nSpire's Piko-6 meter [45] is a wireless infrared connected device which gives FEV6 and FEV1/FEV6 readings.

6. Gulf Coasts Data Concept's accelerometer/Magnetometer Data Logger X8M-3mini [46] is a compact, continuous data collection device used for fall detection.

**Table 2.2-1 Summary of the selected studies related to patient monitoring applications**

| Author and Year | Target Area or Population | Study Aims | Outcomes/ Findings | Platform/ Type of Sensor Used |
|---|---|---|---|---|
| **Etemadi et al. 2016 [47]** | Long-term monitoring; chronic care monitoring | To develop a low power, low cost patch for measuring activity using ECG and seismocardiogram (SCG) sensors | The developed patch measured the combined activity, environmental context, and hemodynamics, for longer than 48 hours with continuous recording | Three-channels of SCG; one-lead ECG; the pressure sensor; an average current consumption of less than 2 mA from a 3.7 V coin cell (LIR2450) battery. |
| **Thomas et al. 2016 [48]** | Non-invasive continuous blood pressure (BP) monitoring | To develop a wrist watch-based BP measurement system using ECG and photoplethysmogram. | The study recorded the average root mean square error between the measured systolic BP | A PPG sensor with both IR and red LEDs; two differential electrodes; third bias electrode; BioWatch comes with two analog front ends (AFE): the TIADS1292 for acquiring ECG signal and the TI AFE4400 for reading PPG. |
| **Wu et al. 2015 [49]** | Biofeedback system to monitor and learn from physiological signals | To develop a wearable biofeedback system for personalised emotional management using heart rate variability | The results indicated that the real-time HRV biofeedback is significantly effective in cases of negative emotion | A conductive textile material as the electrodes for ECG and breathing activity; a differential separation filter and a common signal conditioning |
| **Xu et al. 2016 [50]** | Treatment, in-community rehabilitation and athlete training | To develop a contextual online learning method for activity classification based on data captured by low-cost, body-worn inertial sensors | Real-time learning system and contextual multi-armed bandits (MAB) approach that enables efficient, personalized activity classification | Context driven activity classification and feedback; a set of sensors with a smart device attached to the user; activity classification module (ACM) and the context classification module (CCM) |
| **Sardini et al. 2015 [51]** | Posture Monitoring and Rehabilitation | To develop a wireless wearable T-shirt for posture monitoring during rehabilitation or | The wireless wearable sensor produced reliable data compared with the data obtained | A copper wire and a separable circuit board; the actuator is a vibration micromotor (Pico Vibe) |

| | | | | |
|---|---|---|---|---|
| | Exercises | reinforcement exercises | with the optical system | commercialized by Precision Microdrivers |
| **Spano et al. 2016 [52]** | Remote patient monitoring; ECG monitoring | To develop an ECG remote monitoring system that is dedicated to non-technical users in need of long-term health monitoring in residential environments and is integrated in a broader Internet-of-Things (IoT) | Developed an integrated 1) ECG prototype sensors with record-low energy per effective number of quantized levels; 2) an architecture providing low marginal cost per added sensor/user; and 3) the possibility of seamless integration with other smart home systems through a single IoT infrastructure | The wearable ECG sensor consists of a battery-powered chest belt; two dry plastic electrodes and the electronic printed circuit board; The circuit extracts, filters, amplifies and digitizes the ECG signal, which is then acquired by the microcontroller |
| **Melillo et al. 2015 [53]** | Risk assessment of vascular events and falls in hypertensive patients | To design and develop a flexible, extensible, and transparent, and to provide proactive remote monitoring via data-mining functionalities | Future vascular event was predicted within the next 12 months with an accuracy of 84% | BioHarness Bluetooth logging protocol application was used to collect the data |

## 2.3 Mobile Monitoring Applications with Clinical Decision Support and Machine Learning

### 2.3.1 Overview of Mobile Monitoring Applications

With the increase in adoption of mobile patient monitoring applications, it is expected that the variety of new data sources will be created, which will complement the electronic health record. Using machine learning, the available data could be transformed into the meaningful and/or actionable data. But, the current issue with the expert systems or knowledge-based systems is their accuracy and reliability. The majority of current intelligent models are based on the specific domain knowledge, low scalability and focused on small timeframes. The current state of the overall monitoring applications can be further enhanced with integration of versatile tools in the health record locally or in the cloud for real-time processing.

Machine learning techniques are well suited for healthcare domain for its complexity and variation in health data. The health data is complex and scales very rapidly, to be considered as part of the ‘big data’ processing [54]. Several open-source frameworks such as Hadoop [55] are frequently used to store a distributed database in a scalable architecture, as a basis for tools (such as Cascading, Pig, Hive, etc.) [55] that enable developing applications to process vast amounts of data (by the order of terabytes) on commodity clusters [55].

### 2.3.2 Smartphone-based Clinical Decision Support Applications

Smartphones are emerging as preferred choice of tool to provide real-time information, alerts, reminders, clinical workflow and clinical decision support [56]. There are several standards for a high-quality patient decision aid such as international patient decision aids standards [57]. Four basic features of most smartphone applications include: (1) data sharing; (2) data organization (alerts and history); (3) decision support/interpretation; (4) user knowledge and support. These feature can be further enhanced by integrating it with the wider hospital’s source systems to provide clinicians with complete health record [58].

### 2.3.3 Smartphone Applications in the Secondary Care

Manual paper/hard copy-based ‘tools’ and ‘scales’ are being automated with easy to use graphical user interface (GUI) via smartphone apps to integrate the advanced technology into medical settings. A smartphone-based wound care application [59] was developed to replicate the paper-based pressure ulcer scale (PUSH) [60], Braden scale [61] and the Bates-Jensen tool [62]. This system automated the existing tools and let clinicians to create, view, access, delete and re-assess patient records related to wound care. Critical design consideration has been given to smartphone application such as simplicity of GUI and simple options to find and view information. It is also reported that there is a significant limitation for using mobile tools if a basic task required too many clicks or steps to complete. This includes the use of dropdowns, radio buttons, hide/show, navigation and size of the text. The application was developed for a Nexus 4 smartphone and Nexus 7 tablet and tested by eight nurses, age range 31-60 years. There was a strong correlation perceived between the paper-based forms and the wound care application (app) in terms of content and data entry expectations, with scores of 4.60/5.00 for the Braden Scale and 4.57/5.00 for the PUSH tool [59].

Decision support systems assist clinicians by providing evidence so that they can make a better and timely decisions at the point-of-care. This enable clinicians with more information, individualised data trends and precise treatment plans, so that the clinicians can make informed decisions [63]. In an attempt to engage clinicians and patients during their hospital stay, a smartphone application was developed to provide interactive information to patients [64, 65]. Moreover, ubiquitous devices in clinical decision support applications would become more useful for clinicians by providing flexibility and adaptability to change [66].

Most of the reviewed applications focus on data analysis, diagnosis and/or early detection using complex gadgets, which make them inefficient in non-specialized consultations. Due to the fast growing clinical decision support (CDS) applications, it is recommended that the mobile applications need to be integrated with the wider patient health record, other source applications to maximise their efficiency and to realise the overall clinical benefits [67].

Figure 2.3-1, shows four major CDS depended areas of overall healthcare system, which are key in enabling success of CDS applications in healthcare settings. The four key areas are derived from the reviewed literature [56, 63, 68, 69]: (1) Structured Information – includes standard structured data/ clinical information such as; coded problems of a patient available in the patient record; (2) Information Exchange – includes vast area of cross-platform availability of apps; (3) Transformation – includes current transformations of manual paper-based charts, tools and scales to automated applications; (4) Data Analysis – current functionality available via a smartphone application available for clinicians' to apply and use in the hospital's emergency department, general wards, acute units and/or surgical care. Outcome of this review is emphasised in Table 2.3-1, which summaries ubiquitous healthcare systems with clinical decision support features.

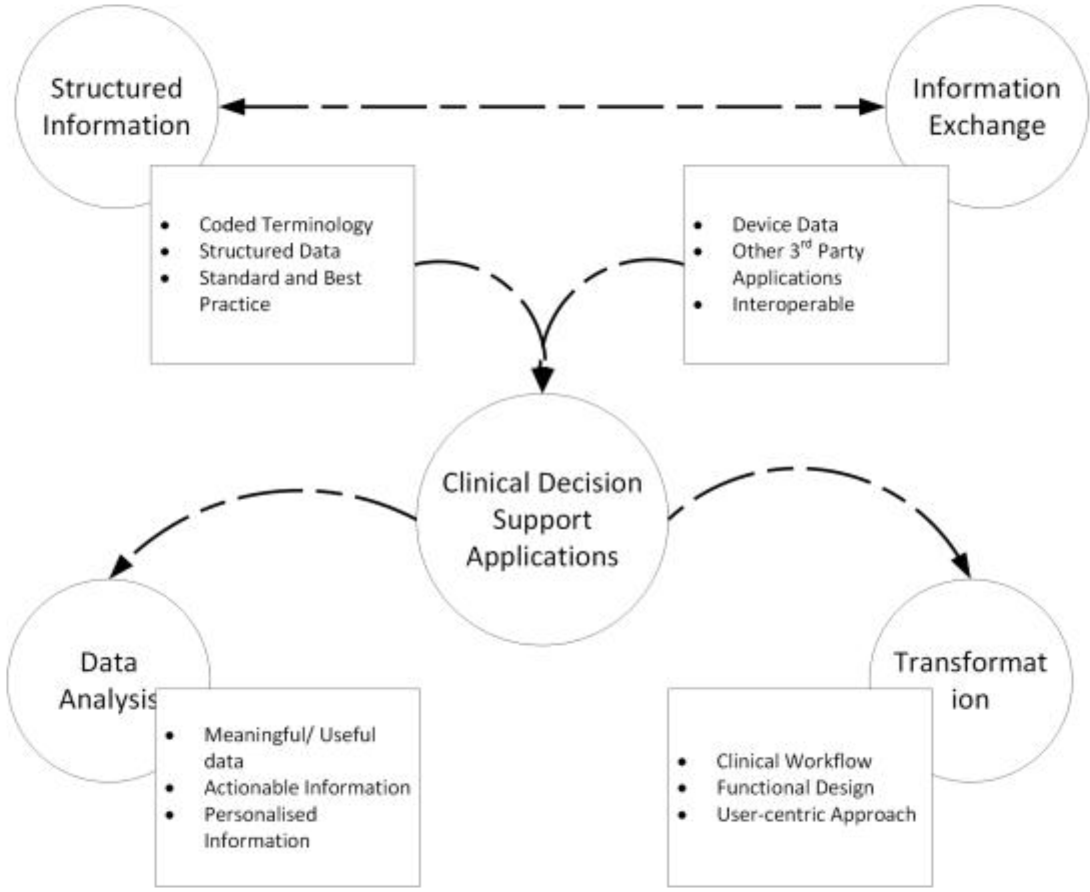



**Figure 2.3-1 The four key areas for efficient and functional smartphone CDS applications**

**Table 2.3-1 Ubiquitous healthcare systems with clinical decision support features**

| Application | CDS Function | Platform/ Devices | Outcome |
|---|---|---|---|
| **Oleg at al. [70]** | Heart rate and ECG monitoring | Ubiquitous devices | A low-power sensor to collect bio-information |
| **Horta et al. [71]** | The analysis and diagnosis ambient assisted living (AAL) | Ubiquitous devices (smartphone and tablet) | Falls prevention and monitoring application using ubiquitous devices |
| **Sclafani et al. [72]** | Various decision support | Ubiquitous devices (smartphone and tablet) including computer/ desktop | Clinical education |
| **Doty et al. [31]** | Measuring ECG, BP, $SpO_2$, RR, Pulse and Temp. | Smartphone device | A wrist-worn band to collect vital data |
| **Dexheimer and Borycki [73]** | Image analysis of CT-brain in an emergency department | Apple's iPad™ | CT Brain image analysis |

## 2.4 Issues and Challenges

In last three decades, there have been significant advancements towards decision support tools, initially with paper-based manual tools, scales, scores and charts, gradually transferred to computerised and semi-automated applications [74]. Currently, there are emerging mHealth applications fully integrated with other EHR systems to support clinicians in their decision-making. While there has been a significant growth and progress in the mobile healthcare area, monitoring application and clinical decision support, but there are still gaps which prevents wider adoption in healthcare settings [75]. Health innovations using latest technologies and techniques offer great advantages, as well as poses privacy and security risk with the patients' personal information, clinician and end-user acceptability, data storage, data access, data organization and its processing [76]. Data processing on local device impacts on the device's battery life, which is currently one of the biggest issues [77]. In the context of this research, it is necessary to identify critical issues related to decision support systems. Therefore, we excluded common smartphone/tablet related issues which are extensively covered by many researchers in literature such as: power consumption [78]; battery life [79, 80]; user acceptance [81]; and clinical data security and privacy [82, 83]. Instead, we focus on the issues related to the decision support capability and their acceptance in hospital settings, data processing and analysis [84, 85] and information exchange, for optimal integration of mHealth applications. Figure 2.4-1, shows the architectural diagram of the smartphone apps and their issues and challenges. The major issues and challenges are categorized into four main divisions: (1) Clinician/user consultation; (2) Data transmission; (3) Data integration; (4) Design and development.

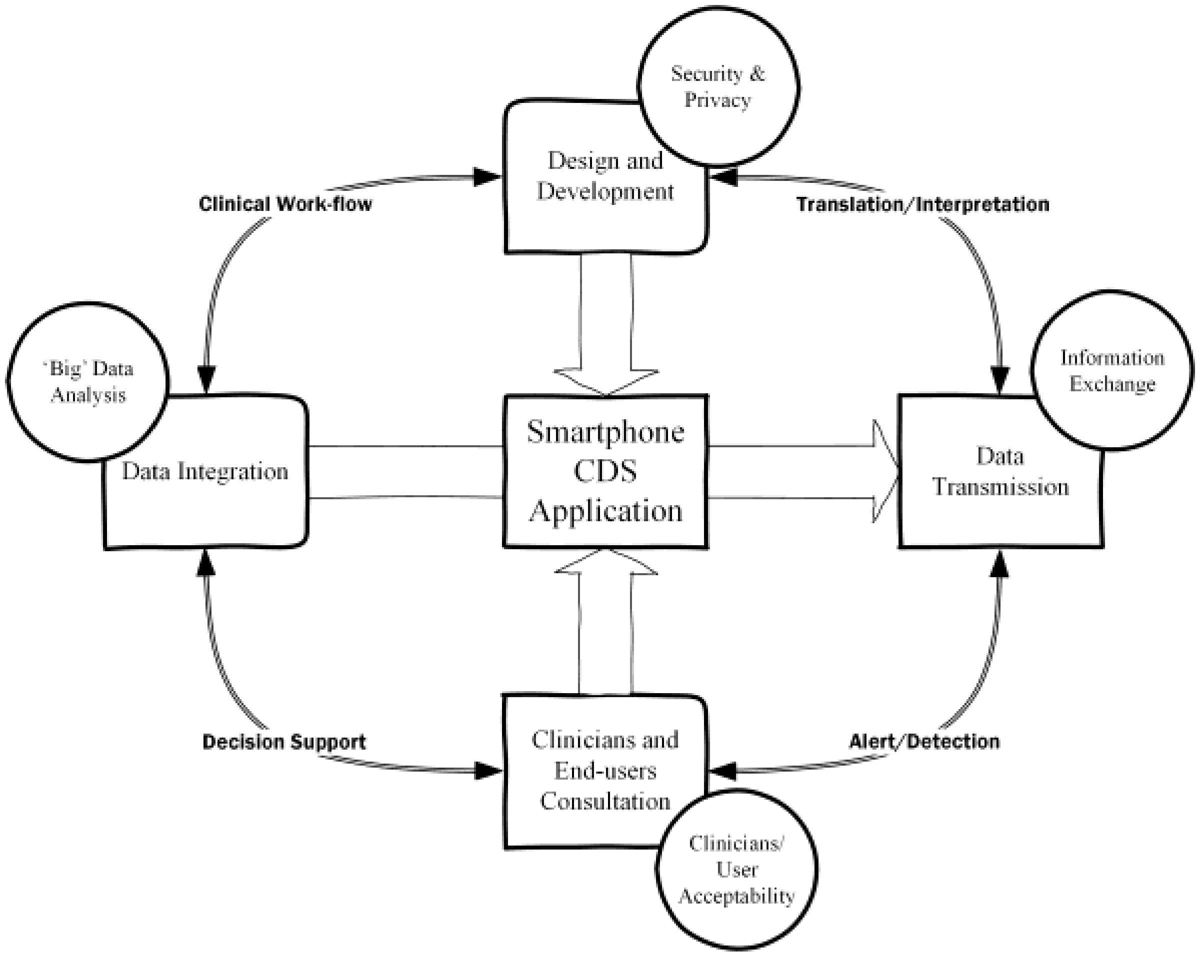



**Figure 2.4-1 Issues and challenges related to mobile monitoring applications**

### 2.4.1 Data integration: Big data analysis

Medical standards compel the use of high-quality data in mHealth applications for accurate and reliable communications. It is essential for any monitoring application, specially, vital sign monitoring applications to capture and transmit the data with high accuracy [86, 87].

Personalised and predictive medicine can greatly benefit from data integration and its machine learning model (big data analytics) [84]. Today, most health systems use a combination of rules-based approaches as well as manual methods to best interpret the health data. Big data analysis seems to be a solution for the medical data which is increasing because of the fast adoption of the electronic medical devices and storing of digital data. However, big data analysis is at its early stages and needs more time to achieve full clinical acceptance [84].

Mostly, such applications cannot be implemented as continuous monitoring applications due to their large power consumptions. Moreover, due to the limited hardware and processing powers of the device, sophisticated data processing and interpretation are limited when compared with high-end personal computers [86]. Secondly, collected data will be pushed to the cloud-based services for processing, and only alerts are transmitted back (generated by the cloud-based applications) and pushed to various other devices. In such applications the alert will be delayed depending upon the internet connectivity and cloud processing capabilities [88, 89].

### 2.4.2 Clinician and end-user consultation: User acceptability

User-centred approach is key to the success of the mobile healthcare application. It is recommended that a close end-user collaboration be established from the early design stages of the application. The poor user acceptance is also one of the key factors limiting the wider clinical adoption of such monitoring applications. The clinical focus should also be applied when considering the healthcare app, as this might be used by the consumer (user) as well as clinician. Highly sophisticated models become irrelevant if the end-users do not understand the intended use, functional aspects, operation and its user interface [90].

### 2.4.3 Data Transmission and Information Exchange

Mostly, mHealth applications are developed either web-based or local machine-based. In both cases, they will be connected to other services for the transfer of information. However, the local application usually does not have data integration capabilities with other clinical databases to fetch patient data for processing; they mostly relay on local patient data and limited to specific area or an issue. Local machine-based applications have the advantage of patients' information security and privacy, but have two critical drawbacks; memory space and limited patient data access [91]. However, fully connected applications have the advantage of analysing more patient data from other data repositories to predict/interpret the decision support. Such applications will also be connected to cloud-based environment for information transmission but require an ICT infrastructure – with cost implications at the initial stage. Another issues is the privacy and security of patients' personal information [83]. It is suggested that there should be balance between clinical use and ICT dependence for mHealth applications. For example, if the medical device or hospital internet connectivity fails then the whole application will be useless for clinicians, because normally all data is stored in the cloud due to the smartphone/tablet's limited space [91, 92].

It is recommended that, in a limited resource setting, it is optimal to use the local smartphone application for the specific healthcare area so that huge ICT-related costs could be saved. Wilcox et al. [93] attempts to minimize such barrier by using advanced data encryption process before and after the data transmits, so that the data available locally as well data available on the cloud is secure and no breach during the data transmission could take place. The issue of integration/connectivity is addressed by using a native application with secure data storage rather than a desktop computer with added layer of data security including a browser security for web-based forms. This poses the risk of mobile device theft and ending up in remote wipe of the whole device data [93], which again points towards the ICT infrastructure to store and handle huge amount of incoming patient data. However, storing information on the hand-held device introduces the risk of losing the device (easier to lose the smartphone device than desktop work station) and one cannot physically steal or lose the cloud.

# CHAPTER 3 Patient Monitoring Application Design and Development

## 3.1 Introduction

This research aimed at developing an Android application to monitor individual's vital signs in real-time. The vital signs data collected by the proposed app includes oxygen saturation ($SpO_2$), pulse rate, blood pressure (systolic and diastolic) and electrocardiograph are collected and streamed/ displayed on the smartphone in real-time. The proposed application has been designed with the close consultations with the clinicians, user-experience designers and review of the existing literature on mobile healthcare application design frameworks [94]. The application has been developed using the Android platform, known for its flexibility and open source nature. This gives an advantage to build an application using the open source features as the development requires medical device integration, 3rd part app integration and external source linkage. It is evident that the mobile application market is growing epically in the healthcare mostly due to the availability of advanced and affordable hardware in the world, which is supporting the global smartphone adoption.

## 3.2 Scope and Approach

The Android app 'Health Plus' is solely designed and developed for clinician-as-a-user and for the acute care setting. The Health Plus application currently can receive, process, display, and record health (vital signs) information provided by the medical devices. The collected data is stored in a structured format and used for pre-population and provides rich clinical decision support functionality in real-time within the application. The application design is focused to give clinicians the best user experience by making the application navigation as simple as possible. Furthermore, this application allows user to connect to the 3rd party application and online authentic services for mining and viewing of the information. The application continuously monitors pulse rate, oxygen saturation and BP, allows user to view information in real-time, store the data in structured database and use/re-use the data for rich clinical decision support via clinical risk assessments and scores.

The goal is to provide the clinical information easily and conveniently for clinicians to view, access and act on the information provided by the monitoring devices. The collected information is then processed in real-time to provide clinical decision support via clinical assessments, risk scores and scales. The proposed application enables clinician to access, view, share and communicate with other care team members efficiently. The application is capable to handle non-critical care situation with vital signs viewing and monitoring tools with added clinical decision support such as an early warning score.

## 3.3 The Six Screens (6S) Framework for best User Experience for Mobile Health Applications

### 3.3.1 User-centric approach

This research postulates the '6S' application design framework highlighting three common issues currently facing by the wider mHealth application domain. The three conclusions are (1) Evidence of smartphone application tested/evaluated in hospital care settings involving senior clinicians (2) Continuous involvement of medical professional and end-user in the app design for an acceptable user experience and (3) Restrict clinicians to 'view' only information instead of view, do, act and share information. In the literature, it is highlighted that the mobile applications capability to act as a data collector, information viewer, and effective communicator could be well utilised in the healthcare settings for effective healthcare delivery [72, 95]. Moreover, the mobile healthcare application with good user experience even accelerated the clinician engagement and mobile technology adoption in clinical care [90, 96].

### 3.3.2 The 6S Approach to the Application Design

The ‘6S’ refers to the Six Screens approach for a mobile application in order to provide the best user experience to the clinicians. This research investigated and explored hundreds of medical applications available in the app stores for clinicians [56] as shown in Table 3.3-1. It is established that the clinical success could be achieved if the app is simple-to-use, engaging, optimal balance between too many or too few tasks in one screen. Overall, it is found that the app should allow users to view information, do tasks, act on the available information and ability to share information with other clinicians.

From the literature, it is reported that the current mobile healthcare apps lack user experience, including; The question asked by majority of clinicians is “Will this application save time?” the proposed design considers what’s useful from the clinician’s perspective, and the work environment of a nurse or clinical professional under which the app will be used.

**Table 3.3-1 Clinical applications available in the market for patient monitoring**

| **App Name** | **Platform** | **Description** | Screens |
|---|---|---|---|
| Epocrates | iOS and Android | Drug information, assessment, referrals | 5 main screens and 6-8 sub-screens |
| UpToDate | iOS and Android | Medical knowledge | 3 main screens and 2 sub-screens |
| Doximity | iOS and Android | Doctor networking | 5 main screens and 6-8 sub-screens |
| Read by QxMD | iOS and Android | Medical Literature | 5 main screens and 6-8 sub-screens |
| New England Journal of Medicine | iOS only | Medical articles and Image and Videos | 6 main screens and 6-8 sub-screens |
| Isabel | iOS and Android | Diagnosis assistance | 6 main screens and 5 sub-screens |
| Figure 1 – Medical Images | iOS and Android | Medical images | 6 main screens and 6-8 sub-screens |
| DynaMed Mobile | iOS and Android | Clinical decision support tool | 5 main screens and 4 sub-screens |
| Medscape | iOS and Android | Medical reference tool | 6 main screens and 4 sub-screens |
| Virtual Practice for Doctors | iOS and Android | Free, mobile-based EMR | 5 main screens and 6-8 sub-screens |
| AliveECG | iOS and Android | Record, display and transfers Single-channel ECG readings | 4 main screens and 8 sub-screens |
| BP Log | Android | Manual Record and display BP recording, list and graph view with date and time | 2 main screens and 4 sub-screens |
| DiabLog | iOS | Family/Social support for Diabetes and self-management via devices | 3 main screens and 5-6 sub-screens |
| iBP | iOS and Android | Record, display and transfer BP recording, symptoms support and self-monitoring | 6 main screens and 5-6 sub-screens |

The proposed app adopted the following global best practices to give the clinicians best user experience using a standard terminology for the development of the app:

- Number of steps, clicks and navigation on the screen required to complete a task is important. The common issue is where there are too many steps mandatory to complete a task. In an emergency situation and/or in a busy hospital environment it is not possible to complete a list of lengthy tasks.

- Use of icon and images instead of text, empower users without any language barrier.

- Font size consistency.

- Too little or too much information, including warnings, messages, notifications or external links in one screen.

### 3.3.3 The 6S Framework for Application Design and Development

The proposed 6S framework is designed and developed by adopting the below three approaches:

- Firstly, we investigated the current mobile apps available for clinician-as-a-user in acute care as well as community care with or without clinical decision support to find the optimised and balanced measure for the appropriate number of main screens required for a successful healthcare application.

- Secondly, the user feedback, clinical engagement and consultations conducted to design the framework with appropriate number of screens required to capture the key information required by the clinician. Initial six screen design framework (app wireframe) used for initial consultation before app development is shown in **Appendix A**.

- Finally, the app was reviewed by the wider user group including, researchers, clinicians and engineers for user experience, user engagement, simple to use and ease to adopt.

Figure 3.3-1 shows the *simple to complex* user workflow for mobile healthcare applications with four levels of complexity. The simple to complex are derived from the internationally recognised Electronic Medical Record Adoption Model (EMRAM) by The Healthcare Information and Management Systems Society (HIMSS). The x-axis shows the simple to complex matrix aligned with the four levels of complexity comprising of view only information, do-able tasks and actions via clinical decision support.

**Level 1**: Stand-alone applications – A majority of applications today fit in this category by providing clinician with limited and specific point-of-care information for one particular use case or speciality.

**Level 2**: Integrated with other 3rd party systems – It is difficult to manage the clinical and information workflow within the application to provide the third party systems information such as patient's electronic health record, laboratory information or radiology information system.

**Level 3**: Clinical documentation functionality – Capturing the data via clinical documentation is a challenging task to perform on a mobile device due to its complexity of documentation management, viewing and workflow around it.

**Level 4**: Medication management and clinical decision support – Medication management introduces whole new level of complexity to perform basic yet key decision support for drug-drug, drug-allergies, drug-food allergies.

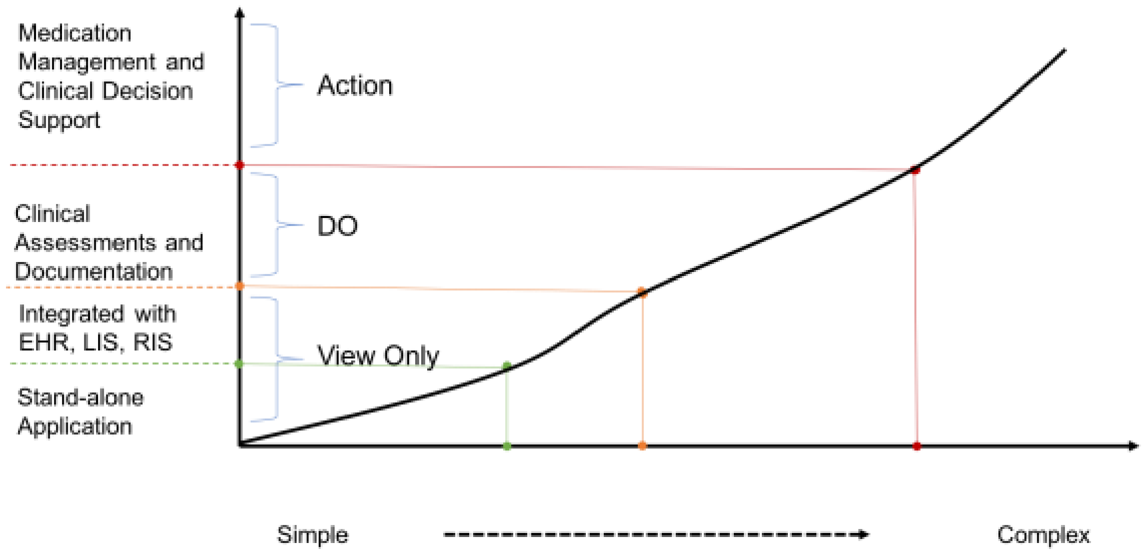



**Figure 3.3-1 Simple to complex maturity and clinical workflow for mobile healthcare applications. EHR is an electronic health record, LIS is laboratory information system and RIS is radiology information system**

The 6S framework covers the above complexity and various levels of integration required for a successful mobile healthcare application, the six screens concept is described in Table 3.3-2:

**Screen 1**: Login – This should be the first entry point for the app including login, welcome and home screen. There is a possibility of sub-screens for first time registration or the identity confirmation.

**Screen 2**: Context – This screen should help user to put the context for which the application will be used. Example could be selecting patient, topic, disease, type of care, etc.

**Screen 3**: View Information – Viewing the key information related to the user’s query will give the user a background and in some cases current information to decide on the next steps. Example could be the previous vital signs, previous medications, history of falls or admissions in last 30 days.

**Screen 4**: Data capture – Allow user to capture new information or update previous information from within the app.

**Screen 5**: Task and Actions – After having access to the previous and current information, this screen will enable user to perform actions based on the known information. The ability to ‘do’ or ‘act’ within the app will enhance the user engagement when compared to ‘view’ only application.

**Screen 6**: Contact – This screen should help user to reach beyond the current application boundary, in case of getting more information, connecting with other person, system, and advanced communication tools should also be part of this screen.

**Table 3.3-2 Six screen summary description with its intended use and best-practice guidelines**

| Screen Number | Title | Description | Feature/ Functionality | Complexity |
|---|---|---|---|---|
| 1 | Login | Login; welcome; Home or initial screen | Mandatory security and privacy | N/A |
| 2 | Context | Patient; specialty; location; type of service or role-based service | Clinician-as-a-user; clinical settings; | Simple |
| 3 | View Information | Real-time; current info or history/ related information | Source system integration; holistic view of health information | Simple to complex |
| 4 | Capture Information | New data capture; various data sources | Structured data capture; real-time information | Complex |
| 5 | Actions | Task; reminders, warnings; alerts | Data analytics; Machine learning; clinical decision support | Complex |
| 6 | Contact | Various communication channels | Communication; information sharing | N/A |

### 3.3.4 User Engagement

It is evident in the literature that the clinicians will use the app only if they are motivated to do so. The proposed application is designed with the below considerations in mind:

- App is designed using well-documented interaction design patterns, as outlined in BJ Fogg's model [97].

- We identified the user’s daily needs through early engagement and design feedback.

- Explored the user of different engagement techniques like gamification, but rigorously tested their use with real-world users in real-world context.

## 3.4 Application Design Architecture

### 3.4.1 Initial Application Design Sketches

We used a simple approach to design the initial application phase with clinicians for their engagement. This method proved to be successful, as the clinicians were engaged throughout the application design and development. Initial six screen design sketches of the proposed app are shown in **Appendix A**.

### 3.4.2 Application Architecture Model

After the user feedback and engagement, the app has been designed using the above process and by adopting the standard user experience design patters. Figure 3.4-1 shows the high-level design architecture diagram to illustrate the complete application workflow. The application allows multiple entry points to capture clinical notes, various data type entry and actionable information as these are the most common features used by the clinician in their daily shifts.

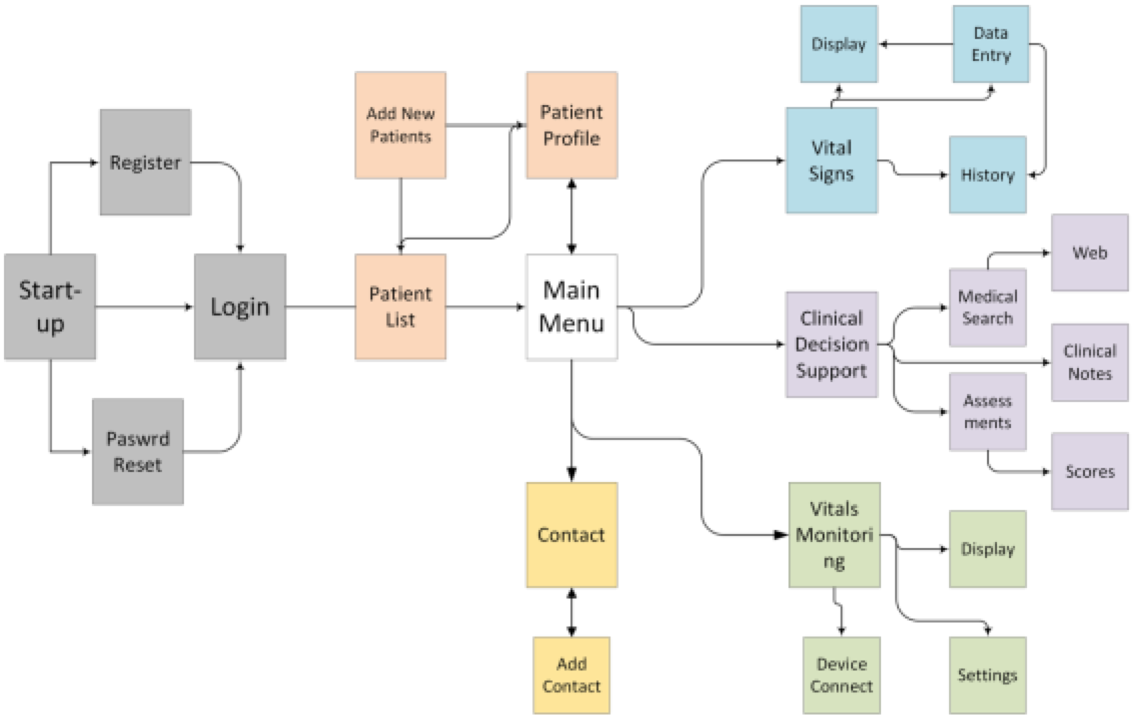



**Figure 3.4-1 High-level design architecture diagram illustrating the complete application workflow**

### 3.4.3 Structural Blocks

Below are the key structural blocks of the proposed application.

- Viewing Information: Multiple entry points have been created to view the information in list view as well as in the graphical view, such as, viewing of historical data, recent or real-time medical device connected vital signs data.

- Data Capture: The vital signs information is captured by the connected medical devices as well as the manual data entry for custom data types.

- History: Data trends and data history can also be viewed for data analysis.

- Integrated Access: the captured data is surfaced on multiple entry points as pre-population for ease of information access and sharing.

- Evidence-based healthcare: The application externally calls the Mayo Clinic evidence-based authentic medical knowledgebase for any clinical investigation.

- Use of in-built features: The proposed application uses the smartphone's in-built calling (voice, internet), messaging, location, Skype (via Skype app) and email (using client email) for smooth communications.

Extended design architecture diagram is shown in **Appendix B**, the Unified Modeling Language (UML) class diagram is shown in **Appendix C (partial view)** and the UML class diagram is shown in **Appendix D (full view)**. The activity class diagram for the medical devices integration is shown in **Appendix E** and its associated classes diagram is shown in **Appendix F.**

## 3.5 Monitoring Application Development

### 3.5.1 Development Tools and Elements

The integrated development environment (IDE) is used for the development of the proposed Health Plus application [98]. The IDE is developed by Google and based on IntelliJ IDEA. The Android Studio IDE supports the flexibility and wider integration which makes it suitable for such a healthcare application development [98]. Some of the key features of Android which helps the application development are; the ability to update and use the latest SDK supported by the training material; build and debugging environments makes it easy for testing the app in real hardware, and; code inspector tools to check the bugs in real-time under build environment.

### 3.5.2 Development Languages

Android studio and development environment fully supports the Java language for application development and XML to describe the visual elements. Android SDK is supported by the vast amount of libraries to make the development easy and smooth. The Extensible Markup Language (XML) is used to describe the relationships of the visual elements of activity and class.

### 3.5.3 Android OS version

- The proposed Android application is built the Android OS version 5.0 (Lollipop).

- The proposed Health Plus application can communicate to any Bluetooth enabled device with Android platform version 5 or less.

## 3.6 Integration and Interface Considerations

### 3.6.1 Medical Device Integration and Connectivity

The proposed application could be used for vital signs monitoring, viewing real-time vital information and search for an evidence-base medicine using authentic knowledgebase. The proposed application collects the real-time data via standard Bluetooth (BT) protocols from wireless medical devices. The collected data is encrypted and stored locally in a structured database for data processing. The stored data is used for pre-population and clinical decision support via clinical risk assessments, scores and scales [83, 99-101].

The application registers the medical device details such as serial number and MAC address via a secure gateway in the application registries, so that only registered device(s) could be visible and connected to the mobile via Bluetooth. The app records the device data in specific individual's heath data profile, as the application can store hundreds of patients and devices. The application works with the Wi-Fi, 3G and 4G networks to perform the online synchronisation, 3rd party apps integration and database connectivity.

### 3.6.2 Data Transmission, Permissions and Communication

The proposed application could be connected to any standard Bluetooth compatible medical device, the Bluetooth device connectivity protocol outlines the process for each authenticated wireless medical device. The data source is from medical devices and body sensors which collects the physiological parameters and connected with the personalised body area network. The data collectors could be smartphone applications, desktop/ laptop/ notebook or health appliances, which helps in data collection.

To interface and connect to the wireless medical devices, we used standard Bluetooth protocols for platform variability and scalability. The Bluetooth communication operates mainly on 2.4 GHz and device connectivity could be established using serial port profile.

The proposed application adopted the "IEEE Personal Health Data Exchange Protocol - ISO/IEEE 11073-20601" as standard best-practice framework to connect with medical devices. Extending 11073-20601, provides interoperability between the medical device and the destination profile, such as when pulse oximeter health device profile is selected for data transmission continuously [102, 103].

To use the Bluetooth features in the proposed application, we declare and set the Bluetooth permission to open so that the medical device and smartphone could be always connected and this enables connection setup, pairing, data transmission and device visibility. But in this case, we want the app to initiate device discovery or manipulate Bluetooth settings, hence we declare the BLUETOOTH_ADMIN permission in addition to the BLUETOOTH permission. Most applications need this permission solely for the ability to discover local Bluetooth devices. The other abilities granted by this permission should not be used, unless the application is a "power manager" that will modify Bluetooth settings upon user request.

Figure 3.6-1 shows the example of how Bluetooth permission in Android application is setup using the manifest file after declaring the Bluetooth permissions in the generic function. The code snippets related to the medical device integration and data streaming on to the proposed application is shown in **Appendix G**.

```
<manifest ... >
  <uses-permission android:name="android.permission.BLUETOOTH" />
  <uses-permission android:name="android.permission.BLUETOOTH_ADMIN" />
  ...
</manifest>
```

**Figure 3.6-1 Declaring the Bluetooth permission(s) in the application manifest file**

### 3.6.3 Interaction with other 3rd Party Applications

The proposed app (applicable to Android application in general) consists of various activities. Each user interface is created as an activity to perform an action or a specific task. Tasks and actions such as make a skype call, send a text message or track a patient location. The navigation from one activity to another activity is defined by the “Intent”. Using “startActivity()” as an intent to start an activity, the system uses the Intent to identify and start the appropriate app component related to that specific task/ action. The ‘Intent’ protocol could be used for activity navigation within the app or even in-between the two different apps, such as making a call or capture a photo.

The proposed application uses the ‘Intent’ activity to allow clinician to make a phone call, write a message, make a Skype call, email using the local mail client and show an address on a map (using google maps).

### 3.6.4 Activity Lifecycle

The ‘Activities’ in the application are handled by an activity stack. Each new activity is considered as a running activity and placed on the top of the stack, same principal applies to all the activities. Some of the ‘activities’ categories are:

1) Running activity: when the activity is on the top of the stack and on the foreground of the screen.

2) Paused activity: where the activity is paused but alive in the background. Too many paused activities causes performances issues and in case of low memory the system terminates these activities.

3) Stopped activity: where an activity is stopped and hidden to the user. This activity will be hidden to the user and may be completely terminated by the application manager. Upon request again, this activity will be restarted again.

Figure 3.6-2 shows the key Activity state paths [104]. The call-back protocols are visualised by rectangles which performs operations, when navigating between two Activity states. The major Activity states are shown as ovals.

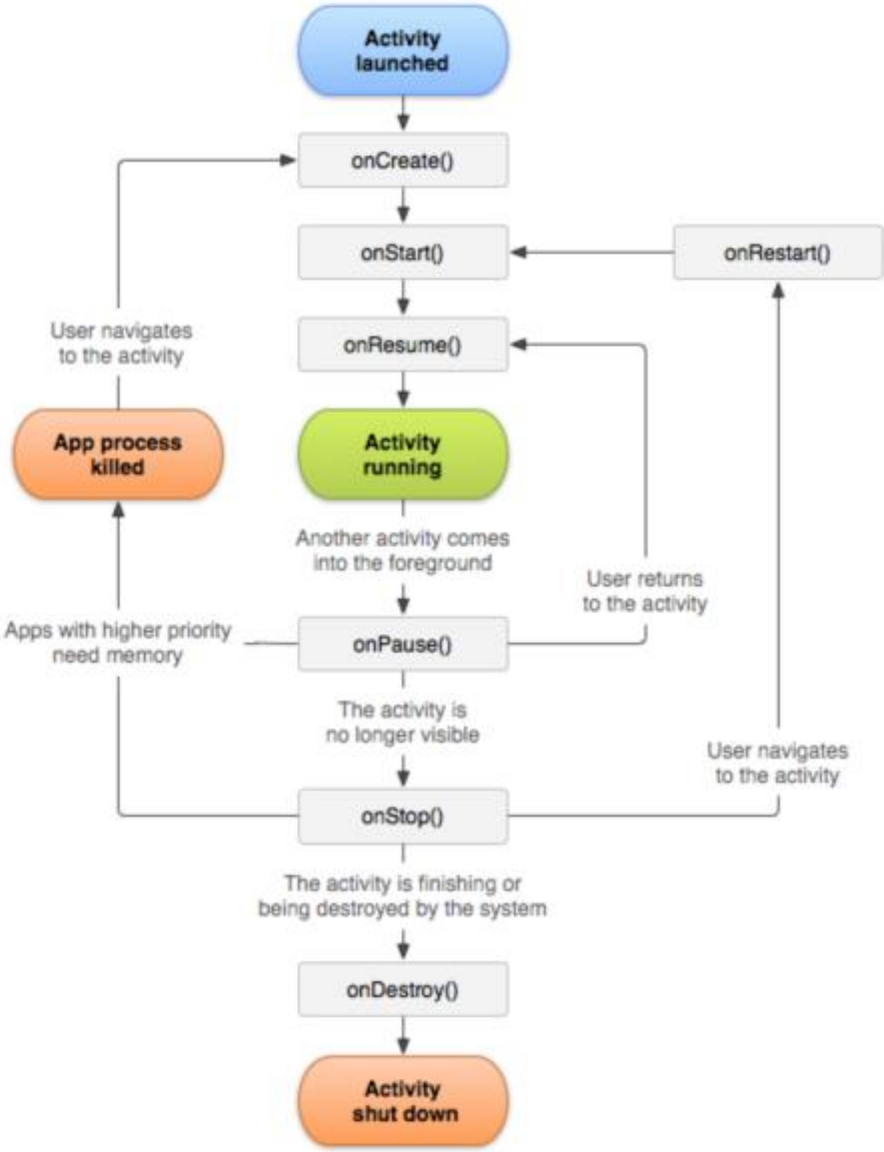



**Figure 3.6-2 The important application state paths of an Activity [104].**

### 3.6.5 Wireless Medical Devices

The medical devices integrated with the Health Plus application for the real-time data collection are described below. Due to the complexity of this application, where multiple devices are integrated with the smartphone database containing multiple user profiles, each medical device details such as serial number and MAC address is recorded in the mainframe application against one individual profile. So, that the data could be recorded and stored against the same user who is wearing the medical device. This measure restricts the device data to be stored against any other user profile and the device data is securely transmitted via Bluetooth to the registered device only. The two devices used in this project are discussed below.

### 1) Nonin's Onyx II Model 9560 finger pulse oximeter

Nonin's Onyx II finger clip oximeter [42] shown in Figure 3.6-3 is a wireless Bluetooth device which records oxygen saturation and heart rate continuously. The Nonin's Onyx II Model 9560 finger pulse oximeter is a lightweight portable finger clip device capable of detecting the user's pulse rate, blood oxygen saturation, and their finger photoplethysmograph waveform [42].


**Figure 3.6-3 Nonin's Onyx II finger clip oximeter**

### 2) Alive Heart and Activity Monitor

The Alive Heart and Activity Monitor, as shown in Figure 3.6-4 includes a single channel, 2-lead ECG as well as a 3-axis accelerometer. The Health Plus application receives the ECG information in real-time from the device and displays the data in a graphical view as well as the heart rate is displayed in the tabular view for easy viewing of vital signs.


**Figure 3.6-4 The Alive Heart and Activity Monitor**

Other devices can also be connected to the proposed Helath Plus application, see Table 3.6-1 with potential medical devices which could be connected to the proposed application in future using the similar standard Bluetooth protocols and data transmission techniques. The medical device specification, connectivity and functionalities are also given for in-depth analysis.

**Table 3.6-1 Medical device specifications and functionalities**

| Device | Make/ Model | Connectivity/ Transmission | Device Size and Body Location |
|---|---|---|---|
| **Blood Pressure** | Bosco-Medicus BT Monitor [41] | Wireless/ BT | Small/arm |
| **Pulse Oximeter** | Nonin's Onyx-II pulse oximeter [42] | Wireless/ BT | Compact/finger tip |
| **Blood Glucose** | Accu-Chek Compact Plus Blood Glu. meter [43] | Wireless/ IR | Small/ fingertip blood |
| **Ear Temp.** | Omron's Instant ear thermometer [44] | Wireless | Small/Ear |
| **Body Temp.** | G-plus body thermometer [105] | Wireless/ BT | Compact/ armpit |
| **Spirometer** | nSpire's Piko-6 spirometer [45] | Wireless/ IR | Small/ air blow |
| **Accelerometer** | 8-XM3-mini 3-axial accelerometer [46] | Wireless | Compact/ chest |

# CHAPTER 4 Vital Signs and Clinical Decision Support Integrated Application

## 4.1 Introduction

Today, practically every function in the healthcare is supported by some sort of decision support mechanism for accurate and better healthcare delivery. Integration between the hospital source systems, 3rd party laboratory applications and electronic health record is now available in clinical settings [106]. The integration of multiple source system provides holistic information to the clinicians to make better and informed decision, unfortunately, very few such applications exists today. Majority of applications in practice are still operate as stand-alone applications with limited scalability and low integration with other systems, hence, forcing clinicians to look for one health record/ clinical information related to one individual in more than one system or place.

The data is captured in semi-structured formats, backed up locally as well as on a cloud, sent to Health Information Exchange (HIE), portals and various other repositories. Performing machine learning and other data analysis and prediction techniques is also getting acceptance in healthcare [107, 108]. Clinicians have to look for the authentic patient information in more than three places on an average and draft the clinical scenario to treat the patient. This poses the huge issue of the data wastage happening in the electronic health record, because one system doesn’t talk to another system and so on [109, 110].

This chapter discuss the clinical decision support features available in the proposed application for the clinician to make timely and informed decisions. The proposed application has embedded clinical decision support functionality with alerts, reminders, optimised user workflow, clinical assessment forms, colour coded/ interpreted decision support and evidence-based medicine via medical knowledgebase integration.

## 4.2 Login and Registration

The proposed app adopted the standard mobile app security protocol for enhanced safety and security of the application using Android's built-in advanced security schema. The following core security features has been implemented in the proposed app's security framework.

The Android Application Sandbox is a basic protocol used to keep application data, authentication details and encryption information in a separate storages for enhanced security and privacy, is adopted as part of the proposed app. The data encryption protocols has been implemented in the application framework as part of the extended application protection, so that the data is 100% protected in case of fire and theft.

Data protection is applied using the Android application-defined permissions to restrict the access to the application features, data storage and Activities. There are two fundamental ways that the mobile authentication services work, local/ internal authentication and web/ external authentication [111, 112].

### 4.2.1 Local/ Internal Authentication

The default Android restrictions applies to any file created on the local storage, which is accessible only to the main application (source app). It is recommended to avoid the "MODE_WORLD_WRITEABLE" or "MODE_WORLD_READABLE" modes for IPC files because they do not provide the ability to limit data access to particular applications, nor do they provide any control of data format [113]. In order to add another security layer to protect the sensitive healthcare data, we implemented the local file encryption protocol. The protocol encrypts the local files and stores it separately to its encryption key, protected by the multi-factor authentication [114].

### 4.2.2 Web/ External Authentication

The proposed application has a capability to connect the authentication service to the online/ external sources for advanced three-way authentication protocols. Figure 4.2-1 (A) shows the login screen where user required to enter alphanumeric password and there is a 'register' option for the first-time user to register as per their role (nurse, doctor, consultant, specialist) for added privacy and roles-based protocols. Figure 4.2-1 (B) Shows the registration screen for the first-time user, with mandatory and option data fields required to be filled by the user.

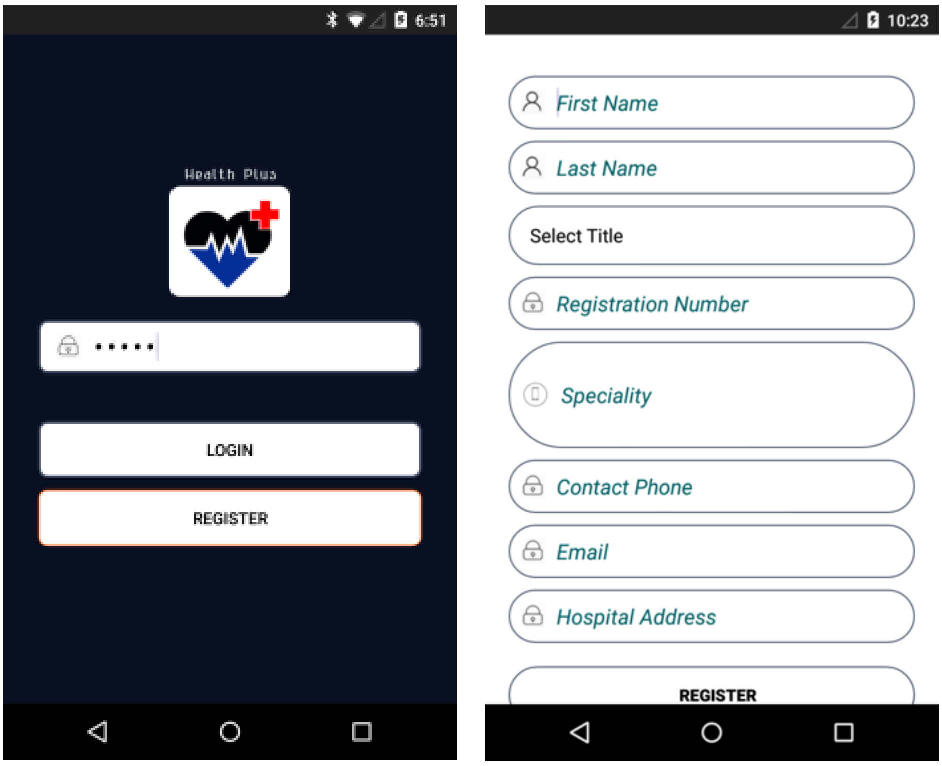
The developed application adopted the token-based authentication protocol, the workflow is described below:

- Upon starting the application, the app prompts user to enter username/email and password.

- The username or email and password data will be sent (OVER SSL) via a POST request.

- An access token will be created after the validation of the received information for a limited / set time only.

- The application stores the received time-based access token key. Once the token key expires, the same (above) process is followed for set number of user defined cycles.




**A** **B**

**Figure 4.2-1 (A) The login screen and (B) The first-time registration screen**

## 4.3 My Patient List

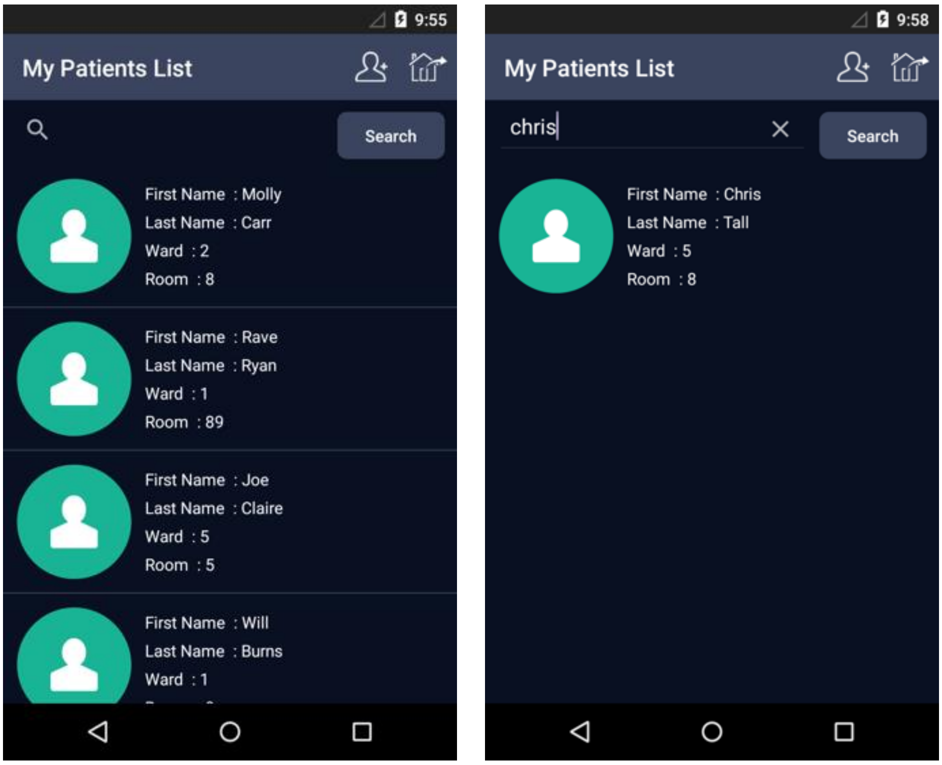
Figure 4.3-1 (A) shows the 'My Patient List' screen with the standard patient banner with the screen title 'My Patient List', add new patient icon and logout icon. Add new patient screen is similar to that of the Figure 4.2-1 (B). The core features of 'My Patient List' are:

- User-based optimised patient list, so that the user can see user-assigned patients as well as the complete list of patients.

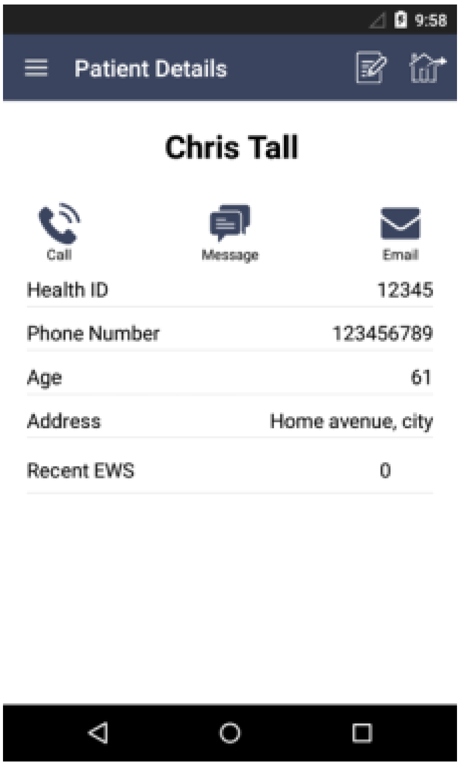
- Fully search-able patient list provides an easy way to search for the patients based on their name(s), health ID and date of birth as shown in Figure 4.3-1 (B).

- Patient profile summary card with patient's first name, last name, ward and room details are made available for easy view as shown in Figure 4.3-1 (A) and (B).

- Figure 4.3-1 (C) shows the patient details/ profile screen with first name, last name, unique health identifier, call, message and email options with age, address and recent early warning score (EWS). The EWS will give the clinician with a good understanding of health condition. The configuration/ application modifications in future to replace the EWS or add another risk score in any screen is simple and straight forward.




**A** **B**




**C**

**Figure 4.3-1 (A) The full list of my patients; (B) The patient list search functionality and (C) The selected patient profile screen**

## 4.4 Vital Signs Monitoring

Figure 4.4-1 (A) shows the tabular view of basic vital signs, (B) shows the vital signs data filled with real-time decision support and (C) shows the historical data of the vital signs. The proposed application allows multiple entry points for the vital signs entry including the real-time automated medical device data, some key features are:

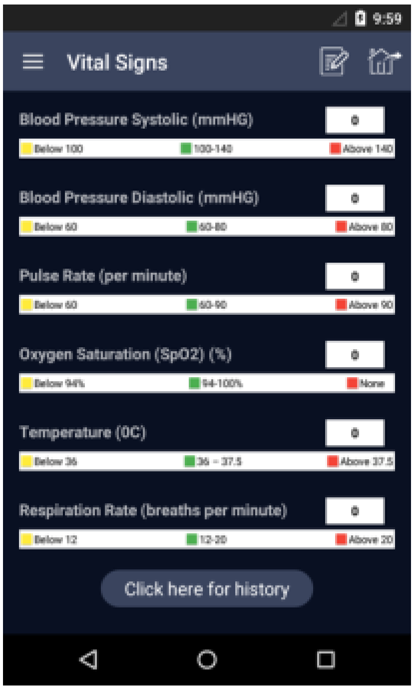
- Basic vital signs included are BP (systolic and diastolic), pulse, $SpO_2$, temperature and breathing rate.
- Vital signs are presented in tabular format with visible fixed threshold values with amber for below normal value, green for normal range and red for above normal value as per the standard guidelines as shown in Figure 4.4-1 (A) and (B).

- The proposed application can also handle real-time flexible threshold based on the three previous data values to calculate the standard deviation, maximum and minimum for each patient.

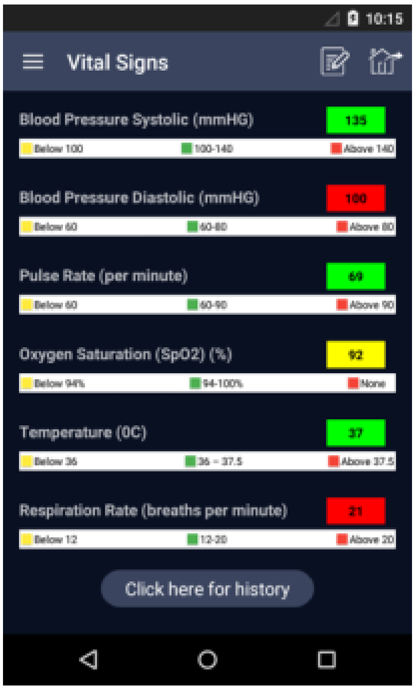
- Figure 4.4-1 shows the vital signs filled with the recent vital signs in colour coded values as per the individual vital sign. Instead of showing the continuous real-time data stream to the clinical we focused on showing the actionable/ meaningful data to the clinical for timely care.

- Vital signs are recorded via Bluetooth medical devices, clinical assessments, manual entry and it is possible to be connected to any 3$^{rd}$ party system or cloud server to receive the vital data.

- Previous vital data is stored and viewed via vital history screen, with date, time and colour-coded value of each individual vital sign for easy navigation. Example shown in Figure 4.4-1 (C) is for the pulse rate. The historic vital signs data screens including; systolic and diastolic BP, pulse, $SpO_2$, temperature and breathing rate is shown in **Appendix H**.




A

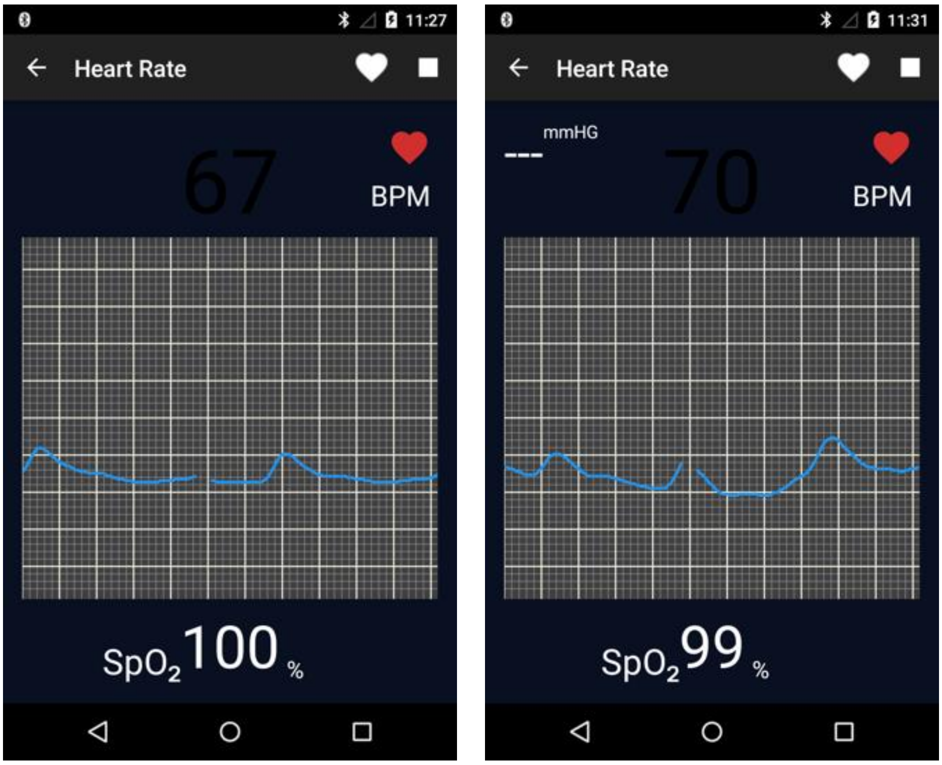



B


C

**Figure 4.4-1 (A) The vital signs as a tabular view with standard threshold values; (B) The colour coded vital signs as point-of-care-decision support and (C) The historical vital signs data**

Figure 4.4-2 (A) and (B) shows the graphical view of the pulse rate and real-time recording of the SpO2 and pulse is being displayed. Pulse values are displayed in the top centre of the screen and SpO2 values are shown at the bottom centre part of the screen and the centre of the screen is showing the continuous waveform of the pulse rate.




**A** **B**

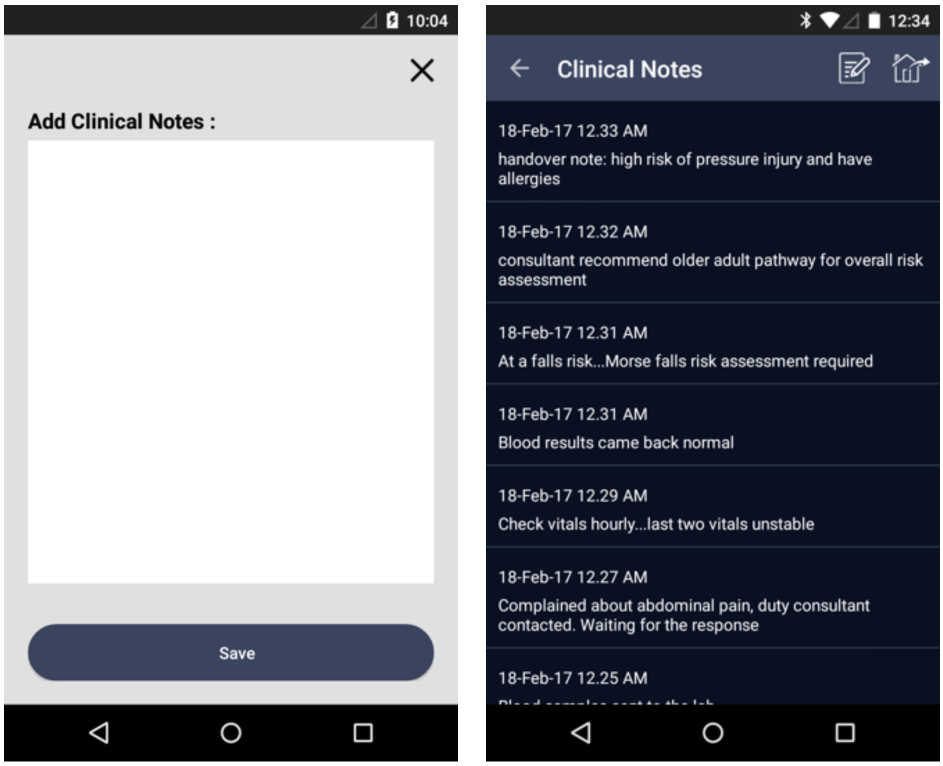
**Figure 4.4-2 (A) The graphical view of the pulse oximeter (SpO2) values in real-time (bottom of the screen) and (B) The pulse rate (centre top of the screen)**

## 4.5 Clinical Decision Support

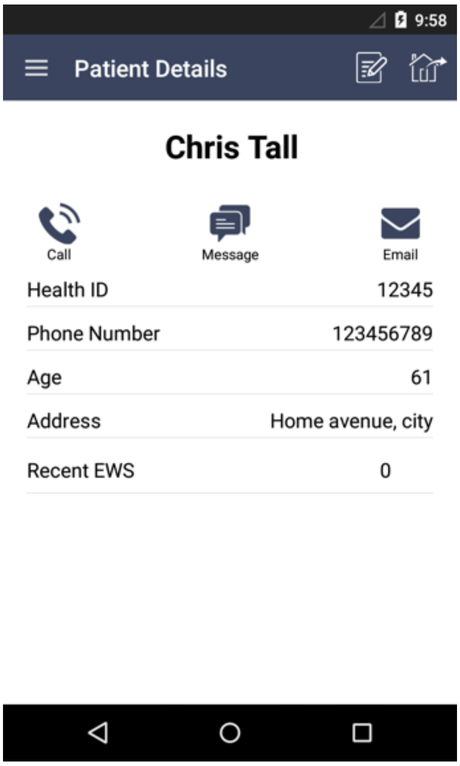
Clinical decision support is embedded throughout the proposed application to better support the clinicians to make better and informed decisions. One of the unique feature of Health Plus app is the underlying data architecture design and storage structure, which allows the vital data to be stored, used, re-used and pre-populate within the app for rich clinical decision support. The details of each clinical decision support feature is discussed in the following sections.

### 4.5.1 Clinical Notes

The clinical notes provide clinician with the place to record running notes, not directly related to the course of the treatment but may have key tasks or actions for other clinician or care team member. Another use case is to make a clinical handover transparent and error-free (change of duty clinical or end-of-shift process). The proposed app enables the clinical user to add a ‘quick’ running notes from multiple screens (multiple entry points) for enhanced clinical experience. Figure 4.5-1 (A) shows the process of adding a clinical note; (B) shows the summary/ list view of the recorded notes with date, time and first line for easy and quick reading/ understanding and (C) shows the notes capture entry point via the patient details screen (right side of the patient banner).




**A** **B**



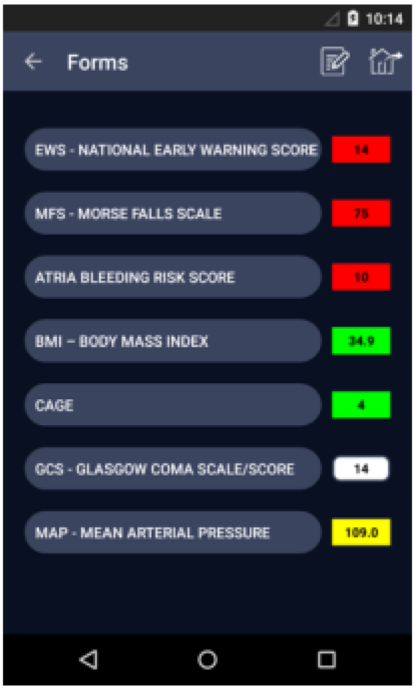

**C**

**Figure 4.5-1 (A) The clinical notes recording screen; (B) The clinical notes entered by the clinician and (C) The clinical note entry point (top right side under the patient banner) from the patient profile page**

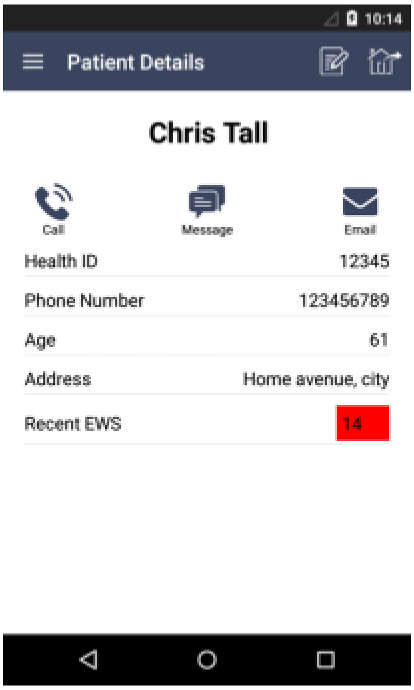
### 4.5.2 Clinical Tools and Calculators

Evidence-based clinical decision support tools and calculators are used by the medical professionals to make informed decision. Majority of clinicians use the clinical tools and calculators to understand the current patient health condition. Figure 4.5-2 (A) shows the clinical decision support tools and assessment scores in a list view. 'Forms' screen shows the name of the clinical decision support tool and its recent score (the latest score will be populated automatically once the assessment is completed); (B) shows the colour-coded values from the completed assessment tool and (C) shows the latest value from the early warning score populated on the patient details screen in real-time.


**A**




**B**




**C**

**Figure 4.5-2 (A) The list of clinical assessment mobile forms; (B) The completed clinical assessment forms with colour coded outcomes as clinical decision support and (C) The recent early warning score populated in real-time in the patient profile screen**

Current list of clinical decision support and assessment tools are given below:

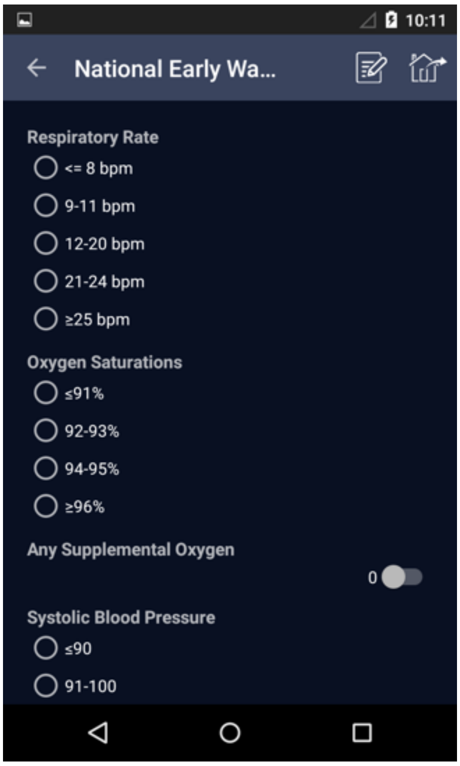
- Early Warning Score (EWS)
- Morse Falls Scale (MFS)
- ATRIA bleeding risk score (ATRIA)
- Body Mass Index (BMI)
- CAGE Questions for Alcohol Use (CAGE)
- Glasgow Coma Scale (GCS)
- Mean Arterial Pressure (MAP)

### 4.5.3 Early Warning Score

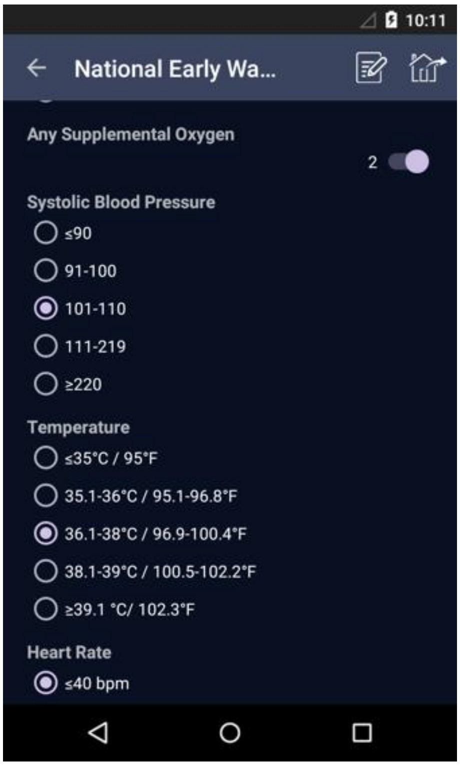
The Early Warning Score (EWS) serves as the first line of warning/ alert in case of any fluctuations in the individual's vital signs. Further deterioration is minimised by using the EWS score as the reference for escalating the care for timely intervention. Today, every nursing documentation standard protocol requires nursing staff to measure and monitor the EWS, record EWS score and appropriate care and treatment plans according to the latest/ most recently calculated EWS for each individual.

The EWS scoring tool is based on the complex computational model which assigns calculated weightage/ score to each physiological parameter (vital sign), including; respiratory rate, oxygen saturations, temperature, systolic blood pressure, pulse rate and level of consciousness. A weightage/ score is allocated to each vital sign based on the deviation from its normal range (threshold-based set ranges).

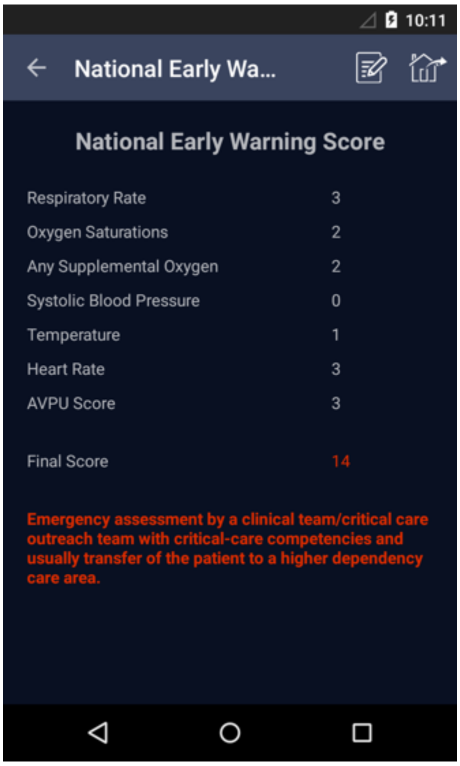
The proposed app offers mobile optimised and intelligently designed EWS assessment score as a rich clinical decision support feature. Figure 4.5-3 (A) shows the first half of the EWS form and (B) shows the second half of the EWS form. The EWS assessment score is designed for the clinician to easily complete the assessment by selecting a check box, radio button or a switch ON/OFF as a simple user interface. Figure 4.5-3 (C) shows the summary screen of the completed EWS, divided into sections with its values (calculated from the entered data), final EWS score as a colour-coded value and its interpretation (standard and best-practice recommendations) depending on the EWS score.




**A**




**B**

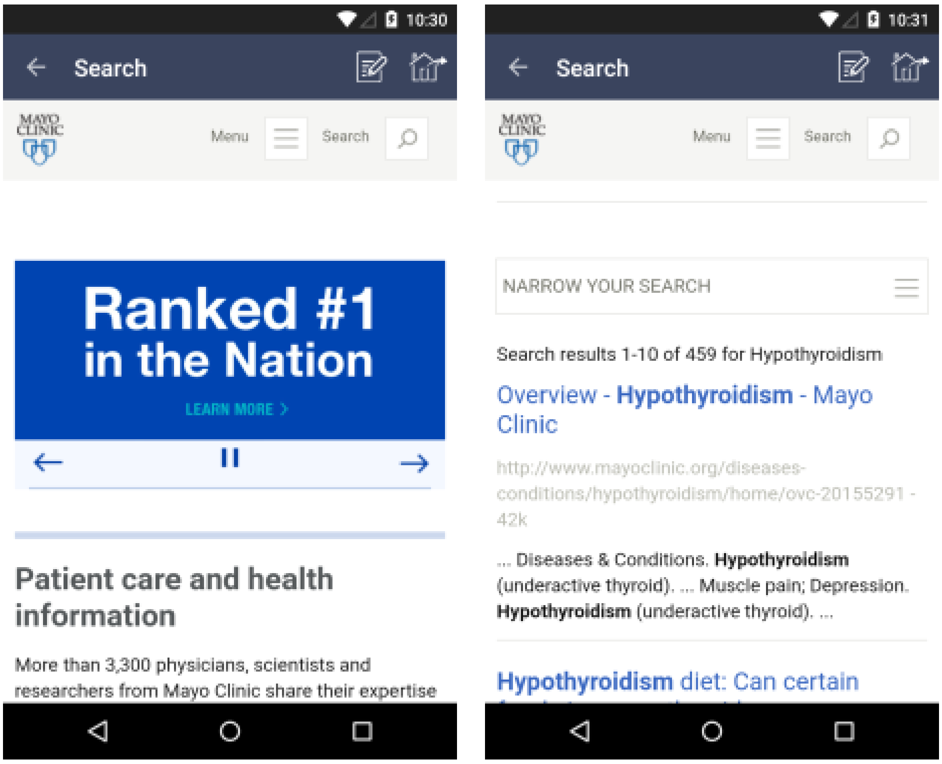



**C**

**Figure 4.5-3 (A) The national early warning assessment form; (B) The national early warning score with user data entry and (C) The summary screen of the completed national early warning assessment with final score and recommendation**

### 4.5.4 Evidence-based Knowledgebase Integration

The app is currently integrated with the 'Mayo Clinic' online clinical knowledge-based to provide the clinicians with evidence-based and authentic medical information at the point-of-care as shown in Figure 4.5-4. The app connects with the knowledge-based within the clinical decision support screen using the search function (text and/ or icon). The user can search any clinical term and browse in-depth information on the overview, symptoms, treatment, plan, medicines, care plans, allergies, relationship with other diseases, laboratory orders and recommendation on the next steps. The user then (or at any time) return to the 'clinical decision support' screen to perform the other activities. The last/previous session will be paused upon navigating away from the screen and will resume when the clinician connects back again with the knowledge-base, without exiting the ongoing activity for high app performance and fast connectivity. The screens of extended 3$^{rd}$ party integration using the Mayo Clinic is shown in the **Appendix I**.




**A** **B**

**Figure 4.5-4 (A) App integrated with evidence-based medical knowledge-base and (B) Clinical workflow and information by using the search term 'Hypothyroidism'**

## 4.6 Contact & Clinical Communications

Figure 4.6-1 shows the clinician contact screen for the clinical user to communicate the patient health condition, results, advice, treatment plan or a specialist consultation using; call, email, message and Skype (telehealth consultation). Easy and transparent communication between the clinicians is a key to overall success of the healthcare delivery. The multidisciplinary team approach requires frequent and fast communication in real-time for the whole care team to act collectively. The proposed app allows the user (clinician) to easily and quickly connect with other care team members using messaging (chatting), call, email (reports, images, etc.) and also a virtual face-to-face consultation using video (telehealth) call.


**Figure 4.6-1 The clinician contact page for on-duty clinician communication via call, message, email and Skype video calling**

## 4.7 Use Case Demonstration of the Health Plus Monitoring Application

### 4.7.1 Use Case #1: Nurse-as-a-user - Monitor Older Adult's Vital Signs at the patient's Bed Side

Mr A is 89 year old, male, lives with his wife in a retirement village. He cares for his wife, who has dementia and has declined services in the past. While he is keen to be as independent as possible, he is becoming very fatigued, unwell and worried about their situation.

Mr A was admitted to a hospital with myocardial infarction, a possible lower respiratory infection, chest pain and congestive heart failure. Mr A was admitted on Wednesday and was very fatigued. The plan on admission was for the acute illness to be managed with antibiotics and diuresis. In the next two days Mr A's vital signs need to be monitored by the duty nurse so that any deterioration could be alerted in real-time for prompt action [115, 116].

In the above scenario, the nurse can monitor Mrs A's vital signs using the Health Plus application, Step-by-step nurse workflow is described below and also shown in Figure 4.7-1.

1) Nurse's first time registration as an application user (one-off only)

2) Login into the app using the registration details

3) Add patient or confirm the patient name, NHI number, ID and date of Birth (first time only)

4) Select the patient (Mr A)

5) Check the medical device connectivity and data transmission

6) Nurse can check current vital signs in real-time, vitals history, manual vital sign entry

7) Nurse can fill standard assessment form or a risk score

8) Add clinical notes for any significant changes

9) Nurse can call, message, Skype, email on-duty consultant, registrar or lead nurse

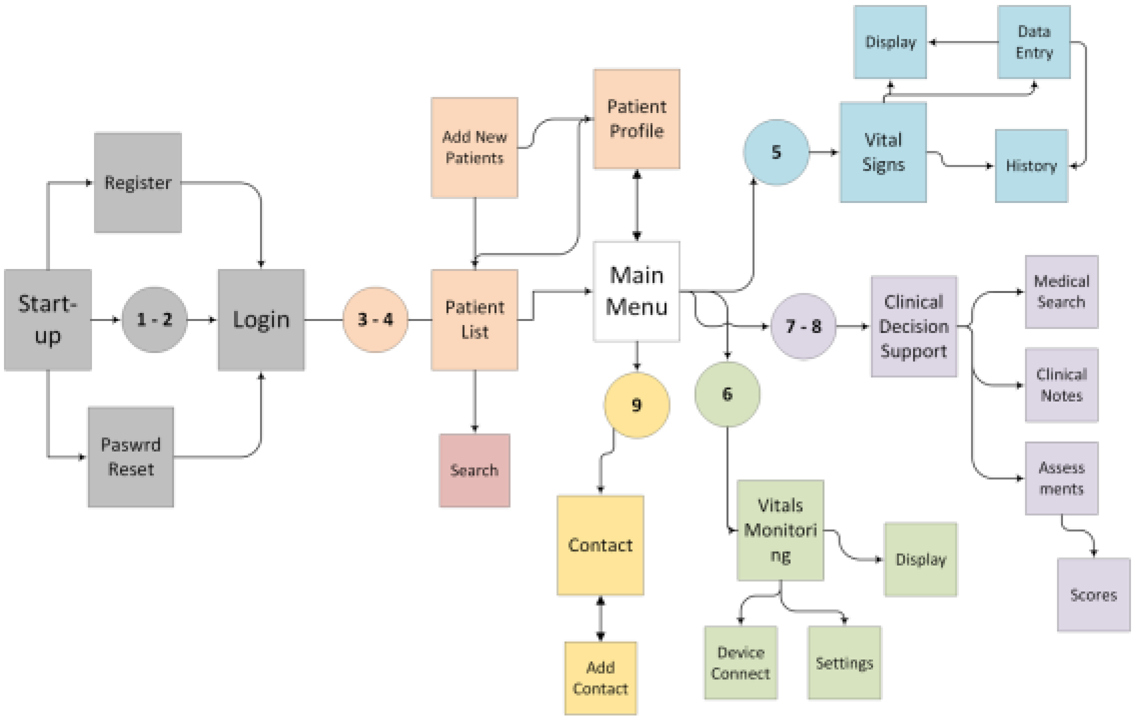



**Figure 4.7-1 Use Case #1 as a Nurse: Monitor Older Adult's Vital Signs at the patient's Bed Side**

### 4.7.2 Use Case #2: Doctor-as-user - Treatment plan for a post-surgical patient using Clinical Decision Support

Patient B is 47 years old, male who arrives in the post-surgical care unit after a successful hip and head surgery. Patient B's vitals were not stable during the surgery, highlighting this, the surgeon requested a repeat of vitals every 15 minutes for two hours.

The nurse noticed the changes in the oxygen saturation and pulse, and notifies the on-duty doctor of the changes in Patient B's status [115, 116]. Doctor can use the Health Plus application to see the Patient B's vital history, recently completed warning scores, assessments and also search evidence-based medical databases for further insights into the patient B's situation. A step-by-step workflow for doctor is described below and illustrated in Figure 4.7-2.

1) Doctor's first time registration as an application user (one-off only)

2) Login into the app using the registration details

3) Confirm the patient first name, last name, NHI, ID and date of Birth

4) Select the patient (Patient B)

5) Check real-time vital signs in graphical view or table view

6) Analyse vital signs historic data

7) Add some clinical notes for next on-duty nurse

8) Check clinical assessment score such as early warning score

9) Search evidence-based knowledge for some possible conditions and care plans and pathways

10) Email the current vital signs to the Heart specialist and a text message as well

11) A video call via Skype to Heart specialist for quick consultation

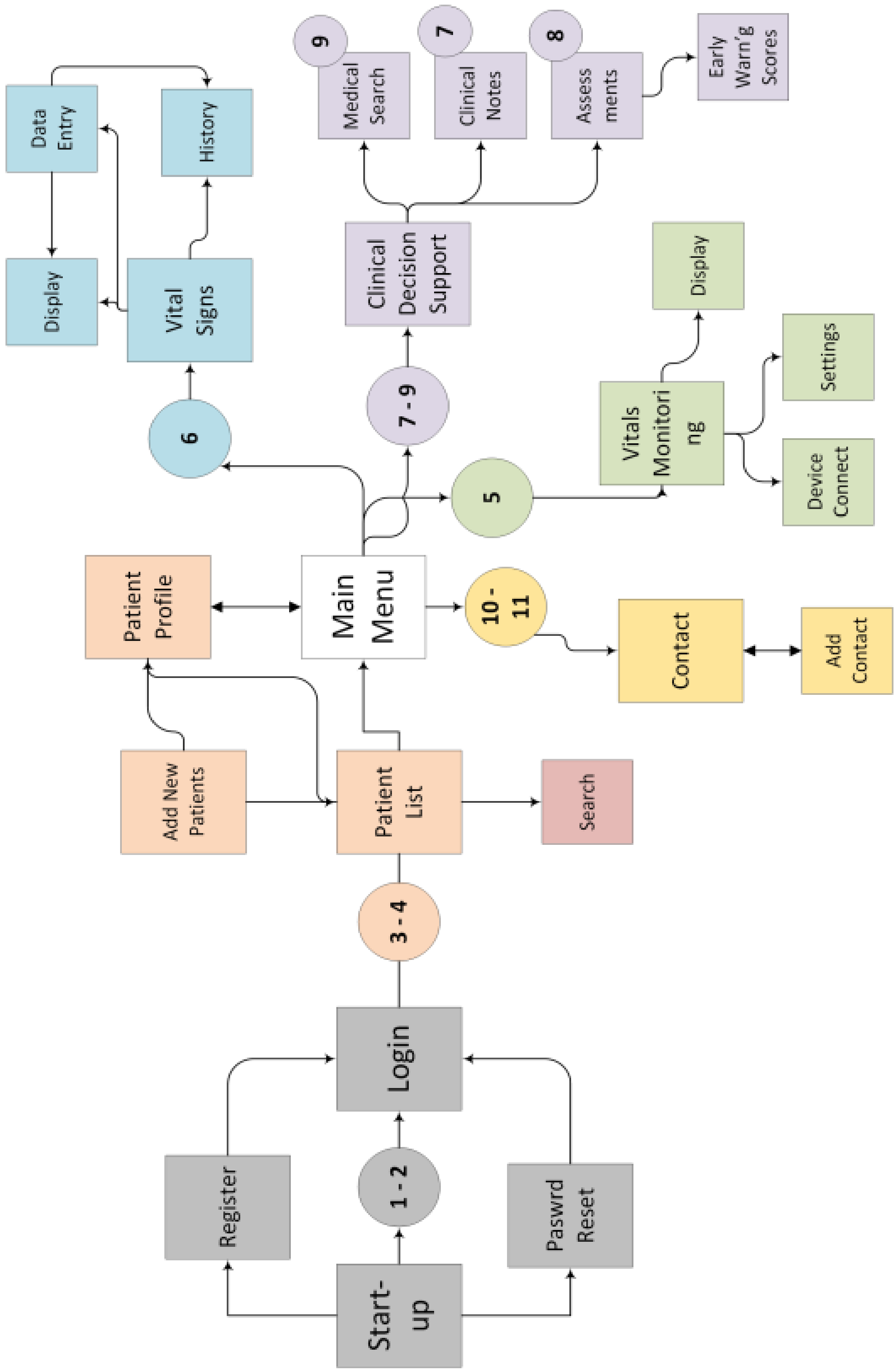



**Figure 4.7-2 Use Case #2: Doctor-as-user - Treatment plan for a post-surgical patient using Clinical Decision Support**

# CHAPTER 5 Discussion and Conclusions

## 5.1 Overview

Mobile healthcare applications currently used as a data collector, data transmitter, information viewer and communicator. Most of the smartphone healthcare app used to collect data from various sensors, wireless medical devices and appliances and surface the real-time raw information with limited time and storage capacity. The collected data is then transferred over the internet to local server or cloud. All that is achievable today due to fast internet, Wi-Fi, 3G and 4G networks. Another element which boosts the global adoption of mobile healthcare application is the uptake of mobile app usage for healthcare, fitness, activity and well-being [117, 118].

There is a good amount of research going on currently on smartphone-based healthcare apps to enable clinicians with easy to view medical information. Initial market analysis suggests that most of the healthcare applications are not user focused and lacks clinical user acceptance, accuracy and stability. An empirical review of 500 best Android apps in the UK market suggests that there is an immediate need to support the healthcare app workflow related to the clinical user and raise the market gap of poor user engagement and user-centric approach [4, 5].

Smartphone-based healthcare monitoring apps are used as a primary tool to collect vital signs (physiological parameters) from the individual, the collected data is available for viewing in raw form, which in some cases confusing for clinician to observe. The collected data then transmitted to a local server or in the cloud using internet protocols, this poses challenges related to the security and privacy and the delays and inaccuracies due to the network errors, especially in critical care settings. Clinicians often uses this information as a base line to understand the individual's range and threshold values (normal and abnormal vital signs) [119]. William and Michael [120] emphasised on the importance of data quality and accuracy particularly for the electronic systems. the stored data is then used for point-of-care decision support and various other data analysis.

This research tried to address the current mHealth application gaps by investigating the global/ standard design concepts of such apps and identified and adopted the best application development frameworks and guidelines. Special focus has been given to the clinician-centred focus and user experience.

## 5.2 Discussion

Vital signs monitoring applications using emerging healthcare technology can establish efficient and reliable way of healthcare delivery. Some advanced features of smart phones including short messaging services (SMS), email, reminders, as well as in-built features such as accelerometer, location tracking, camera, to name a few are also seems to encourage the adoption of mobile healthcare apps in clinical settings. Furthermore, the mobile healthcare applications are now seamlessly integrating with the 3$^{rd}$ party applications, source systems, web services and also with the patient's electronic health record [121]. There are some concerns towards the adoption of this technology which indeed becomes the barrier for global implementation of these systems. For example; security and privacy, reliability, efficiency, acceptability, cost, usability, mobility, clinical testing and system testing under various possible scenarios are some of these serious concerns [26, 83, 99]. Smartphone-based vital signs monitoring applications lack user engagement and clinician involvement into the design and development, which leads to poor uptake, low user satisfaction and may have indirect impact on the overall healthcare delivery. [121]. It has been reported that clinicians cannot use monitoring applications because they are too complex to use and difficult to operate

[122]. Therefore, such applications are of little use for such users even though the application's overall performance is acceptable.

This research is backed by the strong literature review to understand and establish the current gaps in the smartphone-based healthcare applications in acute care settings (hospital). Due to the mobility, the issue of data privacy and security is the most identified, followed by the accuracy and usability. There is a growing evidence available that identifies the user experience, user engagement and user acceptance is also equally important and should be addressed. Currently, there is no balance between the technical design and development vs information presentation, which could be a reason delaying the global adoption of mobile healthcare application, especially in acute care, outpatient and community care settings.

The key findings of this research work, covering the core issues and challenges with the mobile healthcare monitoring apps are given below:

- Smartphone-based monitoring apps lack the fundamental understanding of 'Why' and 'Who' – Majority of apps are heavily focused on the technical considerations to make it a clinical success and thus, failing the clinical acceptance globally. The negligence of user engagement from the early design stage to final development stage is required to match the technology with the clinical care scenarios, as discussed in Section 2.2. Limited apps are available for the clinicians as a user for acute care settings, due to the low accuracy, no clinical focus and unable to manage the complex acute care workflows.

- It is evident from the literature that there is a clear gap in user experience and user engagement with the mobile healthcare apps designed and developed for clinicians. Poor user experience is causing the delay or slow uptake of mobile apps in healthcare settings, which is also posing some serious challenges towards the global adoption of such technology in acute care settings. As discussed in Section 3.3, there is an immediate need of a mobile healthcare app design and development framework to serve as a standard protocol and guideline with developing the apps for clinicians.

- Medical device integration is a key to success for mobile healthcare applications due to its mobility and the global increase in the wireless medical device advancements (IoT). The integration between IoT/ medical devices and the apps is a current challenge to realise the fully integrated healthcare application. Section 2.4 covers the current issues and challenges need to be addressed.

- The complexity of CDS computation requires significant amount of processing power during data analysis and also at the time of processing/executing the complex clinical decision support algorithms/ models. These complex models are beyond the current capabilities of the ubiquitous devices to support point-of-care delivery.

The proposed application attempts to address the above challenges, the major learning outcomes and key contributions are highlighted in Section 5.3.

## 5.3 Conclusions

### 5.3.1 Major Learning Outcomes

The key topics covered in this research are:

- Smartphone-based Vital Signs Monitoring Application
- Development of the 6S framework for mobile healthcare apps

- Medical Device Connectivity, integration and Interoperability
- Real-time Clinical Decision Support functionality

#### *5.3.1.1 Smartphone-based Vital Signs Monitoring Application*

Majority of development in patient monitoring applications have focused on specific use-case, age group or a specialty. Bergmann and McGregor conducted the study on the acceptance of mobile device among the older adults (60 years and above). The study found that the 90% of the participants were satisfied with the use of mobile technology and use of wireless wearable medical devices for vital signs collection. However, due to the low number of participants and very focused intervention, it is difficult to justify the acceptance for the whole age group, nevertheless an encouraging and positive outcome for the healthcare apps [121, 123].

The proposed application answers some of the above questions by adopting the best-practice standards and guidelines for the functional design and development of the application. The app targets the key gaps in this by using clinician-as-a-user and is used in acute care settings. Moreover, the underlying app architecture enables to capture and store the structured data to perform rich clinical decision support in real-time within the app. This research highlights the real innovation in clinical decision making by using the collected clinical data effectively to provide clinicians with rich decision support at the point-of-care.

#### *5.3.1.2 The 6S Framework for Mobile Healthcare Application User Experience*

There is an immediate need to adopt the global best-practice guidelines/ framework for the mobile healthcare apps for consistent and efficient user experience. This seems as a key barrier towards the global mobile healthcare application adoption, especially in the acute care, critical care and emergency care settings. The user experience is also closely related the simple to complex matrix for the app, as discussed in Section 3.3.3. It is simple to manage a stand-alone app with high user experience but it is very difficult to get higher user acceptance for a complex mobile healthcare app due to the management of information from multiple sources. The proposed app tries to address the common issues related to the user experience, such as, balance between too much and too few info on each screen, too many steps required to complete a task, use of image/ icons vs text, workflow requiring navigation in and out of the app and active vs passive interaction with the user for personalised user experience [124-127].

##### *5.3.1.3 Medical Device Connectivity and Interoperability*

This research reviewed the literature and functional design concepts for wireless sensors and devices and identified the current market gaps and challenges in terms of data quality and accuracy; security and privacy; cost and availability and user acceptance and user experience. Moreover, this project has highlighted the potential of deployment of such technologies and believe that wireless medical devices/ sensors/ wearable technology has been one of the leading edge and immensely evolved technologies over the last decade. This research also examined how advances in such technology could be achieved by improving the above-mentioned issues and challenges.

### 5.3.2 Clinical Decision Support

Today, majority of clinical applications have some sort or shape of basic-to-intermediate intelligence available to support the clinician make better and informed decisions [128-130]. Some of the basic decision support available for clinicians are:

- Clinical documentation: clinical documentation with decision support rule/ algorithm such as early warning score or nursing assessments, scales, etc.

- Alerts, reminders, warnings, notifications, actions and tasks.

- Viewing information: best-practice guidelines, standard protocols, medical knowledge-base and evidence-based clinical information.

### 5.3.3 Issues and Challenges

Two core 'areas of concerns' identified, which are related to smartphone technology have appeared as the product of this work, and they may serve as a useful guide for researchers, engineers and medical professionals towards improving hospital care in using smartphone computer-based healthcare apps. Firstly, clinicians and patients are the underused resources in smartphone apps design and development; early collaboration of developers and clinicians along with the target users are critical towards the successful healthcare apps being implemented in the hospital care settings. Secondly, appropriate use/representation of data including data analysis, interpretation, translation, integration and processing should be transparent and presented to the medical professional in a simple and easy to understand. As the new data sources are emerging, it is critical to represent the raw data in a meaningful/useful way, so that the clinicians are supported the rich information at the point-of-care to make appropriate treatment decisions. Currently, most systems lack clinical or secondary care implementation; very few apps are available today which incorporate and address all the critical aspects of the smartphone apps including design, development, implementation and user/clinicians collaboration.

## 5.4 Future Work

Further enhancements to the patient monitoring application will mature the current application to better handle the clinical care environment.

Some of the areas to make further improvements are user experience to increase the overall application's user experience. Another area is the real-time synchronisation of patient data by using cloud as a back-end service. Although the current application manages fairly moderate clinical decision support mostly nursing assessment and scores, the application cannot handle or monitor the complex decision support using any 3rd party data integration or a complex care pathways.

### 5.4.1 Future smartphone-based CDS applications

Future CDS applications must leverage existing capabilities of the sophisticated features (hardware and software) of the ubiquitous devices and integrate with the electronic patient health record (EPHR) [131]. Smartphones in contrast to personal computers, bring in much needed 'flexibility' and mobility to perform the critical tasks on-the-go, very useful in the healthcare settings [132]. Smartphone's advanced built-in sensors and functionality is understood to be one of the driving forces towards the global adoption of such technology in hospital care [133]. There is some promising research going-on which may help the adoption of mobile healthcare applications with sophisticated clinical decision support functionality [78, 134-137].

It is quite early to establish the success of smartphone application (especially their decision support capabilities) in hospital care. However, the literature suggests mobile health applications (using ubiquitous devices) are fast emerging as a decision support tool for clinicians in hospital care [72].

### 5.4.2 Machine Learning in Healthcare

It is forecasted that the healthcare information could be uploaded on to the cloud where pieces of observations from all the ubiquitous devices would be integrated. Furthermore, by utilizing data analytics and machine learning techniques could be applied to the healthcare for precise care, accurate outcomes and individualised treatment (precision medicine) [138, 139].

### 5.4.3 Improvements in Overall Mobile Application Workflows in Clinical Care Settings

Clinical workflows such as electronic medical records, nursing communication tools and personal health records are required to be connected to the wider healthcare delivery ecosystems for efficient clinical outcomes. The smartphone-based clinical decision support applications could be seen as a potential standard/ best practice tools that will help the clinicians to deliver better and accurate outcomes. Some of the identified and recommended enhancements in this area could be:

- The design, implementation and evaluation of these technologies require rigorous and systematic workflow methodologies. The patient-orientated workflow methodology and the available automated tool can assist researchers with collecting data that can greatly help clinicians in decision making [90-92]. Ng et al. [140] recommended five main characteristics of smartphone apps in order to be clinically acceptable: (1) Information exchange to support such apps, (2) Evaluation of apps including testing and user training, (3) Careful planning to develop robust and safe application (4) Stakeholder involvement towards decision support tools and (5) traditional face-to-face interaction should not be reduced or compromised and final decision making should be based on the clinicians' experience and knowledge and not on the smartphone application's recommendations [141, 142].

- The use of fully integrated application in acute care can achieve huge clinical as well as financial value. The current app is integrated to medical devices and there is a lot of room to further integrate such apps with patient health record, laboratory system, radiology information systems, ordering tests and collecting blood results, etc. which all can be processed by the mobile apps using 3rd party secure APIs – this is a current challenge but likely future for mobile healthcare apps.

- Using the in-build feature, such as camera, can be used for accurate patient identification before giving medicines, any treatment plan, etc. This is possible using the patient's barcode printed on the patient's wrist band and turning it into the QR code so that the mobile app can be used as point-of-care patient identification tool.

- The use of sophisticated clinical tools and algorithms could be processed in the cloud using the collected data automatically. The clinician will be provided with the latest risk score automatically using the machine learning in the background (on the cloud) and only push the key alerts, notifications and reminders on the mobile application.

- There is a high need for such apps at the patient's bed-side, replacing the current manual process of vital signs collection. The automation in vital signs with accuracy will provide clinician with timely and informed decision support to take appropriate actions.

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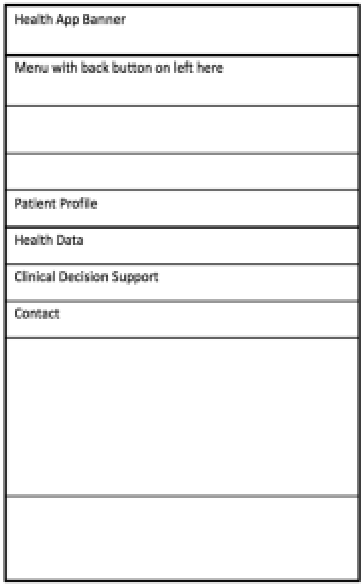
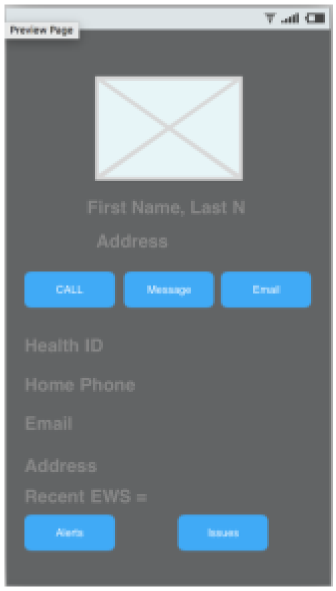
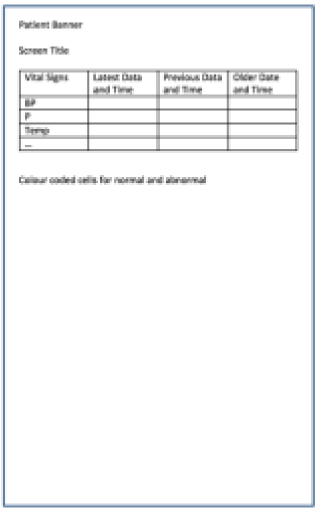
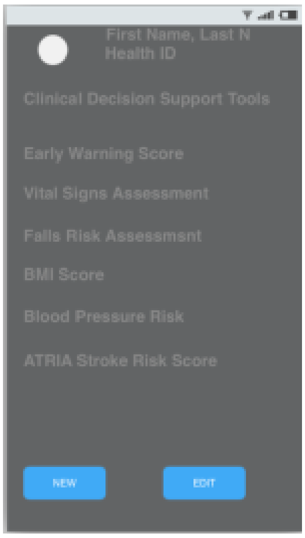
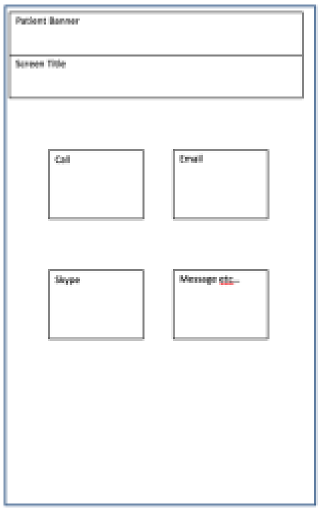
# Appendix A – Initial Application Design Sketches

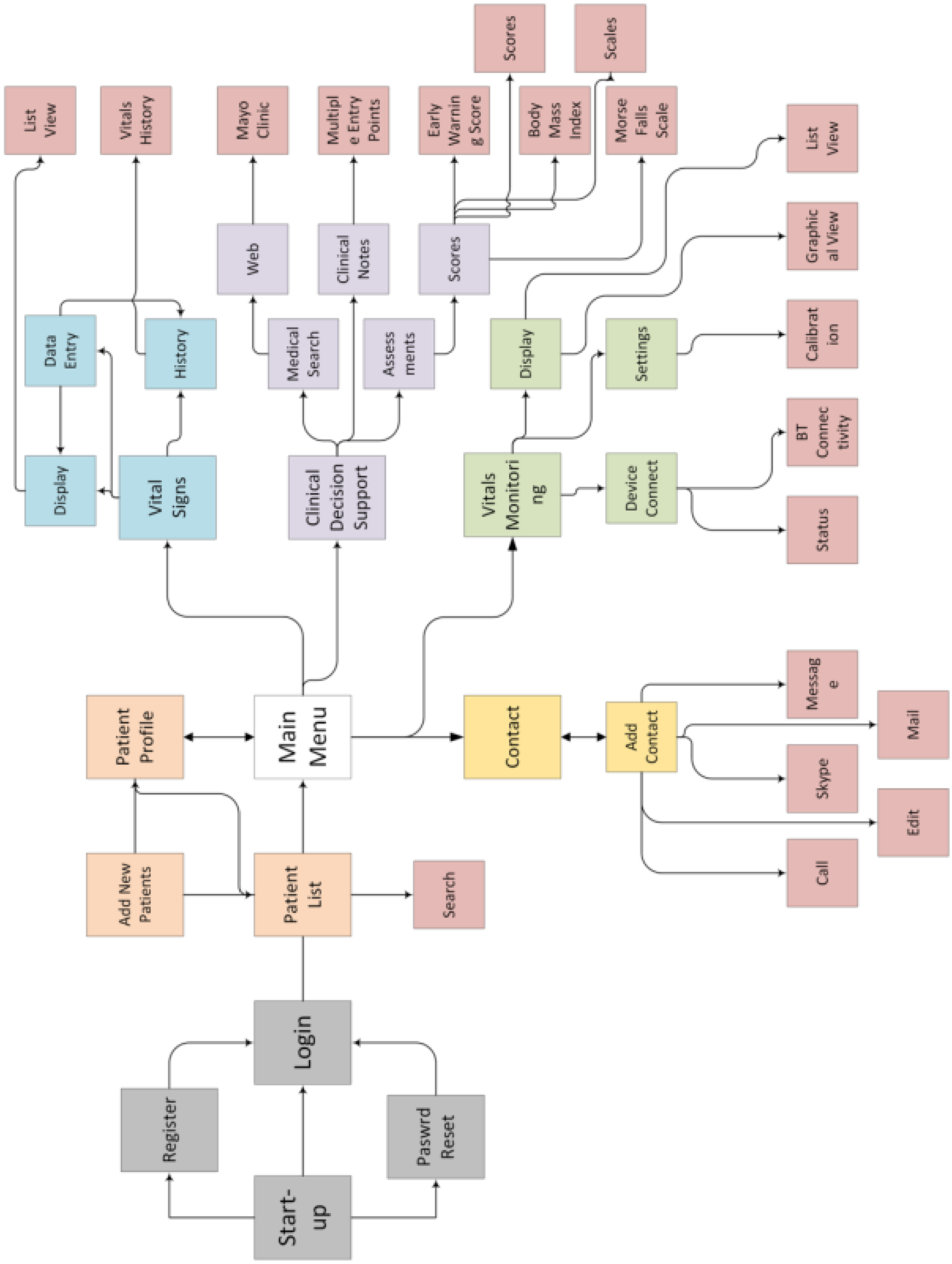



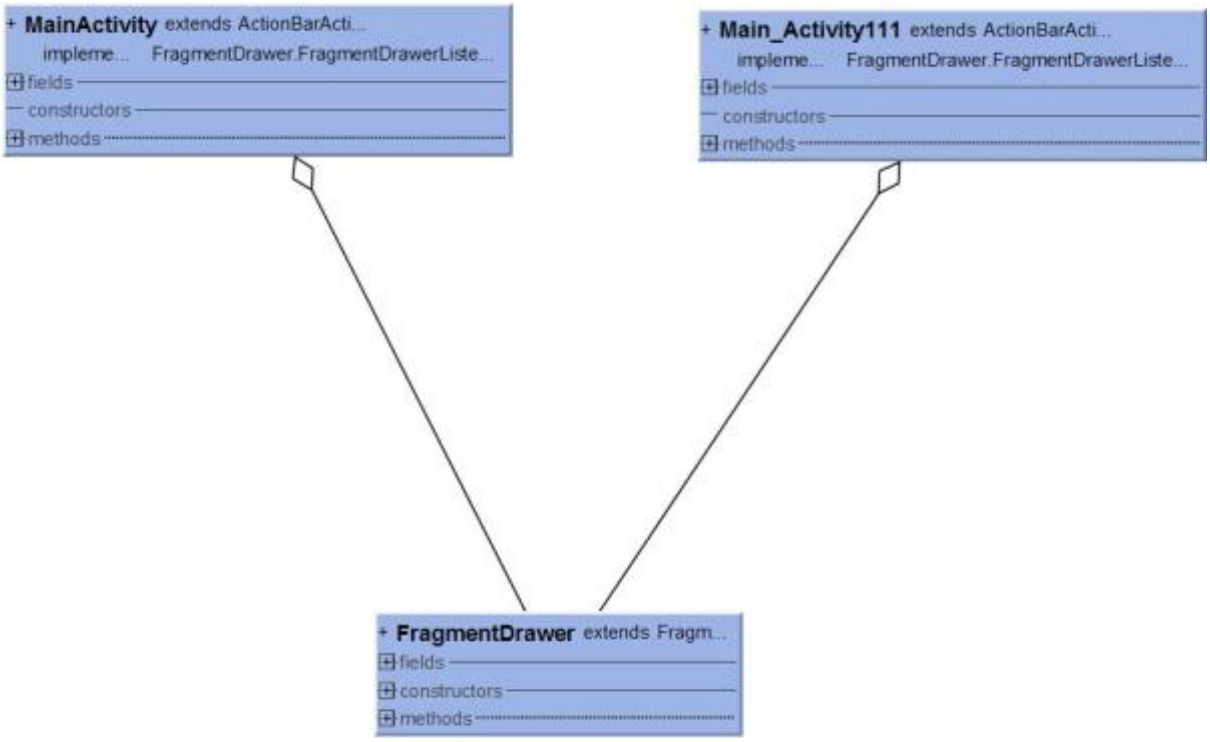



# Appendix B – Extended Design Architecture Diagram



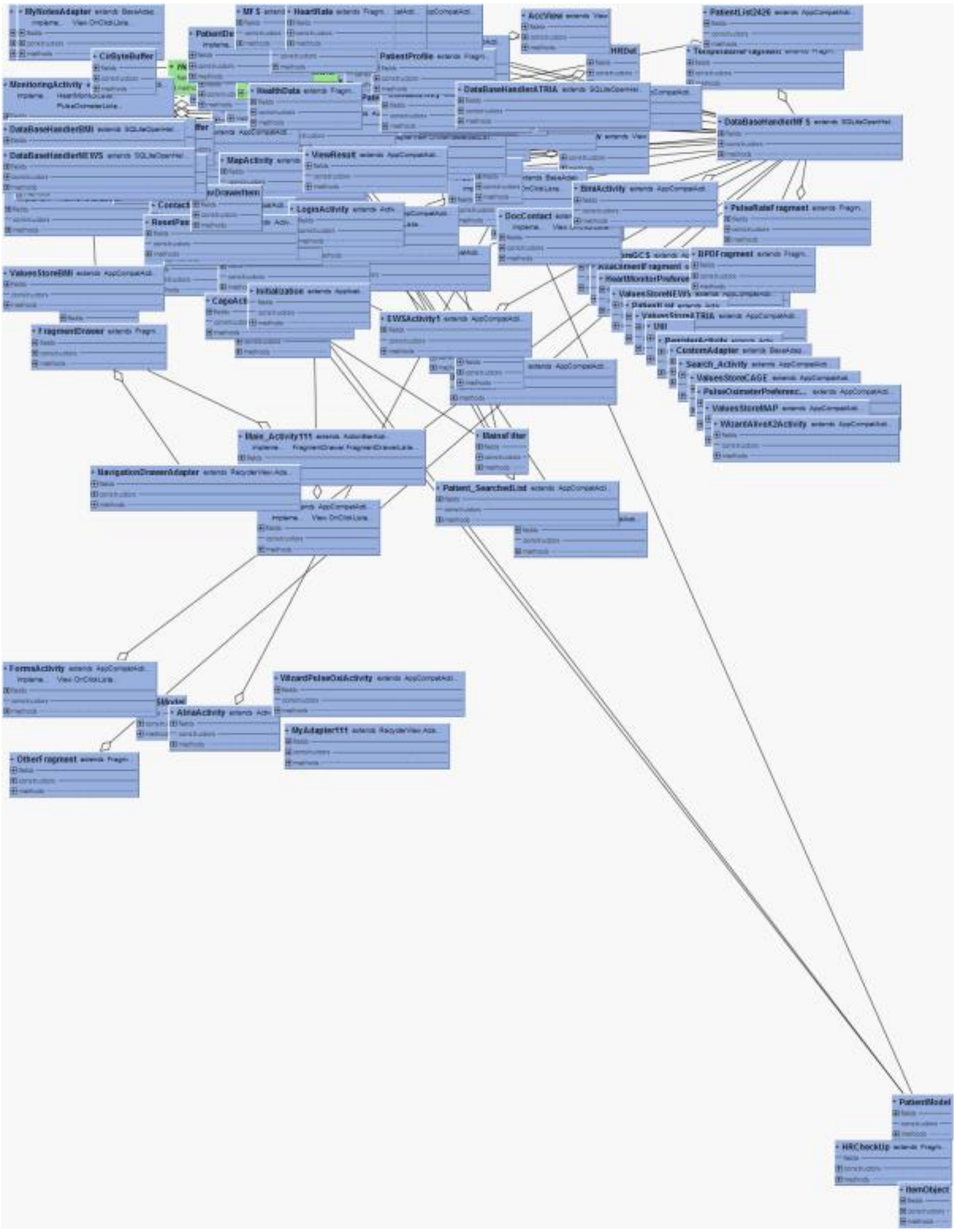
# Appendix C – The Unified Modeling Language (UML)

## Class Diagram (partial view)

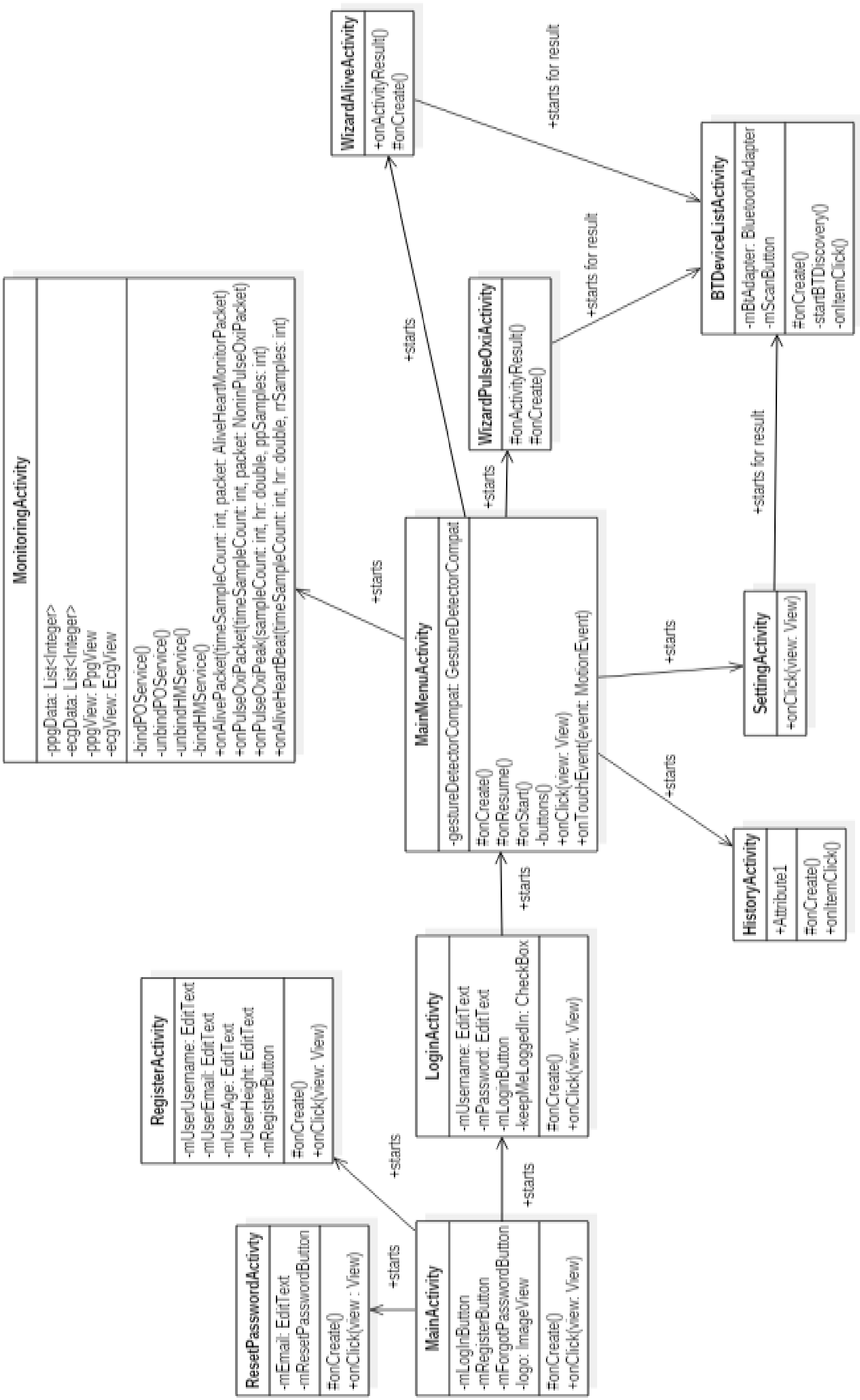


# Appendix D – The Unified Modeling Language (UML)

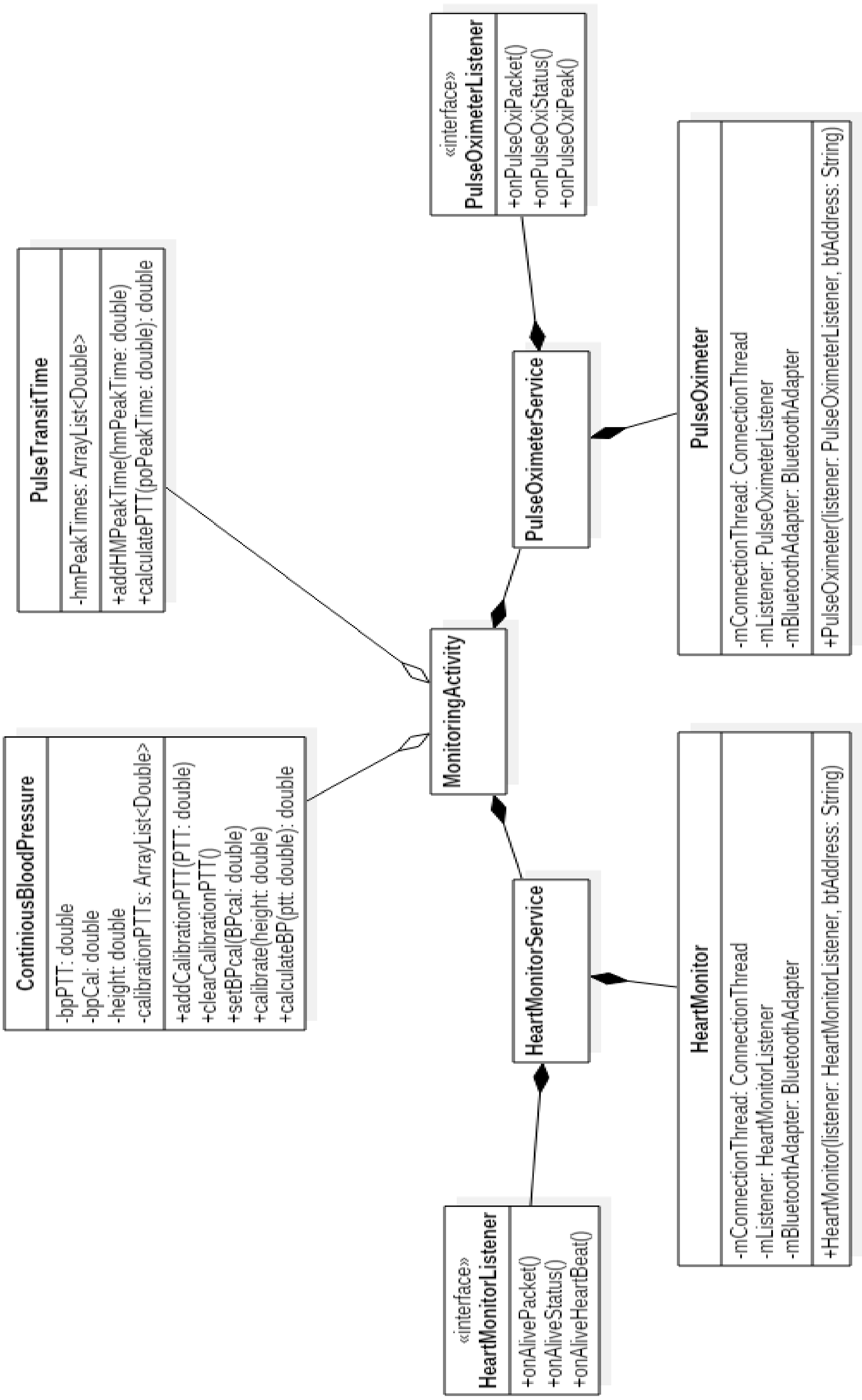
## Class Diagram (full view)



# Appendix E – The Class Diagram for the Activity Class of the Heart Guardian Application



# Appendix F – The Class Diagram for the Associated Classes of the MonitoringActivity Class



# Appendix G – The Code Snippets of medical Device Integration

```java
// Create the result Intent and include the MAC address
Intent intent = new Intent();
intent.putExtra(EXTRA_DEVICE_NAME, btname);
intent.putExtra(EXTRA_DEVICE_ADDRESS, btaddress);

// Set result and finish this Activity
setResult(Activity.RESULT_OK, intent);

finish();
```

**The selected device name and address added to the activity**

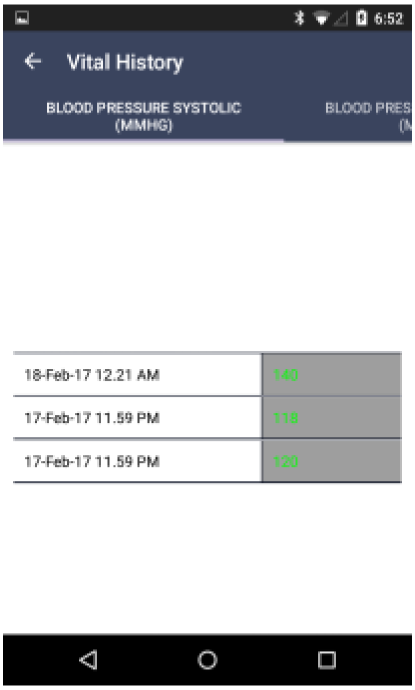
```java
@Override
protected void onActivityResult(int requestCode, int resultCode, Intent data) {
    super.onActivityResult(requestCode, resultCode, data);
    if (resultCode == RESULT_OK)
    {
        SharedPreferences prefsHM = HeartMonitorPreferences.getSharedPreferences(this);
        SharedPreferences.Editor editor = prefsHM.edit();
        editor.putString(HeartMonitorPreferences.PREF_HM_BTNAME,data.getStringExtra(BTDeviceListActivity.EXTRA_DEVICE_NAME));
        editor.putString(HeartMonitorPreferences.PREF_HM_BTADDRESS,data.getStringExtra(BTDeviceListActivity.EXTRA_DEVICE_ADDRESS));
        editor.apply();
        finish();
    }
}
```

**In ‘onActivityResult’ the device name and address are stored**

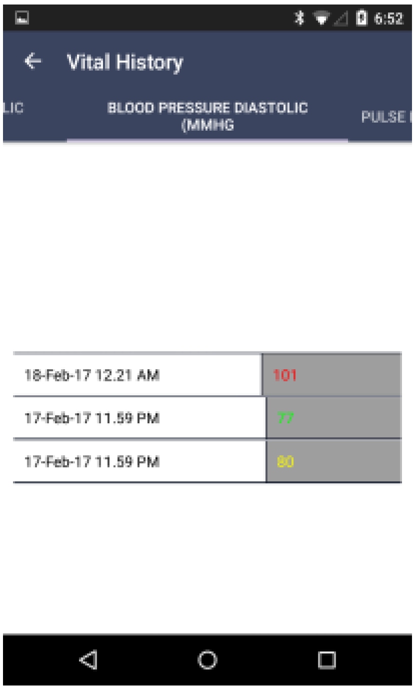
```java
// Look up preferences to see what connections to start
SharedPreferences prefs = PulseOximeterPreferences.getSharedPreferences(this);

mBTAddress = prefs.getString(PulseOximeterPreferences.PREF_PO_BTADDRESS, "");

if(mBTAddress.length()>0 && pulseOximeter ==null) {
    mStatus = PulseOximeterStatus.PO_STATUS_CONNECTING;
    pulseOximeter = new PulseOximeter(this,mBTAddress);
    pulseOximeter.startConnection();
    mRunning = true;
```

**The ‘onStartCommand’ method for a medical device**

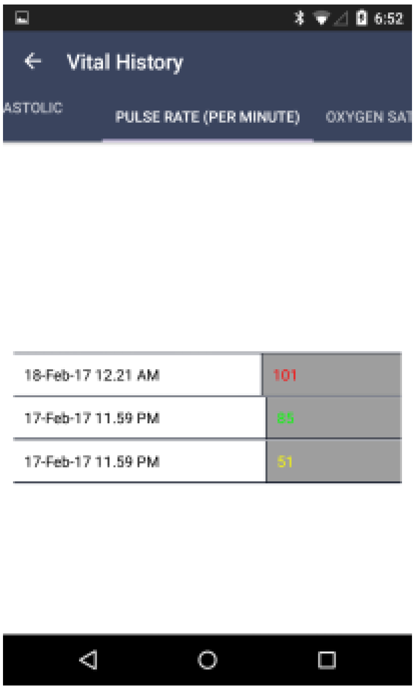
# Appendix H – The Extended Screens of the Historic Data



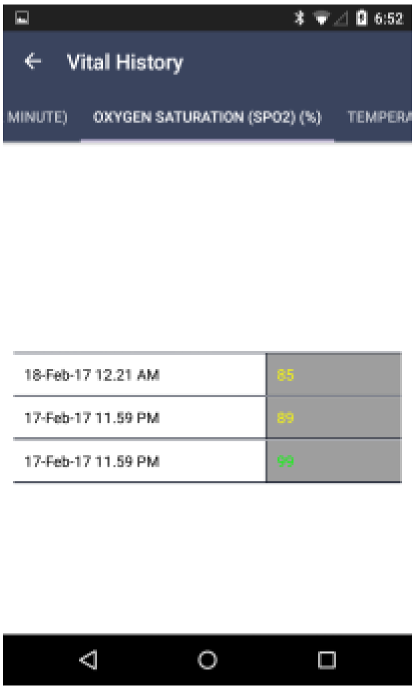

**Vital History: Blood Pressure Systolic**



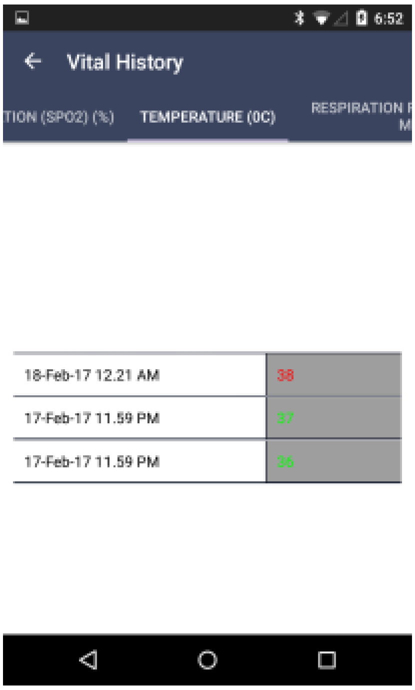

**Vital History: Blood Pressure Diastolic**



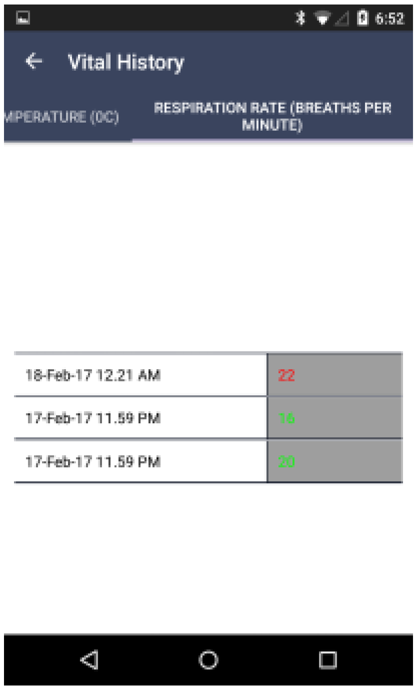

**Vital History: Pulse Rate**




**Vital History: Oxygen Saturation**

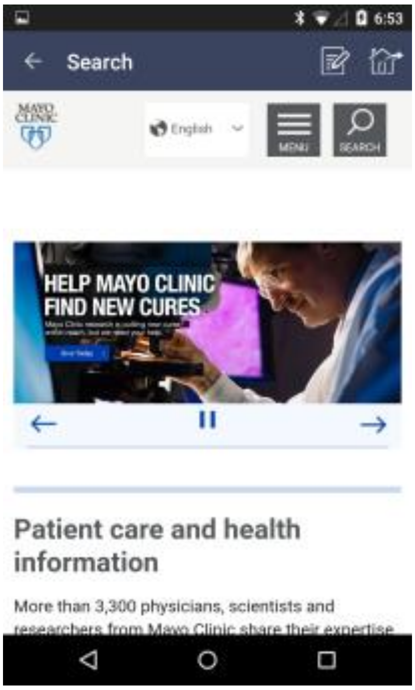



Vital History: Temperature

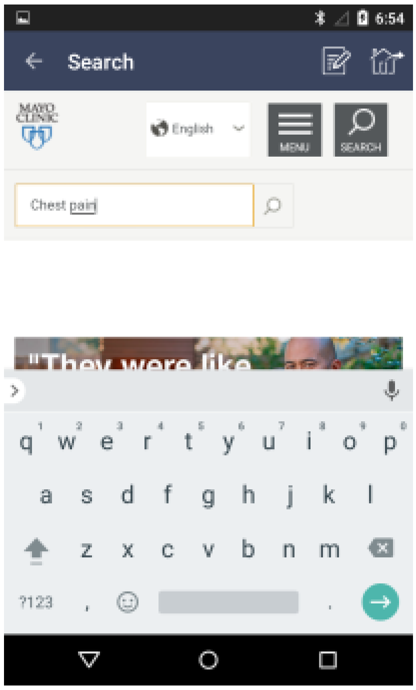



Vital History: Respiration Rate

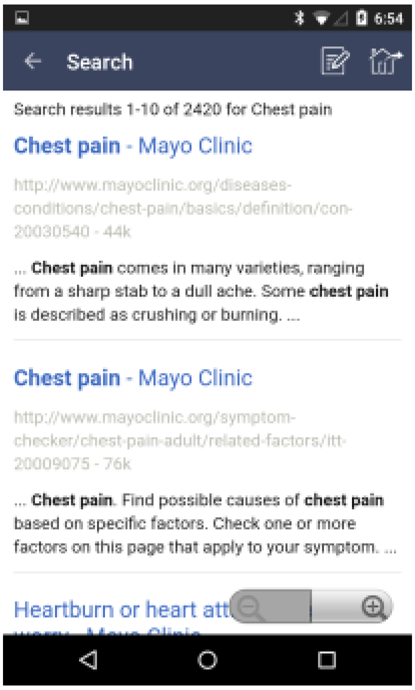
# Appendix I – The Extended Screens of Evidence-base



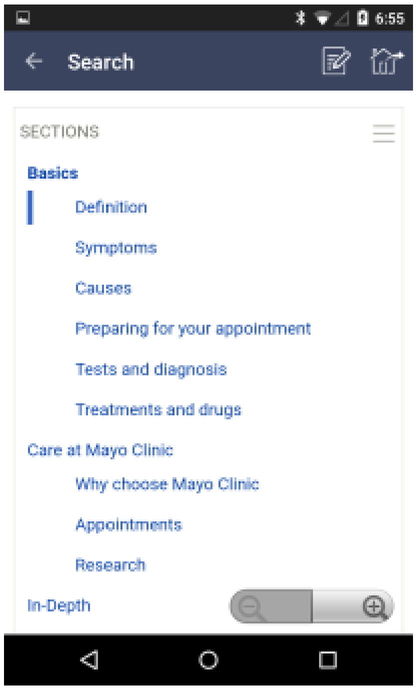

**Decision Support: Mayo Clinic home**



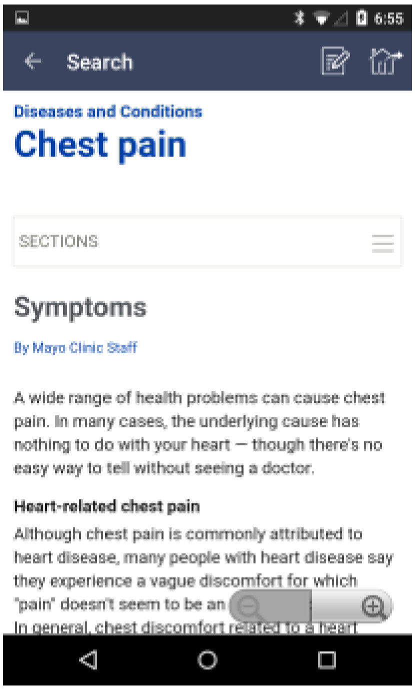

**Decision Support: Mayo Clinic search**



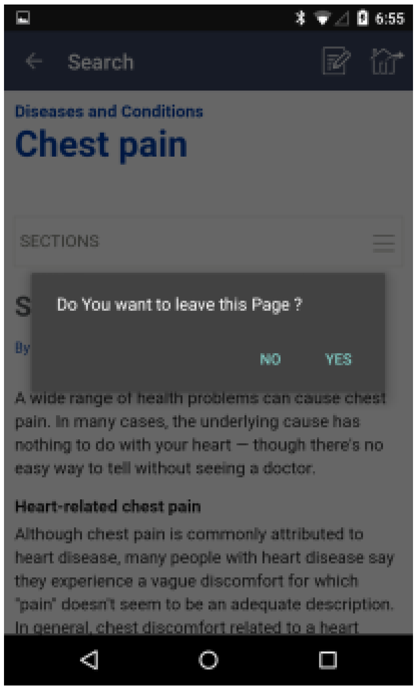

**Decision Support: search 'chest pain'**




**Decision Support: Clinical knowledgebase**




**Decision Support: 'chest pain' symptoms**




**User warning when leaving the screen**