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iCloudECG: A Mobile Cardiac Telemedicine System

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To the Graduate Council:

I am submitting herewith a thesis written by David S. Clifford entitled "iCloudECG: A Mobile Cardiac Telemedicine System." I have examined the final electronic copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Biomedical Engineering.

Xiaopeng Zhao, Major Professor

We have read this thesis and recommend its acceptance:

William R. Hamel, Qing Cao

Accepted for the Council:

Carolyn R. Hodges

Vice Provost and Dean of the Graduate School

(Original signatures are on file with official student records.)

iCloudECG: A Mobile Cardiac Telemedicine System

A Thesis Presented for the
Master of Science
Degree
The University of Tennessee, Knoxville

David S. Clifford
December 2015

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Abstract

With rising healthcare costs and a substantially growing number of patients 65 or over, the benefits of telemedicine and patient self-monitoring systems are becoming increasingly evident. Patients, physicians, hospitals, and even insurance providers benefit from vigilant, cost-effective patient monitoring systems. This thesis describes the development of a portable, smart-phone connected system for continuous cardiac monitoring. The system is capable of continuously monitoring the conditions of the heart, automated detection of cardiac arrhythmias, and real-time notifying patients and physicians of the detected abnormalities. The system consists of four main subsystems: 1) a Bluetooth capable chest-strap ECG, 2) an Android-enabled mobile device, 3) a cloud-based analysis, storage, and notification system, and 4) a web-application portal. Data is collected by the single-lead ECG device, and transmitted to the mobile device via Bluetooth. An application allows the patient to view their ECG output in real-time, view the last 24 hours of recordings, and receive notifications and details regarding any detected abnormalities. The mobile device transmits the ECG data to a remote server for pre-processing and analysis, and then stores the data in a database which the patient or physician can access via a web-interface. The developed system can be used as a telemedicine system for management of cardiovascular diseases.

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Chapter 1

Introduction and General Information

Background

In the United States, medical expenditures accounted for 15% of the gross domestic product [1]. Cardiovascular disease (CVD) made up 15% of the total medical expenditures. The costs of CVD related diagnostics, procedures, and medications have steadily increased by approximately 6% every year for the past decade [1]. In 2014, the Centers for Disease Control and Prevention reported 26.6 million cases of CVD related illnesses—approximately 1 in 10 Americans—611,105 of which were fatal [2]. In the face of the nation's leading cause of death, and its associated costs, researchers and engineers have turned to various systems to streamline CVD diagnosis, monitoring, and treatments.

Electrocardiographic (ECG) devices are widely used, not only in cardiology, but also in general medicine to evaluate patients' cardiac activity. The device measures the surface potentials created on the thoracic surface by transmembrane potentials in cardiac tissue [3].

Figure 1 shows a typical ECG measurement throughout one electrical cycle of the heart. From the reading, three prominent waveforms can be seen—the P wave, QRS complex, and T wave. The P wave corresponds to the depolarization of the heart's atrial chambers, and the QRS and T waves correspond to the depolarization and repolarization, respectively, of the ventricular chambers.

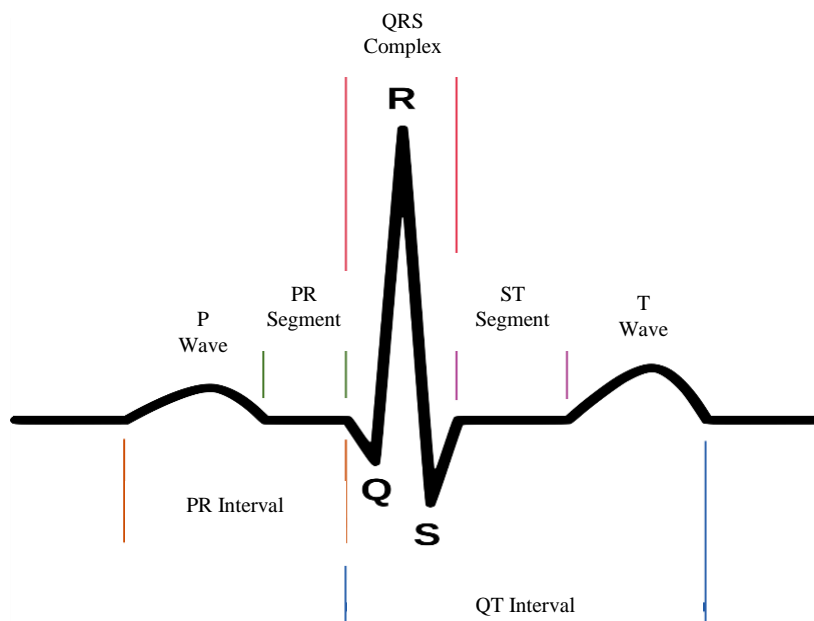


Figure 1 – Example of a normal ECG wave reading cycle; modified from [4].

Figure 2 gives a visualization of the thoracic surface potential (left) created by the electrical propagation through the cardiac tissue (right) at a single instance in time during the cardiac cycle. As time varies, the intensity of the surface potential changes corresponding to the wave fronts that can be seen on the figure. As these wave fronts propagate, the ECG device measures this surface potential intensity at the electrode placement points on the thorax [5], labeled according to standard 12-lead ECG convention. Changes in the conductivity of the heart tissue, the function of pacemaker cells, etc., affect how the electrical waves propagate through the heart, thus affecting the resultant thoracic surface potentials picked up by the ECG device [6].

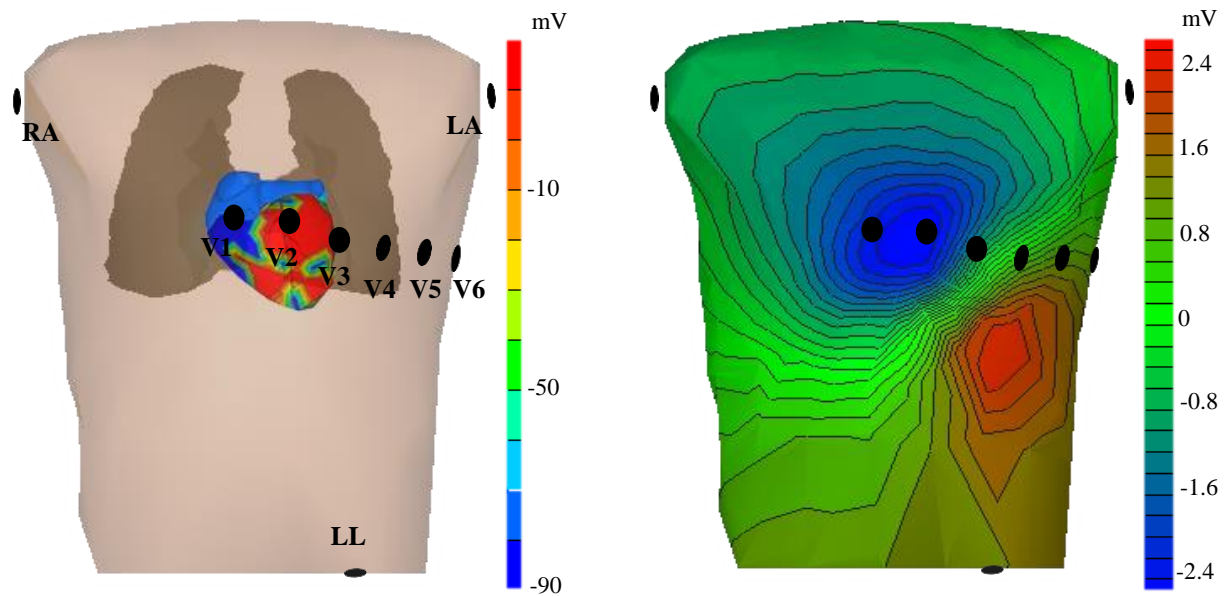


Figure 2 – Visualization of electrical propagation through cardiac tissue (left) and the resultant thoracic surface potentials (right). Black dots represent electrode placements. Generated using ECGSim software.

Figure 3 shows the typical 12-lead ECG measurements corresponding to the surface potential magnitudes at each electrode seen in **figure 2**. Leads *I*, *II*, and *III* are known as the standard limb leads, leads *aVR*, *aVL*, and *aVF* are known as the augmented limb leads, and *V1-V6* are the chest leads. The standard 12 leads are defined as follows [4]:

$$I = LA - RA$$

$$II = LL - RA$$

$$III = LL - LA$$

$$aVR = RA - \frac{1}{2}(LA + LL)$$

$$aVL = LA - \frac{1}{2}(LL + RA)$$

$$aVF = LL - \frac{1}{2}(LA + RA)$$

$$Vi = Vi - Ground \quad (i = 1, 2, 3, 4, 5, 6)$$

We can see from **figure 2** how electrical propagation through cardiac tissue results in the thoracic surface potentials measured by the ECG. Thus, changes in how the electrical waves move through the cardiac tissue, caused by damage or abnormal development, result in changes of thoracic surface potentials. This is how the abnormalities are able to be detected using ECG devices. For instance, atrial fibrillation (AFib) is the most common sustained cardiac arrhythmia in the general population[7]. **Figure 4** shows a typical ECG reading of a patient diagnosed with AFib. This is caused by very rapid, irregular, and uncoordinated stimulations, known as fibrillatory waves,

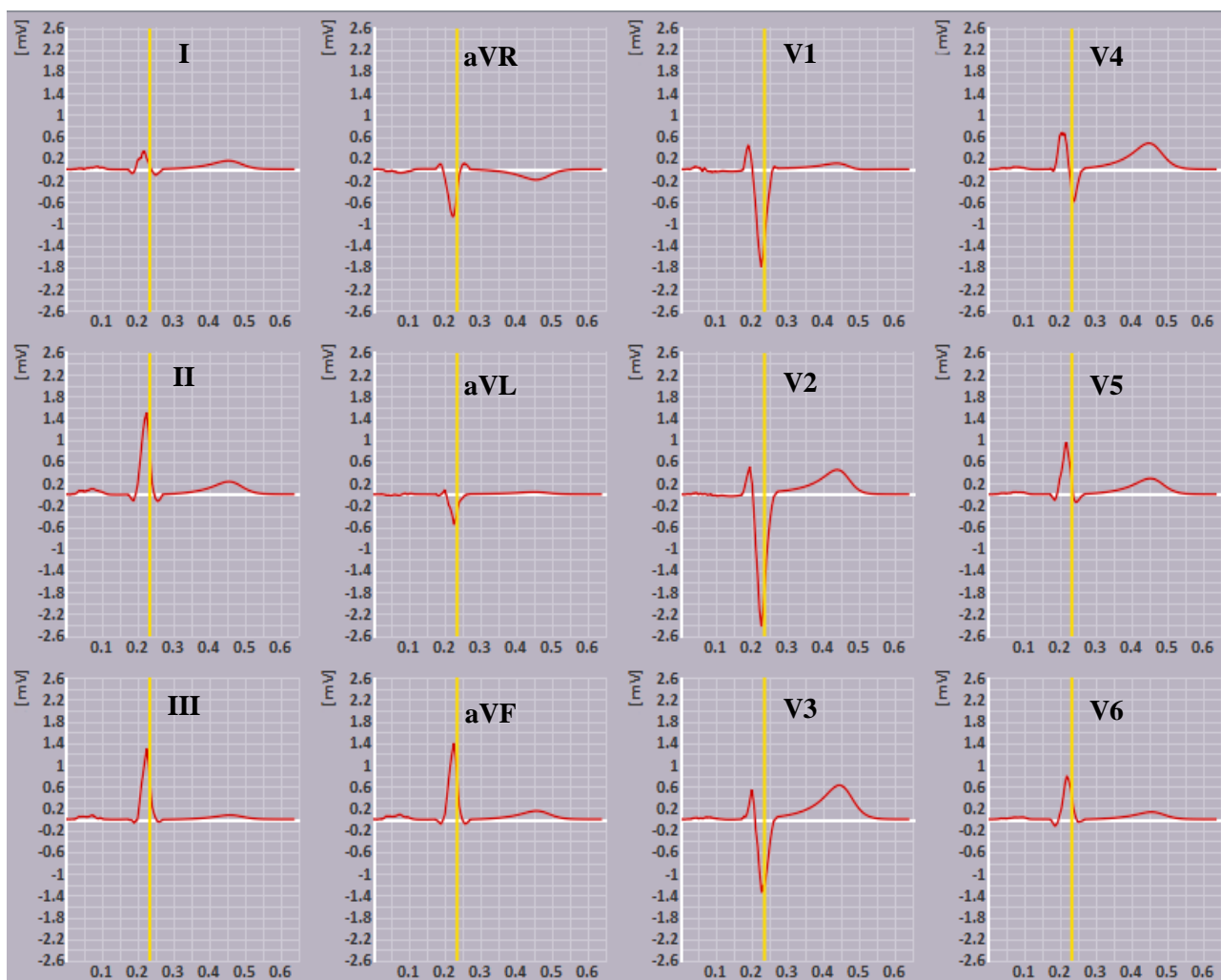


Figure 3 – 12-lead ECG readings corresponding to figure 2.

Generated using ECGSim software

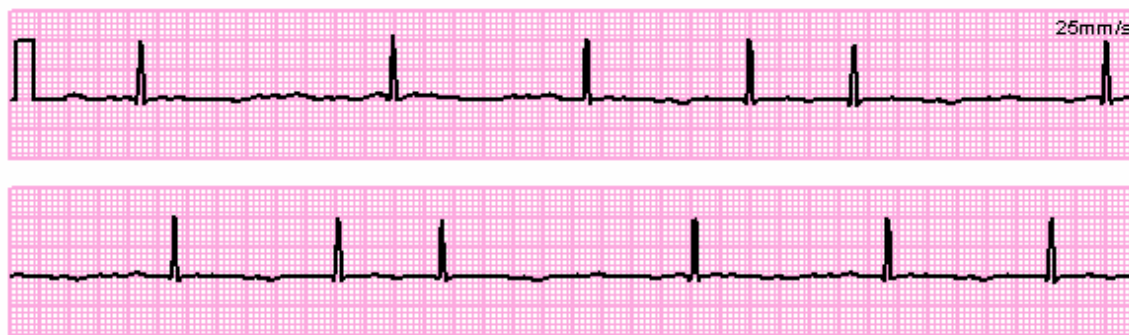
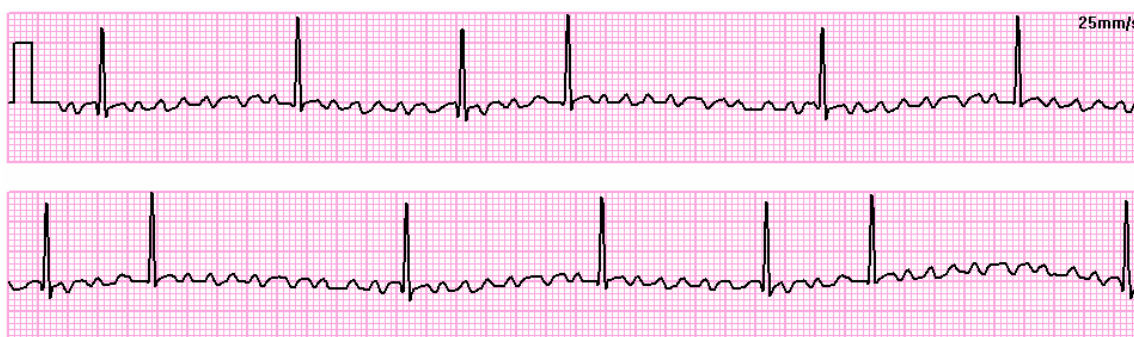


Figure 4 – A characteristic ECG waveform of a patient with atrial fibrillation; copied from [8].

through the muscle fibers of the atrial walls [9]. The atrioventricular node—the connection point between conduction pathways of the atria and ventricles—filters out many of the rapid atrial pulses, resulting in a slower, but still irregular, rate of ventricular stimulation [7]. In the ECG reading, the irregularity of the R waves, corresponding to ventricular depolarization (contraction), can be observed—however, there are no P waves present. Since the fibers in the atrial wall are firing so chaotically, the atria do not experience a whole, coordinated contraction, which would normally produce a distinct P wave.

Figure 5 shows the characteristic ECG reading of a patient with atrial flutter (AFl) which is a condition where re-entrant signals in the atria cause an abnormally fast atrial cycle rate, but in contrast to AFib, these cycles are more regular [10]. Since the rapid stimulation is caused by a re-entrant signal, rather than the fibrillatory waves of AFib, contraction of the atria is much more uniform, producing noticeable waves in the ECG. Once again, the ventricles are insulated from this abnormally fast rate, so the R waves still appear at fairly standard intervals; however, in between the R waves, the rapid pacing of the atria can be observed [8].



*Figure 5 – A characteristic ECG waveform of a patient with atrial flutter;
copied from [8].*

Proposal

To apply both concepts of telemedicine and patient self-monitoring to the field of cardiology, this thesis describes the development of a multi-platform system utilizing portable ECG devices. In its current form, the system allows users to monitor their own cardiac health by wearing a chest strap ECG device connected via Bluetooth to a mobile smart-phone or tablet. Data is automatically uploaded to a remote server for analysis, and the patient is notified if an abnormality is detected. The system can now be easily expanded into a more advanced application as a telemedicine platform. Patients can be assigned to a physician, who would then have the ability to view any of his patients' data and receive alerts of detected abnormalities.

Chapter 2

Literature Review

Telemedicine—the use of telecommunications for medical diagnosis, treatment, and remote monitoring—is one of the tools being used to help curb the costs of healthcare.

Telemedicine allows physicians to provide patient care outside of a clinical setting, giving both patients and physicians drastically increased mobility. This is meant to cut down the need for clinical visits and hospital stays, and allow for earlier detection and diagnosis of various conditions [11]. In many cases, the earlier an illness is detected, the more successful and inexpensive it is to resolve or manage.

A prime example of the benefit of early diagnosis is in the case of a developing myocardial infarction, which is where a section of heart tissue has become necrotic because of a reduction in blood supply known as ischemia [12]. Depending on the severity of ischemia and how quickly it progresses towards total arterial occlusion, ECG abnormalities can provide early warning of the impending infarction [13]. Early treatment, such as revascularization of the ischemic region, can prevent the infarction from forming, or reduce its size [14]. This highlights the importance of early detection.

Patient self-monitoring is another tool used to lower healthcare costs and aid in the early detection of illnesses. Frequent clinical visits can grow to a burdensome cost for most people, especially those without insurance. It is economically unrealistic for patients with conditions such as diabetes to see their doctors frequently enough to properly monitor their blood glucose levels. Therefore, most diabetic patients use portable testing devices to monitor their own glucose levels. Many conditions, such as heart palpitations, can only be fully observed and

diagnosed if they are frequent enough to occur during a clinical evaluation, or by using expensive at-home or portable event monitors (e.g. Holter vests). Patient self-monitoring can provide an inexpensive alternative, where the patient collects their own data, flagging the data sets corresponding to symptom events, and presenting the data to their physician for analysis.

Portable ECG devices have been used in a variety of applications. The most common device used for extensive mobile-ECG recording is the Holter monitor (named for the inventor, Norman Holter) which uses a conventional tape recorder or solid-state storage system to store ECG data to be viewed and processed later by a physician [15]. However, Holter systems are typically very expensive to use, even for only a 24-48 hour period. They also do not allow for real-time data analysis or monitoring, since the data is simply stored until the device is returned for data retrieval.

Jeon et al. improved on the standard Holter system by integrating real-time analysis into their device design [16]. The system consists of a single-lead data collection device with a built-in display and data processor. Analog data is amplified and filtered in a pre-processing circuit, then an ARM processor digitizes the data and applies an additional digital filter before the data is analyzed. Analysis results are then viewed directly on the device display. While this provides real-time analysis, a physician is unable to know the status of the patient or to verify the accuracy of the device's analysis, and the computational capabilities are limited to the power of the small on-board processor.

Fang et al. integrated ECG data collection with mobile-phone communications to allow physicians to receive SMS alerts regarding the patient's status [17]. They used a portable ECG device connected via Bluetooth to a standard mobile phone (Nokia 91) to analyze the data and transmit results to a similar device used by the physician. All data analyses and transmissions are

handled using algorithms and software installed on the device itself, and data retrieval or report generation is handled by software installed on the physician's device. This can put a large strain on the device's processor and battery if data was to be collected and analyzed continuously throughout the day, and limits computational power to the capabilities of the mobile device's small processor.

Wen et al. took the standard Holter design, and integrated an on-board, real-time data analysis system, which could transmit abnormal findings to a remote server via GSM service providers [18]. The Holter is used to collect and store the ECG data, and a software program is used to classify the data into several beat types. If the beat type is of concern, the Holter transmits the data and analysis results to a remote server, where a monitoring service employee is able to review it to determine if an alert should be issued. However, this system still requires the purchase of a complete Holter unit—now with the added cost of an on-board processor, transmission capabilities, GSM service plans, and subscription to a central monitoring service.

A few of the ECG analysis algorithms used in the iCloudECG system were previously developed in Xia et al. [19]. Critical parameters are extracted to determine the presence of the abnormality, but first, artifacts must be filtered from the signal. Common ECG artifacts include 50 or 60 Hz power-line interference, baseline wander, muscle noise, and electrode movement. To remove as much of these interferences as possible a low-pass filter is applied to suppress high-frequency noises and then a moving average filter is applied to reduce baseline wander. These filters are able to remove much of the interference without distorting the physiologically relevant frequencies of the ECG.

To be able to match the user's ECG with characteristic ECGs of various abnormalities, the critical features must first be extracted. These features include the P-wave, T-wave, QRS-

complex, R-R intervals, QRS intervals, and QT-intervals. Using the wavelet transform the ECG can be segmented into its various features [20]. The wavelet analysis method can distinguish the QRS complex from high P or T waves, baseline drift, and artifacts. It also enables measuring the location of onset and offset of the QRS complex and P- and T-waves. Once these features have been extracted, their locations and characteristics can be compared to results obtained from the analysis of representative abnormal ECGs.

Chapter 3

Materials and Methods

The general functions of iCloudECG can be visualized in **figure 6**. This multi-platform system consists of four main subsystems:

- Data collection
- Smart-phone application
- Server-side analysis, storage, and notification system
- Web-application portal

Data Collection

Data is collected using a Bioharness™ 3 chest strap ECG device, made by Zephyr Technology, shown in **figure 7**. This is a single-lead ECG device that uses an adjustable strap which wraps around the patient's thorax, just below the sternum, and has two built-in pads composed of a conductive "smart-fabric". These pads measure the potential difference between the two skin contact points—analogue to the adhesive electrode pads used in most ECG or EMG devices. A processing unit snaps into a slot in the middle of the strap, connecting it to the two conductive pads. The processing unit is removed for recharging and to wash the chest strap. The lack of disposable conduction pads and batteries make this device a convenient and economical solution for long-term wear and monitoring.

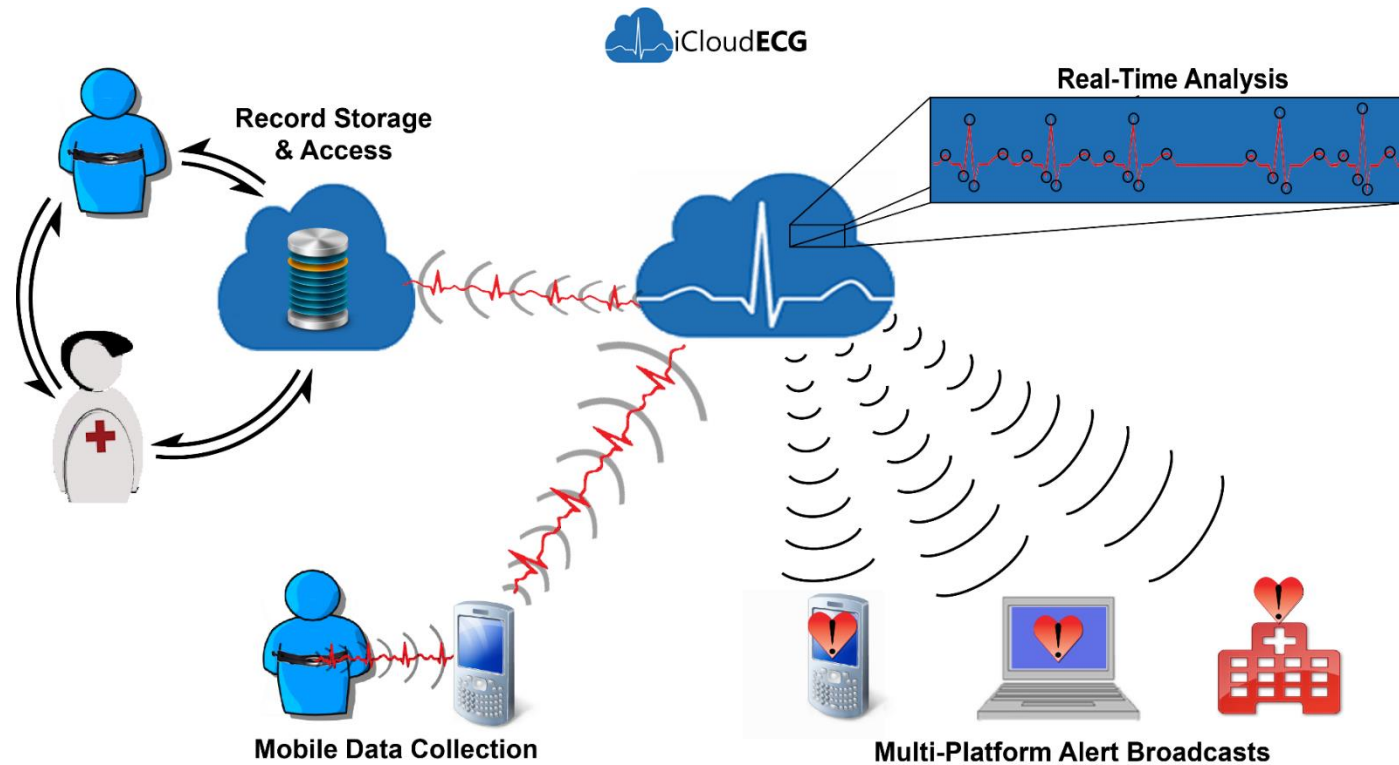


Figure 6 – A general overview of the iCloudECG system. ECG data is sent from the collection device to the mobile phone, then it is uploaded to the analysis server. After analysis, the ECG data is sent to storage, where it can be accessed by either the patient or the physician. The analysis server also generates notifications which can be sent to the user's mobile device or computer, or they can be sent to the patient's physician or hospital.



Figure 7 – Zephyr Bioharness™ 3: portable, single-lead ECG device

The Bioharness™ 3 provides a variety of physiological information, including ECG amplitude, heart rate, breathing rate, posture, and X-Y-Z accelerometer data. **Table 1**, copied from the data sheet provided by Zephyr [21], shows the accuracy of the Bioharness™ device under various levels of activity. The Bioharness™ samples ECG data at 250 Hz, and it transmits data packets via Bluetooth at intervals of approximately one quarter of a second. These data packets contain all of the physiological information previously mentioned, plus information about the device itself, such as battery percentage, battery voltage, device temperature, and strap-worn status.

Mobile Application

An Android [22] phone (Galaxy S5 – SMG900V [23]) is used to pair with the Bioharness™ to receive, process, and present the collected data using a custom built application. The application was coded in Android Studio [24], the official Android integrated development environment (IDE), using Java™ [25] programming libraries.

Table 1 – Accuracy information copied from the Bioharness™ 3 data sheet [21].

| Accuracy* (bpm) | Activity Level | VMU | USARIEM ** % of time | Zephyr % of time | Max Deviation (bpm) |
|---|------------------------------|-------|----------------------|------------------|---------------------|
| ±1 | Laboratory – ECG simulator | | 100 | 99 | 1 |
| ±2 | Low activity (static) | < 0.2 | 99 | 99 | 5 |
| ±3 | Moderate activity (walk/jog) | < 0.8 | 95 | 96 | 5 |
| ±3 | High activity (run) | > 0.8 | 90 | 96 | 10 |
| <p>* Accuracy, with respect to beats per minute (bpm) is given at different levels of user activity, where the activity is quantified in vector magnitude units (VMU).</p> <p>** United States Army Research Institute of Environmental Medicine.</p> | | | | | |

The Android platform was chosen because of the open-source nature of its operating system and libraries, plus the extensive documentation and support provided by Google™ and the Android programming community. A single user account is created to access both the Android application, and the web-portal application. The system automatically syncs data between both platforms.

Figure 8 shows a block diagram illustrating the data flow from the Bioharness™ through the various components of the application. The application can be split into 4 main components:

- Bioharness interface service
- User interface (UI)
- Data handling service
- Remote-server interface service

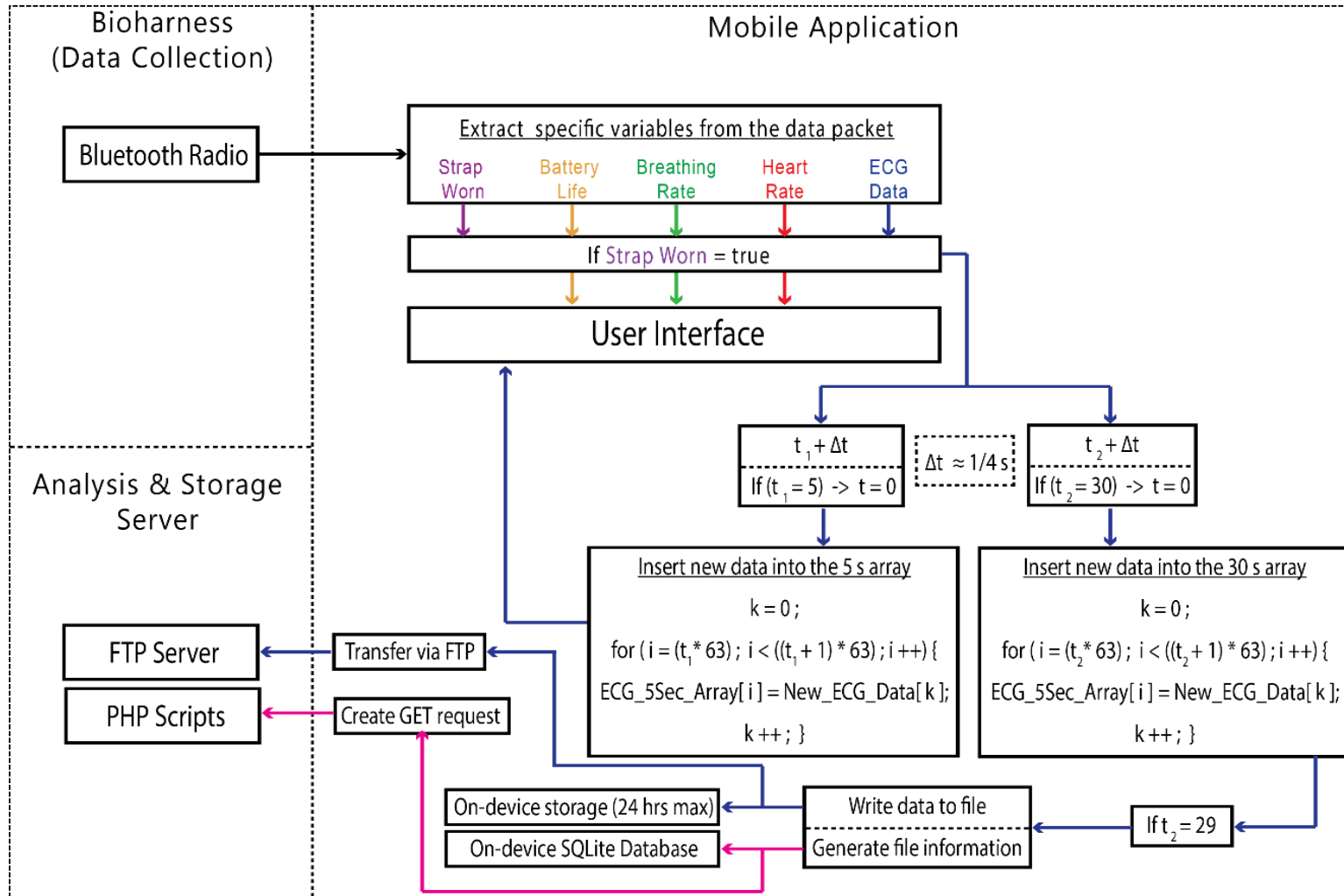


Figure 8 – Block diagram illustrating the flow of data from the Bioharness™ and through the various components of the iCloudECG mobile application

Bioharness™ Interface Service

The Bioharness interface service consists of functions for establishing and maintaining the Bluetooth connection with the Bioharness, receiving the data packets, and extracting the desired data from those packets. This service, as well as the other two main services, will run in the background regardless of whether the application is open, so no user action is needed to maintain continuous data collection. After the initial Bluetooth connection is established, a dedicated function listens for data packet transmissions from the Bioharness. When a data packet is received, other functions are called to process the packet, extracting the desired information. Data packets are received approximately every quarter-second, and the following information is extracted:

- Strap-worn status
- Device battery percentage
- Respiration rate
- Heart rate
- 63 ECG data points

The strap-worn status is used as a check to determine if data collection should continue, and to prompt the user if the device is not being worn properly. The other data is then loaded into *intents*, which are simply ways of communicating between different services or between a service and the main application. All of the data is loaded into an *intent* sent to the user interface, but the ECG data is also loaded into an *intent* sent to the data handling service.

User Interface

At the user interface, the data is presented to the user on the main screen, shown in **figure 9**. The user can view their heart rate, respiration rate, Bioharness battery status, and real-time ECG data. The ECG graph shows the past 5 seconds of data, but is updated in quarter-second intervals. Starting at time $t = 0$, each update replaces data points i , where $(t * 63) \leq i < ((t + 1) * 63)$. At each update t is incremented by $1/4$ until $t = 5$, at which point t is reset to 0.

The user interface also allows the user to be notified about abnormal analysis results, and to view a database of previous records. If the record analysis determines there is an abnormality, those results are packaged and sent through *Google Cloud* to the mobile device. A listener service receives the analysis information and generates an alert notification, which the user selects and is taken to a screen with additional information. The user can also view a database,

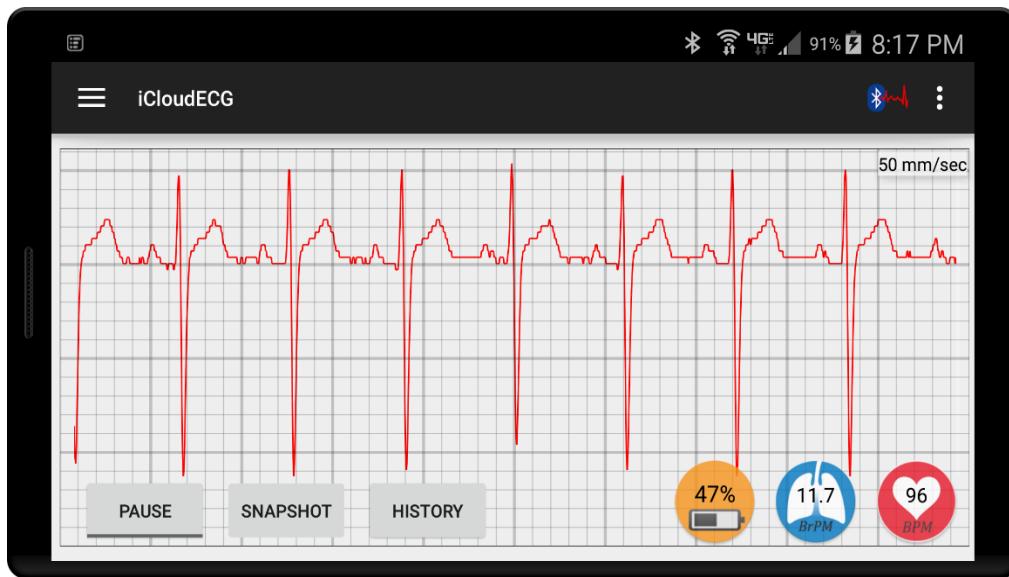


Figure 9 – Mobile application main screen. The user can view their real-time ECG data (5 seconds long), heart rate, respiration rate, and the battery percentage of the collection device.

generated by the data handling service, where they are presented with a list of each record's summary information. The records are color coded to highlight ones with abnormalities—green for normal, and red for abnormal. The user can select a record to either view the plot of its ECG data, or to review details of the record's analysis results.

Data Handling Service

Each new packet of ECG data is also sent to a data handling service. Here, the data is packaged into 30 second long records, which are then stored on the mobile device for review, and transmitted to the remote server for analysis and more permanent storage. By default, a total of 24 hours of data is stored on the mobile device, which equals approximately 2.61 GB.

The data handling service also maintains an SQLite database containing the information about each record—record ID, date/time of capture, heart rate, and diagnosis—which is used to populate a records table where the user can choose which record they would like to review. The heart rate is determined by calculating the heart rate over each 5 second interval of the 30 second record, then the maximum of that set is chosen as the record's heart rate. The diagnosis is initially set to a placeholder value until it is later updated when an analysis summary is received from the remote server.

Remote-Server Interface Service

The final application component is the remote-server interface service. This service handles user authentication or registration, and transmission of data to the server, including user account information, record information, and record data files. The service communicates with the server through a combination of Hypertext Transfer Protocol (HTTP) [26] GET requests and

File Transfer Protocol (FTP) [27] functions. GET requests are simply modified HTTP addresses that include various key-value pairs, for example:

$$\text{http://www.example.com/file.php?param1=value1\¶m2=value2} \quad (3.1)$$

This request would be processed by the PHP script “file.php” which would extract the variables (param1, value1) and (param2, value2), and use them as inputs for various functions. The GET requests are used to check or update the server SQL database, which contains user and record information. For example, when a user signs into the application, a GET request is generated to send the username and password that the user has entered. A PHP script receives this request, extracts the username and password, checks to see if that combination matches what is in the database, and returns either “true” or “false”. If “true” is returned, the user is allowed to proceed into the main application.

Users can create their own accounts online via the web-portal, or using the mobile application. If the account is created on the application, a GET request is sent to the server with key-value pairs corresponding to the various pieces of information obtained from the user (email, password, name, age, etc.). A PHP script extracts this information and stores it in the corresponding database. A similar process is used to insert, update, or delete ECG record information. However, the process of sending the ECG data files is different. The system first sends a GET request with the user’s credentials to a PHP script which authenticates the user. If authentication is “true”, a temporary username and password are returned to the application which are used to open an FTP connection to the server and transfer the ECG data file. A confirmation message is returned to the application stating whether or not the upload was a

success. If the file was successfully uploaded, another GET request is generated and sent to a PHP script responsible for initiating analysis of the ECG data contained in that file.

Server-side Analysis, Storage, and Notifications

The server used in this project is a Dell T7500 running the Ubuntu 14.04 [28] operating system. Apache 2.2.31 [29] HTTP server was used to host the various HTML [30] and PHP [31] scripts, as well as Apache Tomcat 7.0.64 [32] servlets to run the Java™ web-application and ECG analysis scripts. The database was created and maintained using MySQL 5.1. The core functions of the server are: 1) handling incoming requests and data from the mobile application, 2) maintenance of the user and record information database tables, 3) analysis of received ECG data, 4) generation of the notifications sent to the mobile device, and 5) allowing user access to their records and information via the web-application. The data flow between the main components of the mobile device and the server can be understood from the block diagram in **figure 10**.

Requests from the mobile application are handled first by PHP scripts. These scripts extract the necessary key-value pairs from the request, and then uses those variables to perform subsequent functions. If the request is for a database operation, such as inserting a new entry into the record information table, the PHP script first accesses a file containing the username and password necessary to access the MySQL server. It then prepares a query statement using the values obtained from the GET request, for example:

$$\begin{aligned} & \text{INSERT INTO recordtable (recID, recDate, recTime, maxHR,} \\ & \text{maxBR) VALUES (?, ?, ?, ?, ?, ?)} \end{aligned} \quad (3.2)$$

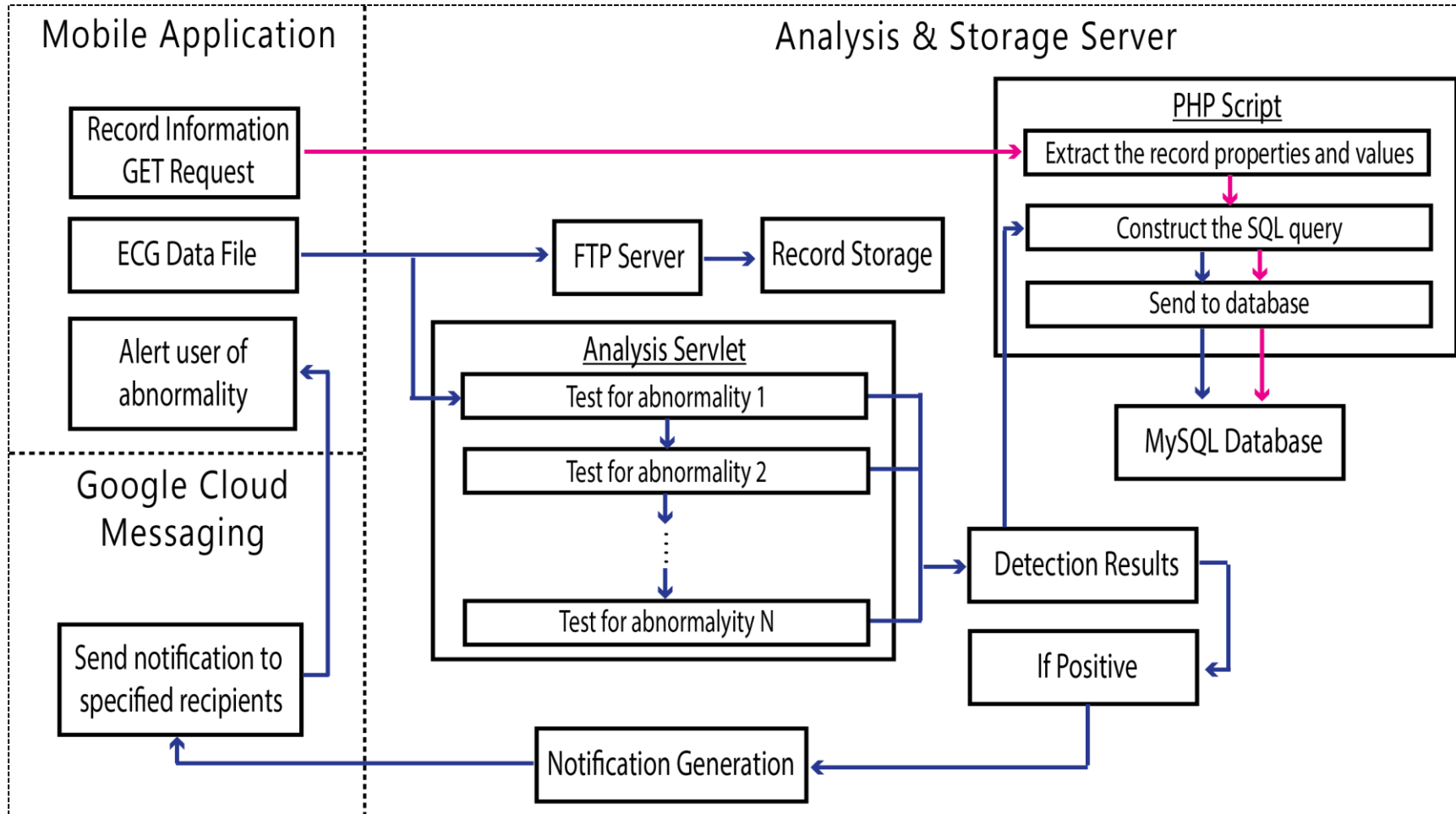


Figure 10 – Block diagram illustrating the flow of data from the mobile application and through the various components of the analysis & storage server

In the query (3.2) a new record is being inserted into the database table called “recordtable”. The first set of parenthesis contains the property names of each value contained in an ECG record entry: record ID, record date, record time, maximum heart rate, and maximum breathing rate. The second set of parenthesis contain multiple “?” that serve as placeholders for each of the property values, which are later bound to variable values—this is to prevent “SQL injection”, a malicious attack where SQL statements are inserted into a query, potentially exposing or destroying the database contents [33].

Data files are sent from the mobile device via FTP functions. The files are stored in a central location by their unique file ID, which is linked to the patient’s username in the record information table. Once a file is received, a success message is returned to the mobile application, which then sends a GET request to a Java™ servlet running on Tomcat. This initiates analysis of the file corresponding to the unique ID contained in the request.

Analysis scripts were created using the MATLAB software from MathWorks [34], to which a plugin is available called “MATLAB Library Compiler” [35] that converts standard MATLAB scripts into Java™ class files. These files can only be executed if the MATLAB Compiler Runtime [36] is installed on the executing server. This runtime contains various libraries of MATLAB functions, which are called by Java™ functions in the previously generated files to perform operations on the input dataset. This allows very complex algorithms developed in MATLAB to easily be converted to Java™ executable files, without the rigorous task of manually translating each MATLAB function into series of elementary Java™ functions.

The analysis servlet contains a central Java™ file that orchestrates the processes. The script first calls a function that takes a file ID, finds and reads the file line-by-line, and inserts the value on each line into an array of type “double”. This array is returned to the main script, where

it is then input to a series of Java™ files containing the algorithms to detect each abnormality. Each of these files returns either “true” or “false” depending on whether the abnormality was detected.

After the dataset has been through each detection algorithm, the script checks to see if any of the results came back as “true”. If so, a short summary of the “true” result(s) is generated to send as a notification via Google Cloud Messaging (GCM). This notification is packaged with two unique identifiers used by GCM—one that is automatically created for each user when they first login to the mobile application, and another that was created specifically for this mobile application. The user’s identifier serves as an “address” used by Google Cloud Messaging to send messages and notifications to that user’s device, and the application identifier simply tells the device to which application the message should be delivered. The message is then sent to GCM servers via another type of HTTP request, where it’s routed to the user’s device.

Web-Application Portal

The final component of the system is the web-application portal. This is a Java™ servlet application that can be accessed using any web-browser with JavaScript capabilities. The application’s Java™ files contain functions to retrieve user and record information from the MySQL database that was previously populated from the mobile application and PHP files. The user accesses the web-application using the same credentials as the mobile application, which are then authenticated using the database.

Using this application, the user can view or manage any records that have been uploaded from their mobile device as well as the analysis results of each record. They are first brought to a “dashboard” where the most recent record is graphed, and the next 3 most recent records can

quickly be chosen to graph instead. They can then navigate to a list of all records currently stored on the server, which contains details about the records, including analysis results. They have the ability to delete any or all of the records, if they choose, or they can share the records as PDF files.

A more important concept behind the web-application is allowing a user's physician to easily view the same records and results. A user would simply need to be linked with the physician's account, granting them access to the user's records in order to perform more detailed analysis of the user's cardiac health. Multiple users can be linked to a single physician, allowing them to quickly switch between the data of each user, enabling them to easily and efficiently manage large numbers of patients.

Chapter 4

User Scenarios

iCloudECG has been designed as a versatile, multi-platform system, with a range of applications. In its most basic form the system can be used by individual users, independently of a physician, to monitor their own cardiac health. The system can also be used by care-providers and relatives to monitor elderly or disabled individuals, or it could be used to monitor athletes during exercises and events. An advanced modification of the system would integrate cardiac physicians, allowing remote monitoring and evaluation of a patient's cardiac health.

Stand-Alone, Personal User

This system would be a viable option for an individual who believes they may be experiencing palpitations, but they fall into any of the following categories:

- They do not have access to a cardiac physician
- Their symptoms are too infrequent to detect during a clinical visit
- They are unable to afford the expensive Holter monitoring system
- They would simply feel more comfortable continuously monitoring their cardiac health

This individual would purchase the ECG equipment—currently the system works with Bioharness™, but can easily be expanded to any portable, Bluetooth enabled ECG—and then simply download the application to their mobile device. The new user would create an account, and once the ECG device is paired to the phone via Bluetooth, they login to the application. The user is automatically prompted to press a button which establishes the device connection, and

data retrieval begins. No further action is required by the user unless the device gets disconnected, in this case the user is alerted and prompted to reconnect.

All other system functions are carried out in the background of the device and on the server. If the system detects an abnormality, the user is alerted via push-notification and an audible tone, and prompted to view more information on the analysis. If the user believes they are experiencing an event, they may quickly flag that particular record with a single button press, allowing the user to easily find it later for review. Optionally, the user can return to the application and view their previous record list, which contains the past 24 hours of recordings. Selecting a record allows the user to either view the graph of its ECG data, or to view details of its analysis.

Additionally, the user can login to the web-application to view their records and analysis results. This is useful if the user wants to view an ECG graphed on a larger screen or view records beyond the 24 hours stored on their device. The user may also want to use the web-application to print or email a particular ECG graph to share with their physician.

Patient Monitored by a Physician

iCloudECG offers physicians the ability to easily and remotely monitor and evaluate multiple patients' cardiac health. A physician interface—either in the form of a mobile or web-based application—would give physicians access to the ECG readings being collected from all of their monitored patients. The system would be performing continuous, automated analysis of each incoming record, and would alert the physician or a designated nurse if any abnormalities were detected. Alerts, either via email or mobile notification, would provide a link to view the suspect ECG reading, allowing quick and easy verification of the analysis.

The user's ability to flag records if they believe they are experiencing an event is an important aspect of the physician based system. When a physician is viewing a patient's record list, he can easily see which records were flagged by the user. This allows the physician to determine if the patient's symptoms are actually being caused by a cardiac event, or if other possible causes should be investigated. Overall, many aspects of iCloudECG would streamline patient monitoring and diagnosis, providing the patient with better quality of care and quality of life.

Elderly Patients

Elderly patients have substantially increased risk of cardiovascular disease (CVD). In the 60–79-year-old age group, 70.2% of men and 70.9% of woman have CVD—increasing to 83.0% and 87.1% for men and woman, respectively, over 80-years-old [37]. Not only are they naturally more likely to develop CVD, but they are less likely to realize they are experiencing many of the symptoms, leading to an even greater increased rate of mortality from CVD [38]. iCloudECG could be used to curb the patient mortality rate for both assisted-living and independent elderly persons by providing early warning of various CVD related abnormalities.

An independent elderly individual could use the system in the same way as the standard stand-alone user, but with a modification to not only alert the user of an abnormality, but also the user's relatives, neighbor, or physician. Notifications can be sent via email to addresses designated by the user, but for higher-risk users a better option would be for the notification recipients to download a modified version of the application. This version registers the recipient's mobile device to receive alert notifications, and connects to the record storage server to allow access to the stored records and analysis results.

A more advanced version of the system can easily be developed for use in elderly care facilities. Similar to the system that would be used by cardiac physicians, multiple elderly residents could be equipped with individual iCloudECG monitoring systems. A centralized account would be established that would have access to each residents ECG readings and analysis results, and staff members could be alerted to abnormalities via notifications to multiple mobile devices.

Chapter 5

Conclusions and Future Works

With a growing percentage of the population being age 65 or over and the rising costs of healthcare, advances in the efficiency, efficacy, and affordability of patient care would not only be of great benefit to patients, but also physicians and even insurance providers. Telemedicine and patient self-monitoring systems have the potential to significantly reduce the average cost of healthcare, while at the same time improving the quality of patients' lives. With cardiovascular disease as the number one cause of death, and its overwhelming presence in the elderly population, cardiology is a primary field in which to implement these technologies.

iCloudECG was designed to give patients and physicians a streamlined cardiac monitoring and diagnostic system—providing continuous ECG monitoring with automated cardiac abnormality recognition and alerts, all without hindering the patient's mobility or taking time away from their lives. The patient cost of iCloudECG would be substantially lower than most Holter systems currently in use, with the added advantages of long term continuous monitoring with real-time data analysis. The system's flexibility make it applicable in a variety of user scenarios: from stand-alone users wanting to know more about their cardiac health, to a remote patient monitoring and diagnostics system for use by cardiac physicians.

Further development is needed on various aspects of the system. The physician side of the system will require consultation from multiple physicians to determine what features would be most useful. A physician application needs to be developed that will organize all of their enrolled patients data and analysis results for quick and easy examination. The web-application portal needs to be expanded with a similar interface. Considerations should be made about who

will actually be accessing the portal—the physicians themselves, or their nurses—and how this will affect the design of the interface to make it easiest and most efficient for those users.

The server-side programming will need to be moved to a cloud-based platform. These platforms provide the ability to purchase more or less computational power and data storage depending on the demand; as more users adapt the system, resources can be added to meet the data analysis and storage requirements [39]. Security also needs to be addressed in migrating to a cloud-based platform, but also in general. Security measures need to be added in the mobile-device to server communication process, and to the server-side processes themselves, to prevent the intercept or access of sensitive patient data.

There is vast potential in the telemedicine field. In the future, this system could expand to incorporate a variety of physiological sensors, such as blood pressure, blood sugar or O₂ levels, and activity monitors. The data would be collected and processed in the same way iCloudECG currently handles ECG data. Patients or physicians would be notified about a wide variety of abnormalities that may have otherwise gone unnoticed. All of that data would also be available for more long-term analysis algorithms, possibly identifying new trends that would forewarn additional health complications.

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Vita

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