ABSTRACT
Cardiovascular disease is the leading cause of death for both men and women in the United States. One of the conditions of cardiovascular disease is arrhythmia, an irregular or abnormal heartbeat. Early detection of arrhythmia can help prevent damages to the heart and heart diseases. An electrocardiogram is the standard clinical tool for arrhythmia detection. However, it is bulky, non-portable, and is mostly used only in medical settings. The lack of availability and the inconvenience prevents people from knowing about their hearts and health. It is therefore important for individuals to have affordable personal heart monitoring devices that allow them to do so. This paper introduces a light-weight sensor pad that works with any smart phone to provide a simple 2-lead electrocardiogram. The sensor pad is powered by the FoneAstra, where the signals are filtered and sent via Bluetooth to the smart phone. An Android library is created to work with this sensor pad. It displays the signals and performs some analysis on the data to provide basic information about the user’s heart rate and heart rhythm patterns.

1. INTRODUCTION
Arrhythmia is a condition characterized by the heart’s failure to contract or beat at the correct time. During an arrhythmia, the heart can beat too fast, too slow, or with an irregular rhythm. The occurrence of arrhythmia is common, for as many as 2.2 million Americans are living with atrial fibrillation (one type of arrhythmia). A recent study has also suggested that 1 in 4 adult Americans over the age of 40 could develop an irregular heartbeat. Most arrhythmias are harmless and can occasionally happen to someone with a healthy heart. However, other arrhythmias can lead to serious health problems and life threatening illnesses. Arrhythmias can often remain undetected by patients, where they dismiss symptoms of arrhythmia as a minor issue such as heart palpitations or occasional heartaches. However, long term arrhythmia can be extremely detrimental to the heart, for it can damage heart tissues and possibly lead to heart attack and sudden cardiac death. It is therefore beneficial and important for individuals to monitor their hearts regularly, especially for those who have congenital heart defects or people with a history of heart diseases.

An electrocardiogram (EKG) is the standard clinical tool for diagnosing arrhythmias. Such a recording shows the relative timing of atrial and ventricular electrical events. It can be used to measure how long it takes for impulses to be transmitted through the atria, AV conduction system and ventricles. An EKG is taken by attaching twelve electrodes to the different parts of the body, including four on the four limbs and six on the chest. The electrodes are connected to a machine that detects the electrical signals and analyze them. This makes the monitoring process cumbersome and inconvenient to be done at home or outside of medical settings, and thus making regular heart monitoring impossible. Therefore, there is a need for an alternative and simpler way to perform this kind of monitoring.

Thankfully, there is such a solution. A simpler form of EKG (2-lead EKG) can be done by simply measuring one’s right and left fingers. By taking the measurement from the fingers, a simplified form of one’s heart’s electrical activity can be recorded, and such a recording is enough to detect arrhythmias. With this solution, one just need to put his/her fingers on a sensor pad, and a 2-lead EKG can be recorded. The sensor pad can be made very small and lightweight, so that it is very easy to carry around. Such a sensor pad can be used in conjunction with a smart phone, where the EKG recordings can be viewed, analyzed, stored, and even shared with care-providers. With the availability of this kind of EKG device, heart monitoring can now be done at any time and in any setting.

For this project, the sensor pad consists of a metal touch pad and a FoneAstra, and this unit is called the touch EKG monitor [2, 3]. The touch EKG monitor unit is made to interface with an android app on the phone via wireless Bluetooth connection to provide arrhythmia detection and the storage of the recordings.

FoneAstra is a low-cost, microcontroller-based, programmable device that provides a general purpose platform. In this project, FoneAstra is enhanced with a voltage sensor to allow for heart monitoring. FoneAstra is energy-efficient and can communicate to mobile devices wirelessly. It can also store the EKG data when no phones are available to receive the data, which can then be retrieved at a later time. These capabilities of the
FoneAstra allow for the use cases to be discussed below.

2. DISCUSSION
Two major use cases are discussed for this project. First, the device can be used as a personal heart monitor for the general public. This includes the elderly, people with history of heart diseases, or anyone who is interested or would benefit from regular heart monitoring. The users can take an EKG sample using the sensor device and a smartphone, and the data will be analyzed and stored on the phone for their reference, or can be sent to a doctor for further analysis. This use case is quite common today where we see a wide array of personal health monitoring through mobile phones, such as blood pressure detection and sleep patterns analysis, etc. Mobile personal health is a growing field, and so with the growing public awareness of cardiovascular diseases, this heart EKG monitor has the potential to become extremely important and useful.

The second use case for this device is in the healthcare settings, particularly those in rural and underserved areas. In these areas, people tend to have less access to health services. An EKG or echocardiogram can often turn out to be too expensive. Hence, this device can be a cheap alternative as a preliminary screening tool for certain heart symptoms. Healthcare workers can conduct tests on patients showing heart problems using this device and eliminate false positive symptoms. Patients who actually show heart irregularities will proceed to receive further tests. When access to health services is limited, this model can effectively increase efficiency and reduce costs.

Some heart diseases cannot be detected through a short sample of EKG but requires a long period monitoring of the patient’s heart activity. In this case, physicians would give patients a monitor to be worn for 24 – 48 hours in order to see any abnormality. The EKG monitor in this project can be modified to conduct a longer period EKG test on the patients. For instance, the EKG sensor unit can be given out to the patients for a week, and can be used to collect EKG data and the data can be stored in the device. After a week, the patients return to the clinic where the EKG data can be read and analyzed by the doctor.

3. RELATED WORK
This project is similar to the research done in the paper “Real Time ECG Feature Extraction and Arrhythmia Detection on a Mobile Platform” in several ways [Patel, Gakare, Cheeran 2012]. In their paper, a real-time detection algorithm is proposed to detect various types of arrhythmias. Their detection system is consisted of a three lead ECG device and a mobile phone, where the three lead device records data and transfers it from the sensor module to mobile phone wirelessly while the mobile phone performs the functions of EKG signal acquisition, filtering, arrhythmia detection, GUI, data storage in database, and wireless transmission to the server. Although their research has very similar goal to ours, they deploy a different method of arrhythmia detection. Moreover, instead of opting for a sensor that requires less skin contact, they use a wearable EKG sensor that needs to be attached to the skin of the user. The purpose of such a choice may be that a wearable sensor is better suited for long-term detection.

AliveCor, a San Francisco based company, has been selling its FDA-cleared heart monitoring device since 2013. It uses a small touch sensor pad that communicates to the smart phone through ultrasound and lets the users view a recording of their 2-lead EKG. It also provides the users the options of having the recordings viewed by a certified physician with extra cost. Recently, it has added an additional feature of real-time atrial fibrillation detection that indicates to the users when a possible atrial fibrillation episode is detected.

The idea of extending the use of the FoneAstra and the touch EKG sensor to healthcare settings in rural and underserved areas was inspired by the Swasthya Slate project done by a group of researchers in India [4]. Swasthya Slate is a device that can conduct various diagnostic tests on Android tablets and phones. Front line healthcare workers can use this device to perform screenings and health analysis, consult doctors and contact emergency services when needed. All health information regarding each patient is stored in the Swasthya Slate system. From healthcare professionals’ perspective, Swasthya Slate help them to better identify and address patients’ needs; from patients’ perspective, Swasthya Slate allows them to receive more efficient and comprehensive end-to-end care. Similarly, touch EKG monitor is just one of the ways we can use FoneAstra in the healthcare setting. Our hope is that the capability of FoneAstra will allow us to combine the touch EKG monitor with other health diagnostic tools to create a powerful system that provides quality care for people in rural and underserved communities.

4. APPROACH
The main code base for this project is contained in two Android libraries, HeartrateDriver and HeartEKGSensor. HeartrateDriver contains the lower level class that interfaces with the touch EKG monitor. HeartEKGSensor contains higher level classes that are responsible for filtering, displaying, and storing the EKG data.

HeartrateDriverImpl is the only class in HeartrateDriver. HeartrateDriverImpl decodes raw sensor data buffers received from sensors into higher level key-value pairs. The values are EKG voltage values. HeartrateDriver interfaces with the touch EKG sensor through the ODK Sensors framework to receive the raw sensor data buffers [5]. The
ODK Sensors framework creates a common abstraction that enables all sensors to be accessed through a unified sensing interface. It handles threading and buffering, and mediates the communication between the physical touch EKG monitor and the driver, so that from HeartrateDriverImpl's perspective, it only needs to define the getSensorData() to decode raw data into data readable by HeartEKGSensor.

The classes in HeartEKGSensor can be separated into two major groups, one is related to data filtering and displaying, and the other is data storage. The HeartrateDriverActivity class does the majority of the work in this library. This is where the users take their EKG data. The class handles Bluetooth connection with the touch EKG monitor, and once the devices are connected and the sensor has started, it calls the getSensorData() repeatedly from HeartrateDriver to get key-value pairs and process these key-value pairs for heart rate and arrhythmia detection. The types of arrhythmia detection performed include:

- Bradycardia
- Tachycardia
- Premature Ventricular Contraction PVC
- Premature Atrial Contraction PAC

While the sensor is running, the EKG values and the user’s heart rate are displayed on the screen.

Once a 30 second sample is done, the user can choose to discard or save the EKG data. If the EKG data is saved, the HeartrateDriverActivity class will run algorithms for arrhythmia detection and calculate the average heart rate during this 30 second period. A summary of the 30 second EKG sample will be displayed by the ViewActivity class. The users can also scroll through the EKG waveform to identify any irregularity.

When a user asks to save the EKG sample, he or she will be taken to the Form Activity screen. The FormActivity class asks for basic information about the user, and saves this information along with the EKG data and the analyzed data into the database. SQLite Database is used in this project, and the classes related to the database functionality are DatabaseActivity, DatabaseHelper, PatientProfileActivity, ECG_Data, and Patient. The DatabaseActivity class displays a list of patients in the database, and allows the user to search for, add new, or view an existing profile.

The DatabaseHelper class extends the SQLiteOpenHelper class. It lays out the structure of the database, which consists of Patients Table, EKG Data Table, and Patients_EKG Data Table. Patients table displays patient name, gender, and birthdate; the EKG Data Table displays date, EKG data, average heart rate, and arrhythmia detection result; and the Patients_EKG Data Table maps the patient id to EKG data id. The DatabaseHelper class also defines functions used by the DatabaseActivity class.

The PatientProfileActivity class allows the user to view each patient profile, which displays patient information and the
list of EKG data this patient has. When the user clicks on the EKG data, the view screen for this EKG trace will be displayed.

Finally, the main activity of the HeartEKGSensor library is the MainActivity class, where the user has the option to what he/she wants to do.

5. IMPLEMENTATION

The software aspect of this project consists of two parts, the touch EKG monitor and the Android application. The former is responsible for reading data from the hardware and transmitting it to the phone. The latter is responsible for EKG signal filtering, analyzing the parameters of an EKG, arrhythmia detection, and data storage.

The software for the touch EKG monitor is programmed in the FoneAstra. Its job is to read 250 voltage data samples from the sensor pad every second, and without data filtering, sends the data in batches to the phone through Bluetooth connection.

The Android application does the majority of the work. Once the data has been received from the touch EKG monitor, it first undergoes data filtering. EKG signals from the touch EKG monitor are affected by various noises such as the 60Hz power line noise, muscle movements, interferences from nearby electronic devices or noises, etc. Hence, the data requires filtering to ensure that it is void of unwanted noises as much as possible. Since the touch EKG monitor already has a built-in band pass and a 60Hz notch filter, power line noise and several other noises will already be filtered out by the time the voltage data gets to the Android library. Thus, the Android library only needs to perform a low-pass filter.

A low-pass filter passes signals with a frequency lower than a cutoff frequency. This filter is used to filter out unwanted noises and interference that often have higher frequency. Our filter allows frequencies from 0Hz to 4Hz to pass, and filters out frequencies from 20Hz to 125Hz. With this low-pass filter, we obtain a cleaner-looking EKG signal.

After filtering, the signal is differentiated to provide the QRS complex slope information. This is the first step in identifying the features of an EKG, which then allows for the determination of the heart rate. The QRS wave of an EKG is where the ventricles of the heart contract and heart rate can be determined by the time difference between successive QRS. A differentiation algorithm is used because in a typical EKG, only the QRS has the steepest slopes. By running through a differentiator, the large slopes can be identified, and hence the location of the QRS waves can be identified.

The top figure shows the original EKG signals. The bottom figure marks the location of the QRS with a vertical line.

After differentiation, the data points are squared one by
one to make all data points positive and nonlinearly amplify the result of the differentiation, emphasizing the higher frequencies, that is the QRS regions.

Following the square function, we applied moving-window integration to the data point. The purpose of the moving-window integration is to help us in heart rate detection, but it also allows us to determine the duration of the QRS waves, which is one of the important indicators in determining arrhythmia. Once we have found the location of successive QRS waves, heart rate is determined by taking the difference in sample number between the two QRS waves multiplied by the inverse of sampling frequency. This gives us a heart rate measure in beats per minute.

This heart rate measurement allows us to determine whether a patient has Bradycardia or Tachycardia. Bradycardia occurs when the resting heart rate of the patient is under 60 beats per minute and Tachycardia occurs when the resting heart rate of the patient is over 100 beats per minute [7].

To determine whether a patient has PAC, we measure the variation of successive heart rates. If the heart rates fluctuates widely and frequently, and the patients has no other arrhythmia symptoms, then the patient likely displays symptoms of PAC [7].

The algorithm for QRS wave duration detection uses the data points from the moving-window integration, calculates the width of each positive graph, and convert the width to seconds. This value tells us how long each QRS wave lasts. Normal QRS width is 70 – 100 milliseconds. Patients with symptoms of PVC have QRS width greater than 120 milliseconds. This is just one of the indicators of PVC. Hence, we use this measurement to determine the likelihood that a patient displays symptoms of PVC [7].

6. EVALUATION
We evaluated this project in two ways. First, we evaluated our algorithm by analyzing patient EKG samples from the MITDB available on PhysioNet [6]. These EKG samples have been analyzed and annotated by physicians to mark locations of QRS waves and the characteristics of every single heartbeat, whether it is normal, an atrial premature beat, or ventricular premature beat, etc. We also used open source software from PhysioToolkit, which provides software that allow us to compare our annotations of the EKG samples to those on PhysioNet. The result of this evaluation on 47 samples from the MITDB shows that we have a 99.07% in QRS sensitivity and a 92.06% in QRS positive predictability, where sensitivity is the number of true positives over the sum of true positives and false negatives, and positive predictability is the number of true positive over the sum of true positives and false positives.

Secondly, we conducted a research study on 20 subjects with diverse ethnicity and ages ranging from 18 to 62 years old. In order to evaluate this research study, we compare our device to AliveCor’s heart monitor. We conducted the study by having the subjects take a 30-second sample of EKG on our device immediately followed by a 30-second sample of EKG on the AliveCor device. In our evaluation, we compared the EKG trace, the heart rate, and the atrial fibrillation detection between these two devices. The result of the study is that all of the subjects have normal rhythm from both devices (no atrial fibrillation detected from our device or from the AliveCor). The heart rate and the EKG trace detected by both devices match each other in general. When they are different, it is likely due to one of the following reasons.

In comparing our touch EKG monitor to AliveCor’s heart monitor, it seems that our device is slightly less sensitive to signals and is more prone to interference. For example, when the room became noisy while a sample was being taken, the noise and the vibration of the noise were caught by the sensor pad and interfered with the subject’s EKG sample. To correct this, we could try to eliminate noise while using the sensor or add additional filters to eliminate unwanted frequencies.

Our device does not perform as well on subjects with smaller heartbeats. This occurs when the subject’s QRS peaks are a lot shorter than normal, and it usually happens to athletes or people with lighter weight. This is because the ventricles of their hearts do not need to contract as much to pump the blood into the body. As the result, there is a smaller difference between the slopes of their QRS waves and that of the other waves. This difference becomes smaller with our low-pass filter, and consequently, our algorithm has harder time detecting the QRS waves.

Our study design can also lead to the difference in the EKG samples between our device and the AliveCor device. This is due to the fact that we did not and could not find a way to take the 30-second samples simultaneously on our device and the AliveCor device. Even though we try to take the two samples as close to each other as possible, the subject’s heart rhythm can still vary greatly within 60 seconds, and thus led to the discrepancy in the samples.

7. CONCLUSION AND FUTURE WORK
The work on this project represents a solid first step towards the creation of a reliable mobile application and a portable EKG sensing device for heart monitoring. This project shows that a device that is traditionally only available to patients in the medical setting is now available to everyone at anywhere. People now have the access to a convenient and portable personal EKG device. More importantly, people now have more control
of their health and well-being.

This project provides the basic functionalities of an EKG monitor and arrhythmia detection. All the code is structured modularly so that improvements and new features can be added easily. In the future, we would like this tool to include more EKG wave feature detection. Our project mainly focuses on QRS wave detection, but we would like to also have detection for P wave and T waves. Having these information will allow us to detect other arrhythmia conditions. We also would like to explore other algorithms for detecting atrial fibrillation to see how they would working differently or better than the one we have.

Additionally, this project is a basic model of how the FoneAstra can be used in the healthcare setting. As we have mentioned earlier in this paper, FoneAstra has the ability to incorporate multiple different sensors to interact with the mobile phone. The working model of our project shows that in the future, additional health sensing devices, such as a blood pressure sensor or a spirometer, can be added to the FoneAstra to create a single system of medical sensors that can be used to perform multiple tests. Whether it is used by an individual at home or by a health worker to conduct physical checkups in a rural town, such a system will not only make our lives easier, but also healthier.

8. ACKNOWLEDGMENTS
I would like to thank Rohit Chaudhri and Bruce Hemingway for investing their time this past year to guide me through this project, answering all my questions, and fixing many of headers that I’ve broken. I would also like to thank my professor, Gaetano Borriello, for giving me the opportunity to be part of the ODK group and to work on this project.

9. REFERENCES


