Abstract—An S-T segment elevation myocardial infarction (STEMI) is a severe heart attack that kills heart muscle every minute it is left untreated. Therefore, early diagnosis and treatment are crucial for patient survival. Currently, Charlottesville ambulances that service the University of Virginia hospital are equipped with proprietary systems that send electrocardiogram (ECG) images while the ambulance is en route to the hospital. From an ECG, a doctor can diagnose a STEMI prior to patient arrival and prepare for surgery, thereby reducing the time delay. However, these ambulance systems are costly and provide no feedback regarding the success of an ECG transmission. This paper describes the development of an inexpensive iPhone application that transmits ECG images over the AT&T data network to the hospital prior to a patient's arrival. The application is designed to dovetail with the existing STEMI-care protocol used by Charlottesville-area Emergency Medical Technicians (EMTs), and it provides a novel red/green light indicator predicting successful receipt of the image within two minutes. The goal of the application is to improve process efficiency and information flow allowing the patient to receive early, appropriate care and the best chance for a successful recovery. Test results, including usability tests, show that the application fulfills all key requirements. A prototype of the application will be evaluated by Charlottesville area Emergency Medical Technicians prior to implementation in emergency response protocols and long term deployment elsewhere.

I. INTRODUCTION

Myocardial infarctions (heart attacks) occur when heart muscle is damaged due to a lack of blood flow from a partially or completely blocked coronary artery. S-T segment elevation myocardial infarctions (STEMIs) are the most severe type of heart attacks, and they kill heart muscle every minute they are left untreated [1]. STEMs are detected by examination of a 12-lead electrocardiogram (ECG), a record of electric activity in 12 areas around the heart. Physicians at the University of Virginia hospital treat STEMs in a specialized catheterization (cath) lab, which is only open during certain hours due to high operating costs. If a STEMI diagnosis occurs during off-hours, the hospital must call in staff members to open and operate the lab, which can take up to 30 minutes. For every 30-minute delay in treatment, the risk of 1-year mortality increases by 7.5% [2], indicating that early diagnosis is crucial for improving patient outcome. Estimations indicate that 400,000 Americans experience a STEMI each year and less than half receive treatment within the federally recommended 90-minute time frame [3].

One method for reducing the time until treatment is a pre-hospital diagnosis of a STEMI, which occurs while the patient is in the ambulance and on the way to the hospital. The diagnosis can be made from a phone call between the physician and the EMS personnel, or after the physician analyzes an ECG that has been remotely transmitted to the hospital. By diagnosing a STEMI before the patient arrives, the cath lab can be activated and made ready to receive the patient thereby saving time and heart muscle.

Fig. 1. A graph of ‘Mortality reduction’ versus ‘Time to treatment’ illustrates the importance of treating STEMI patients quickly. The sooner reperfusion surgery is performed, the less likely a patient is to die from STEMI-related causes. If treatment does not occur within the first 60 to 90 minutes, the probability of mortality reduction drastically decreases. Adapted from [4].

A. Literature Review

Smartphones with flexible software development environments have opened up the possibility of creating customized applications (apps) to facilitate emergency services. When designing a new system, it is important to research and analyze any similar products that are already available. Application stores have created a market for both priced and free programs available for mobile download, and
in Apple’s application store alone, there are nearly 12,000 applications related to health [5]. Among these are several applications dedicated to transmitting medical information. For example, the Washington Hospital Center uses an application called CodeHeart that allows doctors to view video and audio recordings of a patient in transit [6]. FastECG, $2.99 in the Apple store, is an application more closely related to the STEMI application. The application allows the user to take a picture of the ECG, sends it to the fastECG website, and then generates a code that the sender can give to the intended recipient. The recipient enters the code on the fastECG website to view the ECG. Cardiologists have approved the application for its picture quality, reporting that it allows for normal interpretation of an ECG. One downfall of fastECG is missing functionality, specifically auto-focus and auto-flash functions of the camera. The transmitted images are also only slightly compressed to 180kB, making transmission inefficient and slow. Finally, when the user presses send, fastECG attempts to transmit the image only once rather than retrying for a specified amount of time. This decreases the probability of a successful transmission since it depends on having data service at one discrete moment. A vehicle may move in and out of strong service areas in a short amount of time, so a transmission is more likely to succeed if multiple attempts are made. The strengths and shortcomings of these products were considered in order to design an application that fulfilled the various needs of a pre-hospital transmission application.

B. Summary of Contributions

While applications currently exist that promptly transmit readable ECG images to hospitals for pre-hospital diagnoses of STEMIs, there are a number of improvements could be made to these systems. For instance, an application that provides feedback to the user about when a transmission has completed successfully will help to mitigate diagnostic delay. Additionally, compressing the image even further will allow for faster transmission while still keeping readability. This application will be designed around seamless integration to current pre-hospital STEMI diagnostic protocol. Additional feedback can come in the form of a predictive algorithm within the application, one that continually shows a user the likelihood of successful transmission dependent on their current service area. This will allow for more informed conversations between doctors and EMTs, as well as a greater likelihood that an image is successfully transmitted.

II. PROBLEM DEFINITION

In order to reduce the time until treatment, Charlottesville ambulances that service the University of Virginia hospital are equipped with proprietary systems that read and send patient ECGs over voice network via a modem to the hospital. Even at very expensive prices, these systems have significant drawbacks. They provide no feedback to the EMTs regarding the success of individual ECG transmissions, and users have estimated that these devices only transmit successfully about 20-50% of the time. Lack of feedback and a low success rate can cause delays because EMTs do not know if and when a transmission is received. Therefore, the EMTs may wait longer before contacting the hospital, and the physician does not have all pertinent information needed to make an informed decision. In addition, although a majority of the ambulance providers in Charlottesville can afford this equipment, many rural areas around the country cannot. These areas rely on the phone conversations between EMTs and doctors to diagnose a STEMI, and a correct and timely diagnosis is less likely. False positives (patient does not have a STEMI but the cath lab is activated) can result in the hospital and patient incurring unnecessary costs as well as systemic fatigue. False negatives (patient has a STEMI but the cath lab is not opened) can result in treatment delay, and possibly patient death. Any delay in treatment quickly diminishes the patient’s chance of recovery, and therefore patients serviced by ambulances without ECG transmission systems are less likely to make a full recovery.

A. Prospect for Improved Workflow

A mobile application has potential to add value to the systems that are currently being used. All ECG devices available on the market produce 12-lead printouts; however some devices transmit ECG images to hospital servers, while others do not. Machines that do not transmit are thousands of dollars less expensive than ones that do. Using an application to do the transmission would save EMS providers thousands of dollars.

Technology in camera phones has improved to take high resolution images (5 megapixels on the iPhone 4) even in low quality lighting. Transmission using a smart phone is very different than using a proprietary system because applications on smart phones are developed to be flexible. Using a mobile application in the hospital workflow allows for customization with regards to probing for network activity and providing real-time feedback/results to users. Using the application could therefore provide more reliable feedback to users. In addition, the low cost of a mobile application would make ECG transmission accessible to rural EMS providers without funds for expensive systems.

B. Descriptive Scenario

The U.V.a. hospital requires EMS providers to follow a strict protocol when dealing with suspected STEMI cases. Once an EMT suspects a STEMI from a patient’s ECG, they must immediately contact Med Com (a communication/dispatch office within the hospital), identify the incoming patient as a possible STEMI, and request to talk to the attending physician [7]. The U.V.a protocol specifies that ECG transmittal (through the proprietary system) should always be combined with contacting Med Com, but the transmission alone is not enough to activate the STEMI
alert. Med Com will then notify the attending physician, who will communicate directly with the EMT and evaluate an ECG if one has been transmitted successfully. The physician will determine the likelihood of a STEMI and decide whether to activate the cath lab or delay the activation.

C. Potential Value of the Application

The goal of the application is to provide additional value for early diagnosis of STEMI heart attacks. To simulate how an EMS manager might view the prospect of adopting the system, consider a rural operating area with a population of 175,000 people. Assume that STEMIs occur in approximately one of every 875 people (approximated from US population and current STEMIs/year), so that the EMS service responds to approximately 200 STEMIs per year. Also, assume that transmission bandwidth is constant over the entire area and that all doctors and EMTs have the same likelihood of an accurate diagnosis with just a phone call. The value of the application is conditioned on two factors; how effective the EMTs and doctors are at diagnosing a STEMI over the phone, and the prior probability of transmission success in the area. Logically, the application increases in value as EMTs and doctors are less efficient at phone diagnoses, as well as when prior probability of transmission success increases. Below, Fig. 2 and to the right, Fig. 3 illustrate the added value of the application, which can be measured as the difference between the STEMIs recognized pre-hospital with and without the app.

Fig. 2. A graph of number of pre-hospital STEMIs recognized conditioned on prior probability illustrates that as prior probability of transmission success increases, the application becomes more valuable. The difference between the two curves is the number of additional STEMIs diagnosed with the application vs. without.

![Added Value of Application](image)

The program compresses the image to approximately 32 kilobytes in size and divides it into 16 sections. This slicing allows the user to retake the picture as needed.

Depending on the conditional probabilities, this application can positively affect the number of STEMIs that are diagnosed pre-hospital, and facilitate quicker reperfusion. This small scale approach, if extrapolated to a larger operating area, has the ability to drastically increase the number of STEMIs captured pre-hospital without large expenditures for the hospital and EMS providers servicing the area.

Fig. 3. A graph of number of pre-hospital STEMIs recognized conditioned on prior probability illustrates that as prior probability of transmission success increases, the application becomes more valuable. The difference between the two curves is the number of additional STEMIs diagnosed with the application vs. without. As compared to the last figure, it is also evident that the application is more valuable when EMTs and doctors are less proficient at recognizing STEMIs on phone conversations.

D. Requirements

Development of an application is limited by requirements including the resources available, existing infrastructure established on the phone and at the hospital, and certain features EMTs need to be able to access in the application. The requirements for the application were designed in order to allow for flexibility of the application to multiple situations, while still conforming to the University of Virginia’s STEMI protocol. These requirements can be directly traced into each aspect of the application design process, and each was written with the ability to be formally tested.

III. SYSTEM DESIGN

An iPhone application was developed using the established requirements. The application, currently called “STEMI,” runs on the iPhone 4 with AT&T service in the Charlottesville/Albemarle area. The following sections describe the system design and operation.

A. Image Capture and Transmission

Once the machine in the ambulance prints out a paper copy of the ECG, the EMT opens the application, touches the “Click to Begin” button, and aligns the image with the camera view. As seen in Fig. 4, the application provides on-screen directions on how to align the image. The bottom 40% of the image is cropped off because the ECG dimensions are not the same as the camera screen, and a smaller image will transmit more quickly. The cropped image is then shown to the user as a preview. In order to account for unsatisfactory pictures or misalignment, the application allows the user to retake the picture as needed.

The program compresses the image to approximately 32 kilobytes in size and divides it into 16 sections. This slicing...
of the image provides two benefits; it is easier to send smaller pieces of data over the network and sections more relevant to diagnosing a STEMI can be sent first. The phone interfaces with a php script and sends the sections to the server, receiving confirmation each time one arrives at the destination. The transmission will require a server behind the hospital’s firewall to ensure secure storage. The program is designed to continually try to send sections of the image for up to two minutes, at which point the transmission is considered a failure if not completely sent. While the splitting and transmission processes occur, the user is brought back to the main screen and a timer commences. If the transmission completes before the timer runs out, a success sound plays. If the transmission fails, the user is notified and given the option to resend.

B. Feedback

The first level of feedback occurs when the user snaps a picture of the ECG, and the cropped image is displayed again for confirmation, as seen in Fig. 5. This way, the EMT can control exactly what the physician will see when the image arrives at the hospital. The second level of feedback is the timer and time limit that are displayed on the screen after a user clicks “Send”, as seen in Fig. 6. The timer serves to keep track of elapsed time from the beginning of the transmission, and also makes it clear to the user that the image is being sent. The time limit (two minutes) is also displayed to remind the user when the application will stop attempting to transmit. The third and most important aspect of the feedback is informing the EMT of a successful or unsuccessful transmission. If the EMT knows that the physician has received the image, they can place a call to the hospital and have an informed conversation about the patient’s condition. If the transmission fails, the EMT can quickly initiate a second attempt to send the image. In order to alert the user of success or failure, the application uses a combination of visual alerts, sounds, and vibrations. This way, the EMT can care for a patient while the image is sending instead of constantly checking the transmission status by looking at the screen.

C. Transmission Predictor

Another mechanism for keeping the users informed is the transmission predictor icon, visible in the top left corner of all screens of the application. The indicator is either a green checkmark or a red cross. When the icon is green, the user knows that the probability of a successful image transmission is above a certain threshold (for example, 90%), and the probability of success is below the threshold when red. The probability threshold can be set by the user in the settings menu of the application. The purpose of the predictor icon is to prevent wasted time. For example, if there is a low likelihood of a successful transmission, the user may not want to bother taking the time to snap the image. Once the transmission is likely to be successful, the user could then try to send the image.

The indicator status (green or red) is determined by an algorithm that runs in the background of the application. The application is constantly pinging the server and recording these pings in a database hosted on the server. The algorithm queries this database, and based on the percentage of successful pings in a one kilometer radius of the current location, determines the status of the indicator using a logistic regression curve.

D. Graphical User Interface

In compliance with Apple’s Human Interface Principles (HIP), the design of the interface is primarily driven by simplicity and the ability to quickly complete tasks [8]. With this in mind, the design elements are non-decorative in nature, focusing instead on intuitiveness and simple task completion. While there are various tasks a user can perform, the design is centered on streamlining the primary task of taking and transmitting an ECG image. When launched, the application immediately takes the user to a screen with instructions and allows them to move easily into the image capture function of the application.

The interface focuses on maintaining consistency throughout the application as well as consistency with the standard operating procedures used by most other iPhone applications. The application is designed to incorporate multiple different screen views which can be controlled with a tab bar at the bottom of the screen. This is consistent among applications of similar nature. By using a tab bar, the user should feel instantly comfortable navigating through the separate views. Within the application itself, the text, background, and buttons remain consistent to prevent confusion for users.

![Fig. 4. The home screen of the app shows on-screen instructions to align the ECG strip, and a large button to begin taking the picture. The tabs along the bottom are for the camera (current view) and settings.](image-url)
E. Protocol Integration

The application was designed to seamlessly integrate with this current hospital protocol while also providing the red/green prediction indicator. The user can monitor this indicator as the ambulance travels towards the hospital, and potentially retry transmission after entering a region with better service. In addition, EMTs can use the transmission feedback to improve conversations with attending physicians. For example, if the service indicator is red, the EMT can alert the doctor that they will need to make a decision without the aid of an ECG image. Because of this, the application reduces overall diagnosis time by removing the temptation to delay diagnosis in the hopes of successful ECG transmission.

IV. SYSTEM TESTING

A. Usability Testing

Randomly chosen participants were briefed on the purpose of the application and instructed to perform a set of tasks with it. The tasks were general, allowing the participants freedom in how they used the application. This was deliberate, so that participants would have to navigate the application as a real user would. Participants were observed while performing the tasks and completed a survey about their experience upon completion of the tasks. The survey allowed the participant to rank the difficulty of performing each task on a 5-point scale and asked open-ended questions as well. Usability testing was done in two iterations each with a different group of random participants. The first was done after the initial interface was complete, and the second was done after changes were made to the interface based on results from the first round.

<table>
<thead>
<tr>
<th>Question</th>
<th>Average</th>
<th>Low Scores</th>
</tr>
</thead>
<tbody>
<tr>
<td>Find the application?</td>
<td>4.6</td>
<td>0</td>
</tr>
<tr>
<td>Start the camera?</td>
<td>4.8</td>
<td>0</td>
</tr>
<tr>
<td>Align and take a picture of the 12-lead ECG?</td>
<td>4.3</td>
<td>1</td>
</tr>
<tr>
<td>View the image before sending?</td>
<td>4.7</td>
<td>0</td>
</tr>
<tr>
<td>Send the image?</td>
<td>4.8</td>
<td>0</td>
</tr>
<tr>
<td>Find the setting page?</td>
<td>4.7</td>
<td>1</td>
</tr>
</tbody>
</table>

Table 1. Summary of the results given by the 1st batch of users who tested the initial app. Ratings are based on a 5-point scale with 1 = "Very Difficult", 3 = "Neither Easy nor Difficult", and 5 = "Very Easy".

Table 1 shows that in general, participants found the application easy to use. However, participants did have trouble opening the camera because they confused the “Camera” icon and the “Begin ECG Capture” button. This confusion was mitigated when the opening page of the application was changed to include clear instructions on how to begin the ECG capture. Participants also had trouble aligning the ECG picture, as it was not clear that the image would be cropped. As a result, the application was changed to include visual instruction on how to frame the image. The application was also changed to show the cropped image to the user before she sends it, and reminds her of the proper
technique if she chooses to retake the picture. Upon completion of the tasks, all participants were able to identify whether the transmission was successful, because of the sound and vibration produced by the phone.

After the changes above were made to the application, a second batch of participants were picked randomly to test the updated version. Table 2 outlines the results.

<table>
<thead>
<tr>
<th>Question</th>
<th>Average</th>
<th>Low Scores</th>
</tr>
</thead>
<tbody>
<tr>
<td>Find the application?</td>
<td>4.9</td>
<td>0</td>
</tr>
<tr>
<td>Start the camera?</td>
<td>4.9</td>
<td>0</td>
</tr>
<tr>
<td>Align and take a picture</td>
<td>4.2</td>
<td>0</td>
</tr>
<tr>
<td>of the 12-lead ECG?</td>
<td></td>
<td></td>
</tr>
<tr>
<td>View the image before sending?</td>
<td>4.4</td>
<td>0</td>
</tr>
<tr>
<td>Send the image?</td>
<td>4.9</td>
<td>0</td>
</tr>
<tr>
<td>Find the setting page?</td>
<td>5.0</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 2. Summary of the results given by the 2nd batch of users who tested the initial app. Ratings are based on a 5-point scale with 1 = “Very Difficult”, 3 = “Neither Easy nor Difficult”, and 5 = “Very Easy”.

B. Algorithm Testing

At the time of writing, testing of the algorithm is in progress. The test plan includes driving to 20 (predetermined) locations, recording the probability of a successful transmission as indicated by the algorithm, and attempting to transmit an image to a UVA server. The transmission will be recorded as successful or failed depending on whether or not all of the packets are received at the server. A Receiver Operating Characteristic (ROC) curve will be developed and used to determine the predictive power of the algorithm.

V. Conclusion

STEMI response is a time-critical task that requires swift and immediate action. Every second saved making the diagnosis can potentially save lives. A mobile application offers a way to expedite the diagnosis and treatment process. However, emergency medicine is a unique environment in which responders must attend to patients at all times. A device that distracts an EMT from his patient could do more harm than good. The STEMI application requirements were derived from the current workflows of EMTs responding to cardiac patients so that no harm is done. With the integration of the prediction algorithm, EMTs will know whether or not the ECG image is going to be available for the diagnosing physician when the EMT calls. This will save time, as the EMT and physician can make a diagnosis right away, without questioning the availability of the ECG.

Testing results show the application has a simple, streamlined interface, which allows users to quickly and easily perform the tasks necessary for transmitting ECG images. Currently the application successfully transmits clear images when adequate cell phone service is available. However, this application has significant potential for future work. Future work includes installing the application behind the UVa hospital’s firewall, and including encryption capabilities to allow the application to transmit patient-identifying information like names or dates of birth. There may also be opportunities to expand the reach of the application to other health systems, and especially to EMS providers that cannot afford currently available systems.

ACKNOWLEDGMENTS

The authors would like to thank the following individuals: Dr. David Burt, cardiologist at the University of Virginia Emergency Medicine Department; Dr. Mark Sochor, Associate Professor of Emergency Medicine at University of Virginia. The authors take full responsibility for the ideas, concepts, and opinions presented here, which do not necessarily reflect those held by Drs. Burt and Sochor.

REFERENCES