Medical Data Storage, Visualization and Interpretation: A Case Study Using a Proprietary ECG XML Format

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Abstract: Since the implementation of the emergency coronary care units in the 1960s, ECG monitoring devices were used to diagnose and monitor major life-threatening arrhythmias in patients with cardiac disease. Currently, ECG monitoring plays a major role in other hospital departments as intensive therapy units, operating rooms and emergency rooms. ECG monitoring use has expanded from simple cardiac rhythm detection to complex heart analysis like the detection of complex arrhythmias, atrial fibrillation T wave abnormalities, ST-segment elevation in cardiac ischemia and its role is still expanding. We consider there is a critical medical requirement for continuous development of modern medical devices like ECG that allows doctors not only access to better medical systems, but also to customize access and usage of the medical data. In this article we explain the implementation of an open-source ECG system to visualize XML files obtained from GE MAC5500 ECG machines, without using their specific platform, and a way to automatically detected heart abnormalities based on ECG. It deals with reading, displaying and processing data from a medical electrocardiograph.

Keywords: Data Visualization, XML, Electronic Medical Record (EMR), Electrocardiogram (ECG), Vectorcardiogram (VCG).

INTRODUCTION

The electrocardiograms (ECGs) play an important role in medical research, medical education and health care. With the implementation of the emergency coronary care units in the 1960s, the ECG monitoring devices were used to diagnose and monitor major life-threatening arrhythmias in patients with cardiac disease. Currently, the ECG monitoring plays a major role in other hospital departments as intensive therapy units, operating rooms and emergency rooms. ECG monitoring use has expanded from simple cardiac rhythm detection to complex heart analysis like the detection of complex arrhythmias, atrial fibrillation T wave abnormalities, ST-segment elevation in cardiac ischemia and its role is still expanding. Due to their importance, there is an increasing effort in designing and managing ECG databases, augmented by the preoccupation for the creation of Hospital Information Systems (HISs). This has become a complex problem, due to the need not only to store and manage ECG data, but also to communicate with other systems, such as HISs, to automate the ECG workflow, to facilitate the ECG editing process, to compare ECG recordings belonging to the same person or to the same category, or to capture and store incremental ECG changes.

There are several major players in the area of ECG information management systems that offer, beside medical devices, algorithms and monitors, also a central database management with integrated EMRs. One of them is the GE MUSE Cardiology Information System, which is a complex database management system that offers

connectivity from resting ECG, exercise ECG, or Holter acquisition devices. Some of its tasks are to integrate, manage, and streamline the flow of cardiac information, enabling data delivery, distribution and analysis, and also to provide physicians with a GUI-based access to patients ECG information (www.gehealthcare.com).

A sustained effort in the field, during the last decade, is visible; it is performed by medical information research communities, focused to improve and advance the current knowledge in ECG storage and interpretation, like MIT medical laboratory (http://ecg.mit.edu). Current monitoring systems use a 12-lead independent acquisition that enhances pattern recognition, offer a comprehensive suite of ECG interpretation and analysis programs, and store the patient data digitally for retrospective analysis and communication over the Internet. We'll try to take a step further by investigating the possibilities to offer the clinician a data virtualization layer that is transparent and also can be customized to the clinician requirements. This layer is represented by vectorcardiogram generator, which gives a different method (not designed by the ECG manufacturer) of analysing the previous recorded ECG.

METHODS AND ALGORITHMS

In this section we'll examine the implementation of an open-source ECG system to visualize the XML files obtained from GE MAC5500 ECG machines without using their specific platform. It deals with reading, displaying and processing data from a medical

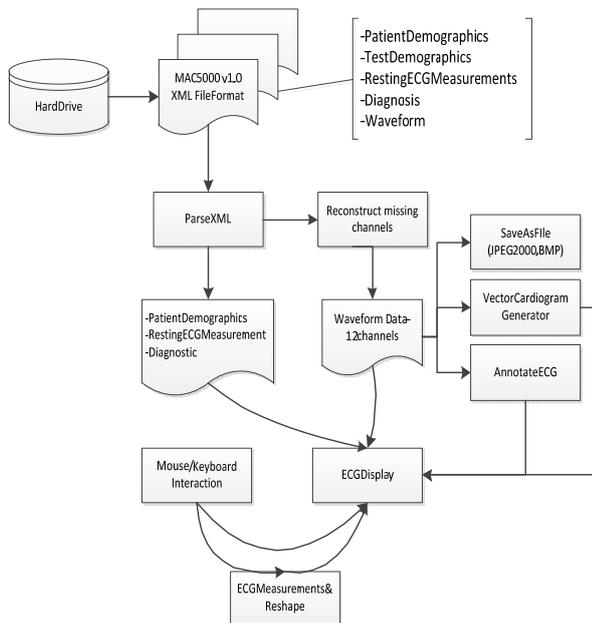electrocardiograph, aiming also for automatic detection of heart abnormalities based on ECG.

Fig. 1. Platform Architecture

An undocumented ECG file format produced by the machine is described in first section. A method is devised for reading and displaying the ECG format, which is implemented in a waveform viewer, is described in second section. Further the ECG waveforms are processed, virtualized and annotated.

The electrocardiogram (ECG) is a technique of recording bioelectric currents generated by the heart. Clinicians can evaluate the conditions of a patient's heart from the ECG and perform further diagnosis. ECG records are obtained by sampling the bioelectric currents sensed by several electrodes, known as leads. The 12-lead ECG system consists of six frontal plane leads (I, II, III, aVR, aVL, and aVF) and six chest leads (V1-V6).

1.1 XML Loading, Parsing and 2D Display

Electrocardiograph machine provides the ECG data inside a file with extension XML. We may see at the first glance that the General Electric (GE) XML file contains at the beginning the declaration XML 1.0

<?xml version="1.0" encoding="Windows-1252"?>

<!DOCTYPE RestingECG SYSTEM "restecg.dtd">

XML (or eXtensible Markup Language) is a mark-up language (like HTML), widely used, since its specifications are available for everybody, everywhere. XML has emerged during the last decade as a major standard for representing data on the World Wide Web. One of the problems with XML, although it was designed to be self-descriptive, is that too many storage models have been proposed to manage XML data. The GE XML file, for example, contains both text and encoded non-text

data. For reading XML we used an open source XML parser called RapidXML.

Because GE doesn't offer documentation for its GE XML file format, we tried to deduce the meanings of different identifiers according to their specific names, which we understand. Some identifiers are not mandatory. Also, the XML file refers to a schema that we don't have access to; therefore we can best estimate the meaning of symbols assuming the risk that we wouldn't know the meaning of some values.

After analysing the XML file, we concluded it contains:

- Data about the patient - items for patient identification: name, surname, age, weight, height, sex
- General information about measurement - the date and time of measurement, the instrument used
- Device settings - sample rate - mainly used in ICEM sampling 500 Hz
- Notes on the diagnosis
- Voltage waveforms in time
- Details of the waveforms - the name, number of scanned samples, units of voltage, voltage step size.

For the ECG recording to have a single file, its beginning is as follows (name and surname patient has been altered to protect personal data):

```
<?xml version="1.0" encoding="Windows-1252"?>
<!DOCTYPE RestingECG SYSTEM "restecg.dtd">
<RestingECG>
 <PatientDemographics>
<PatientID>000012611</PatientID>
<PatientAge>54</PatientAge>
<AgeUnits>Years</AgeUnits>
<PatientLastName>Test </PatientLastName>
<PatientFirstName>Test</PatientFirstName>
</PatientDemographics>
<TestDemographics>
<DataType>Resting</DataType>
<Site>1</Site>
<AcquisitionDevice>MAC55</AcquisitionDevice>
<Status>Unconfirmed</Status>
<Priority>Normal</Priority>
<AcquisitionTime>15:03:14</AcquisitionTime>
<AcquisitionDate>01-26-2011</AcquisitionDate>
<CartNumber>1</CartNumber>
<AcquisitionSoftwareVersion>009A
</AcquisitionSoftwareVersion>
<XMLSourceVersion>MAC5000
v1.0</XMLSourceVersion>
 </TestDemographics>
```

It's obvious that the meaning of some of the identifiers such as age, patient name, and diagnosis cannot be confused. If not by themselves, they complete each other to provide a correct description. For example, the identifier <PatientAge> indicates the patient age, and the value of the identifier <AgeUnits> suggests that it is the age of the patient is given in years.

But there are some fields for which the interpretation is not so evident. For example, one of the most difficult to interpret was the category <Waveform>:

```
<Waveform>
<WaveformType>Rhythm</WaveformType>
<WaveformStartTime>0</WaveformStartTime>
<NumberofLeads>8</NumberofLeads>
<SampleType>CONTINUOUS_SAMPLES</Sample
Type>
 <SampleBase>500</SampleBase>
 <SampleExponent>0</SampleExponent>
<HighPassFilter>16</HighPassFilter>
<LowPassFilter>150</LowPassFilter>
 <ACFilter>50</ACFilter>
 <LeadData>
<LeadByteCountTotal>10000
</LeadByteCountTotal>
<LeadTimeOffset>0</LeadTimeOffset>
<LeadSampleCountTotal>5000
</LeadSampleCountTotal>
<LeadAmplitudeUnitsPerBit>4.88
</LeadAmplitudeUnitsPerBit>
<LeadAmplitudeUnits>MICROVOLTS
</LeadAmplitudeUnits>
<LeadHighLimit>2147483647
</LeadHighLimit>
<LeadLowLimit>268435456</LeadLowLimit>
<LeadID>I</LeadID>
<LeadOffsetFirstSample>0
</LeadOffsetFirstSample>
<FirstSampleBaseline>0</FirstSampleBaseline>
<LeadSampleSize>2</LeadSampleSize>
<LeadOff>FALSE</LeadOff>
<BaselineSway>FALSE</BaselineSway>
<LeadDataCRC32>2523594381
</LeadDataCRC32>
 <WaveFormData>
9v/2//b/9v/4//n/+/8AAPz/+//4//n/+//9/wEAAgD//wEA
BAD///3/AQABAP7//P/0//H/+v8LABcAHQArADcAQ
wBRAFsAYwBpAHAAewB3AGwAegCDAHoAgwCc
AJ8AlQCYAJ4AlQCIAIQAfgB9AHkAbQBQBgAFsAXQ
BfAGMAZQBoAGkAaawBwAHIAaaABXAFQAXQBfA
FgAUQBUAFIASgBMAFUASwA0ACkkALgAnABoAF
AAPAAkAAwD5//T/9P/x/+//7f/r/+r/6f/r/+n/....
```

The XML contains a group of eight elements called <LeadData>. Each element from this group contains a element called <LeadID>, whose value corresponds to the label of one waveform used in ECG(I, II, V1, V2, V3, V4, V5, V6).Some of them are missing (III, aVR, aVL, aVF). The actual waveform signal is included in the <WaveFormData> element. This element contains binary data that are encoded in the 64Base encoding (letters of the English alphabet, decimal digits, "/" and "+") and without using compression. Another element encountered, <LeadSampleCountTotal>, means the number of samples (5000 samples). The value in the element <LeadByteCountTotal> is 10000, which is the total number of bytes; therefore individual samples are stored in pairs of bytes (signed short).

After correctly parsing the XML file all the waveforms are stored in 12 buffers and further displayed on screen using OpenGl 2D primitives: GL_LINE_STRIP.
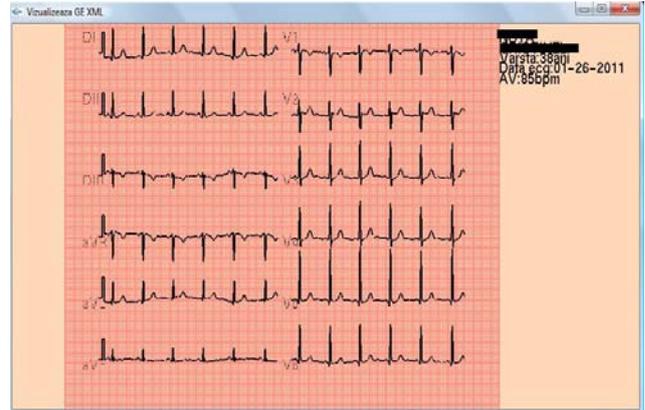

Fig. 2. A screenshot of the main application window

We may see in Fig. 2 that the panel will display in the main window 12 ECG signals (DI, DII, DIII, aVR, aVF, aVL, V1, V2, V3, V4, V5, and V6), and other specific patient information.

2.2 12-Lead Electrocardiogram Reconstruction

The GE XML file format does not include all the lead information. It stores only 8 lead channels: DI, DII, V1,V2, V3, V4, V5, V6. Also, in critical care or emergency situations, a continuous 12-lead ECG monitoring device may not always be available.

The 12-lead ECG system consists of six frontal plane leads (I, II, III, aVR, aVL, and aVF) and six chest leads (V1-V6). Three frontal plane leads are bipolar leads (I, II, and III) and three are augmented leads (aVR, aVL, and aVF). Of the six frontal plane leads, only two leads (DI, DII) need to be known to calculate the remaining four. In practice, most ECG equipment only stores lead I and II to save space without loss of information. The remaining leads (DIII, aVR, aVF, aVL) can be reconstructed (calculated) by using the equations below:

$$DIII = DII - DI$$
$$aVR = -\frac{1}{2}(DI + DII)$$
$$aVL = DI - \frac{1}{2}DII \qquad (1)$$
$$aVF = DII - \frac{1}{2}DI$$

Based on the assumption that the cardiac electrical activity can be represented by a dipole model, the 12-lead ECG system could be thought to have three independent leads and nine redundant leads (Nelwan, 2005). Therefore, fewer selectively chosen leads may still contain enough diagnostic information to represent the full 12-lead ECG compared with the 8 leads stored by GE XML file.

However, in practice, the pre-cordial leads (V1-V6) also detect non dipolar components, which have diagnostic

significance because they are located close to the frontal part of the heart. Therefore, the 12-lead ECG system has eight truly independent and four redundant leads. The main reason for recording all 12 leads is that it enhances pattern recognition. This combination of leads also gives the clinician an opportunity to compare the projections of the resultant vectors in two orthogonal planes and at different angles.

2.3 ECG Annotation

For ECG annotation, the P, T, QRS waves are automatically identified using continuous wavelet transform line corrected (Bert-Uwe Köhler et Al, 2002).

The first stage of the annotation procedure is the detection of QRS complexes. First the ECG signal is transformed with CWT(Continuous Wavelet Tranform) using an Inverse wavelet at a frequency of 12Hz. This amplifies the high frequency QRS part from the low frequency P, T waves and noise. Next the continuous wavelet spectrum of the ECG signal is filtered with an FWT(Fast Wavelet Transform) transform using interpolation filters g, h, g*, h* (Chesnokov et Al, 2002).

The reconstructed ECG signal contains only spikes with nonzero values at the location of QRS complexes. From this signal, the PQ junction and J point can be located as the boundaries of the spike. If the length of the spike is more or less than a predefined QRS length range it is annotated as noise and if the voltage is below a certain threshold, it is annotated as an artefact. The next stage is the detection of the T wave. Every annotated heart beat of the original ECG signal beginning from the detected J point and extending to the possible longest duration of the T wave, which can be adjusted, is analyzed by the CWT at the 3 Hz frequency. The minimum and maximum of the CWT spectrum corresponds to the beginning and end points of the T wave and zero crossing to its center. The same procedure is applied to detect the P wave in the PQ interval but the CWT transform is calculated on the 9Hz. The peaks of Q, R and S waves are identified in the annotated part of the ECG signal from the PQ junction to J point.

The fully automated ECG annotation algorithm used here consists of filtering the signal with continuous (CWT) and fast wavelet transforms (FWT). Wavelet transforms offer simultaneous interpretation of the signal in time and frequency domains. The CWT transform of the signal x(t) is defined as below:

$$CWT_x^{\psi}(\tau,s) = 1 \frac{1}{\sqrt{|s|}} \int x(t)\psi^*(\frac{t-\tau}{s})dt \qquad (2)$$

Where $\psi^*(t)$ represents the transforming function (Inverse wavelet in our case), τ is the translation parameter of the wavelet and s is the scale parameter of the wavelet.

The FWT transform represents the signal at discrete frequency bands. The length of the calculated FWT spectrum is equal to the signal length. The analyzed signal is iteratively passed through high pass and low pass filters defined by numerical coefficients.

We have a 5000-sample long signal sampled at 500 HZ and we wish to obtain its FWT coefficients. Since the signal is sampled at 500 Hz, the highest frequency component that exists in the signal is 250 MHz. At the first level, the signal is passed through the low-pass filter h[n], and the high-pass filter g[n], the outputs of which are sub-sampled by two.

2.4 Vectorcardiogram

The electrical activity of the heart can be modelled with a vector quantity: an electric dipole M whose magnitude and direction changes in time.

Over 90% of the heart's electric activity can be explained with the dipole source model (Geselowitz DB ,1964).To evaluate this dipole, it is sufficient to measure its three independent components. In principle, two of the limb leads (I, II, III) could reflect the frontal plane components, whereas one pre-cordial lead could be chosen for the anterior-posterior component. The combination should be sufficient to describe completely the electric heart vector. By using this combination of 12 standard leads, the clinician can compare the projections of the resultant vectors in two orthogonal planes and at different angles (Polikar, 2004).

To compute the 3D vectorcardiogram we need to calculate heart vector components X, Y and Z using the standard leads system and solving the following expressions or equations(G Daniel et Al, 2007) :

$$X = -(-0.172\,V1 - 0.074\,V2 + 0.122\,V3 + 0.231\,V4 + 0.239\,V5 + 0.194\,V6 + 0.156\,DI - 0.010\,DII)$$

$$Y = (0.057\,V1 - 0.019\,V2 - 0.106\,V3 - 0.022\,V4 + 0.041\,V5 + 0.048\,V6 - 0.227\,DI + 0.887\,DII)$$

$$Z = -(-0.229\,V1 - 0.310\,V2 - 0.246\,V3 - 0.063\,V4 + 0.055\,V5 + 0.108\,V6 + 0.022\,DI + 0.102\,DII)$$

(3)

To compute vectorcardiogram we prefer a simpler method that decomposes the heart vector in 2 planar components: frontal and anterior-posterior.

Here is a simple pseudocode to implement the frontal vectorcardiogram component:

```
projDIx= DIx*cos(0);
projDIy= DIy *sin(0);
projDIIx= DIIx *cos(60);          (3)
projDIIy = DIIy *sin(60);
projDIIIx = DIIIx *cos(120);
projDIIIy = DIIIy *sin(120);
vectorx= projDIx + projDIIx + projDIIIx;
vectory= projDIy + projDIIy + projDIIIy;
```

To compute the anterior-posterior vectorcardiogram we combine the frontal components (e.g. vectorx) with one pre-cordial lead (e.g. V1 or the resultant vector of V1, V2 ... V6).

2.5 Printing and Saving Patient ECG Data

We used the JpegLib open source library to save in 24-bit JPEG file format the output of the screen buffer with clinical accepted results.

We chose JPEG file format because is a commonly used method to store colour images and offers a good trade-off between storage size and image quality.

JpegLib library is written entirely in C which contains a widely-used implementation of a lossy JPEG decoder, JPEG encoder and other JPEG utilities and is maintained by the Independent JPEG Group. It also offers as extension support for Lossless JPEG format.

To output the ECG data on file we used OpenGL function *glReadPixels* () which reads every pixels on screen and we save the packed RGB buffer to JPEG with quality value parameter set to 100.

Also the ECG data can be saved in Windows Bitmap 24 bit file format which stores the data uncompressed and lossless.

3 RESULTS

The system was first validated by 2 licensed cardiologists from Craiova that compared the developed platform with a commercially available system (General Electric MAC5500). Each module was tested thoroughly, using data gathered from a local hospital - a database of 500 ECG records sampled at 500 Hz that contains various morphologies of the cardiac activity including myocardial infarction patients, cardio-myopathy, arrhythmias, atrial fibrillation and healthy controls.

In this system the annotation can be performed in any leads by GUI selection. To verify the accuracy of the system we display vertical lines with different colours in position where the algorithm detected a feature like P wave, QRS complex beginning and end. Also the algorithm generates additional information for each feature like type: P, Q, R, S, T, U, J and complex types: PR interval, RR interval, QT interval, QRS duration.
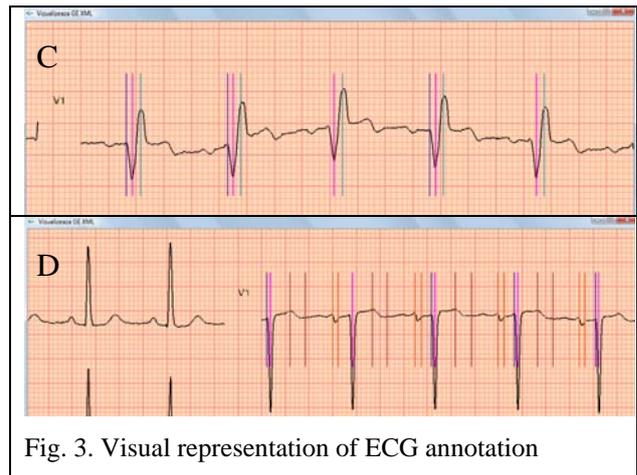

Fig. 3. Visual representation of ECG annotation

In Fig. 3, each line represents the marking of an annotated wave like: beginning of p wave, end of p; R, S waves; beginning of T wave and end of T).

The following table exemplifies three cases of 2D vectorcardiograms generated by the system:
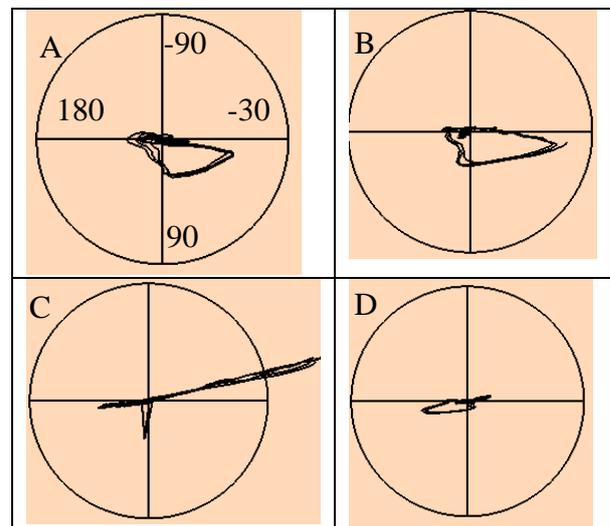

Fig. 4. Different cases of 2D frontal vectorcardiogram

In Fig. 4, the four cases of VCG illustrate respectively:

A. A patient with normal sinus rhythm

B. A patient with normal sinus rhythm and normal ECG. From the figure it can be determined that the heart axis is normal and the heart activity is normal

C. Patient with Electronic ventricular pacemaker. We can see the electric spike axis and also the rightward axis deviation because the pacemaker stimulated right heart chamber. Also we observe relatively normal heart activity and no asyncronism between the two heart chambers.

D. Anterior infarct with rightward axis deviation. From the vectorcardiogram we can easily determine the right axis deviation and we can observe a reduced heart activity.
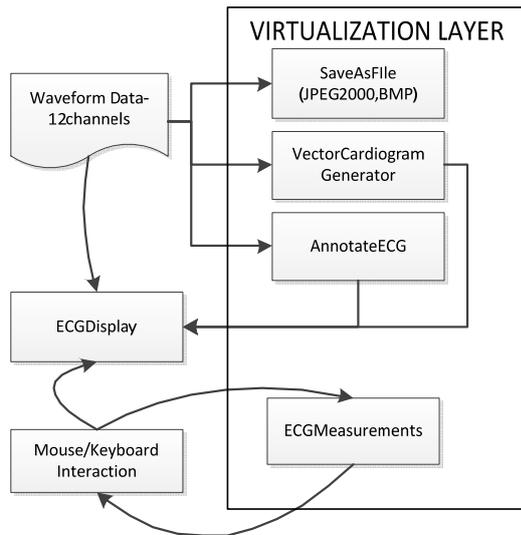
Fig 5.Virtualization Layer

In figure 5 we added a rectangle that points out the role of the virtualization layer. The virtualization layer extends the application features and capabilities beyond its original purpose. In our case we've added support for vectorcardiograph, different annotation scheme and data storage as JPEG and ECG precise measurements, despite the fact the original ECG device was not offering them.

4   CONCLUSIONS AND FUTURE WORK

Over the years, the ECG monitoring has evolved from recording of the patient's heartbeat to complex modules like classification of cardiac arrhythmias or dynamic location of heart ischemic area by assessing the ST-segment changes with great implications in patient outcome.

We consider there is a critical medical requirement for the continuous development of modern medical devices or systems, ECG-based, that allow physicians not only for better access, but also to customize access and usage of the medical data. The need for completion of information in this field is vital. It was an underlying purpose of this paper to investigate the preliminary steps in the development of a 12-lead ECG system that should not only report medical data, but also summarize cardiologists' ECG diagnoses including waveform interpretations, treatment strategies, and disease confirmation. Current systems use a closed-loop development and often ignore the particular hospital needs. Future medical applications should be customizable and flexible long after they left the development stage. The customization or extension, and virtualization of the ECG devices are desirable features which current devices do not implement because of strict regulations regarding medical devices safety. A certain degree of customization and virtualization is needed in the medical field despite the potential risk concerns.

Despite the number of features that our application implements, we still need to further tests and validate each component for accuracy and clinical relevance by working closely with doctors. Also further modules will be added that will deal with different cardiac pathology. We also plan to research further for improved annotation methods and a better usage of vectorcardiogram in the medical field.

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