AN ABSTRACT OF THE DISSERTATION OF

Thidarat Dendamrongvit for the degree of Doctor of Philosophy in Industrial Engineering presented on February 21, 2006.
Title: An Ontology-based System for Representation and Diagnosis of Electrocardiogram (ECG) Data.

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Richard E. Billo

Electrocardiogram (ECG) data are stored and analyzed in different formats, devices, and computer platforms. There is a need to have an independent platform to support ECG processes among different resources for the purposes of improving the quality of health care and proliferating the results from research. Currently, ECG devices are proprietary. Devices from different manufacturers cannot communicate with each other. It is crucial to have an open standard to manage ECG data for representation and diagnosis.

This research explores methods for representation and diagnosis of ECG by developing an Ontology for shared ECG data based on the Health Level Seven (HL7) standard. The developed Ontology bridges the conceptual gap by integrating ECG waveform data, HL7 standard data descriptions, and cardiac

diagnosis rules. The Ontology is encoded in Extensible Markup Language (XML) providing human and machine readable format. Thus, the interoperability issue is resolved and ECG data can be shared among different ECG devices and systems.

This developed Ontology also provides a mechanism for diagnostic decision support through an automated ECG diagnosis system for a medical technician or physician in the diagnosis of cardiac disease. An experiment was conducted to validate the interoperability of the Ontology, and also to assess the accuracy of the diagnosis model provided through the Ontology. Results showed 100% interoperability from ECG data provided through eight different databases, and a 93% accuracy in diagnosis of normal and abnormal cardiac conditions.

An Ontology-based System for Representation and Diagnosis of Electrocardiogram (ECG) Data

by
Thidarat Dendamrongvit

A DISSERTATION

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Thidarat Dendamrongvit, Author

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For my parents

Somsak and Tiparat Dendamrongvit

An Ontology-based System for Representation and Diagnosis of Electrocardiogram (ECG) Data

1. INTRODUCTION

An electrocardiogram (ECG) is an electrical recording of the activity of the heart and is used to aid the investigation of heart disease. The standard 12-lead ECG is a representation of electrical activity of the heart recorded from electrodes on the body surface surrounding the heart. Currently, ECG monitoring systems and output data are proprietary products sold by a multitude of different vendors. The data are recorded, read, and analyzed by different methods depending on computing platforms and software implementation intricacies. Data are not shared among different products, or able to be presented in a ubiquitous manner across heterogeneous computing platforms that do not contain the vendor's product. There is a need to share and integrate ECG data among different devices and systems for various types of uses such as disease diagnosis, administrative processes, and research (European Committee for Standardization, 1993; Health Level Seven, 2004).

Health Level Seven (HL7), a Standards Developing Organization (SDO) associated with the American National Standards Institute (ANSI), has proposed standards for electronic exchange of medical and related data in health care services worldwide. This effort is intended to promote the application of standards for

clinical data exchange among heterogeneous device and computer platforms (Health Level Seven, 2004).

Currently, ECG data is interpreted by physicians using paper records and automated ECG devices. These ECG devices do not provide complete ECG diagnosis based on the HL7 standard. Some of the existing ECG devices do not include automated diagnosis. The other devices may have this feature but they diagnose only specific cardiac diseases with the need of proprietary software and platform.

Extensible Markup Language (XML) has been widely used for data representation in various applications in a variety of industries including healthcare (OASIS, 2004). XML was developed in 1998 by the W3C (World Wide Web Consortium) and has become a standard for exchanging data on the Internet. Many applications adopt the XML data format due to its flexibility. For example, it allows a predefined data structure to be easily modified corresponding to changes. XML Schema, one of the XML-based technologies, defines shared markup vocabularies and the structure of data records constructed in XML formats (Fallside and Walmsley, 2004). With XML, information content is separated from presentation level. Therefore, multiple views of the same data can be easily provided. XML technologies have been used in health care service for sharing electronic patient records and related medical data (Dolin et al., 1999; Gardner and Peachey, 2002). This research applied the XML technologies as a tool to facilitate the development of system-independent ECG output representation and as an

automated decision aid to a medical technician or physician in the diagnosis of cardiac disease.

1.1 Research Objectives

The objectives of the research were:

1. To create an Ontology for representation and diagnosis of ECG data. The Ontology encoded in XML provides a machine readable format. Thus, ECG data can be shared among different ECG devices and systems.
2. To create and evaluate a system for ECG measurements and diagnosis based on the HL7 standard. The system can be used as a decision support tool for automated ECG diagnosis.

1.2 Research Contribution

This research allows heterogeneous presentation of ECG data across multiple platforms. It also provides a mechanism for diagnostic decision support focusing on the HL7 standard. This research integrated ECG waveform data, HL7 standard data descriptions, and cardiac diagnosis rules for decision support. It also explored XML technology for ECG data encoding which provides a representation that is both human and machine readable. The developed Ontology is a main contribution which provides a conceptual bridge between ECG data presentation

and diagnosis. In addition, the research promotes initiatives for interoperability among different systems. Figure 1 illustrates relationships between the Ontology and multiple systems along with the scope of the research and future domains such as nurses, device suppliers, researchers, and administrative to which the Ontology can be extended.

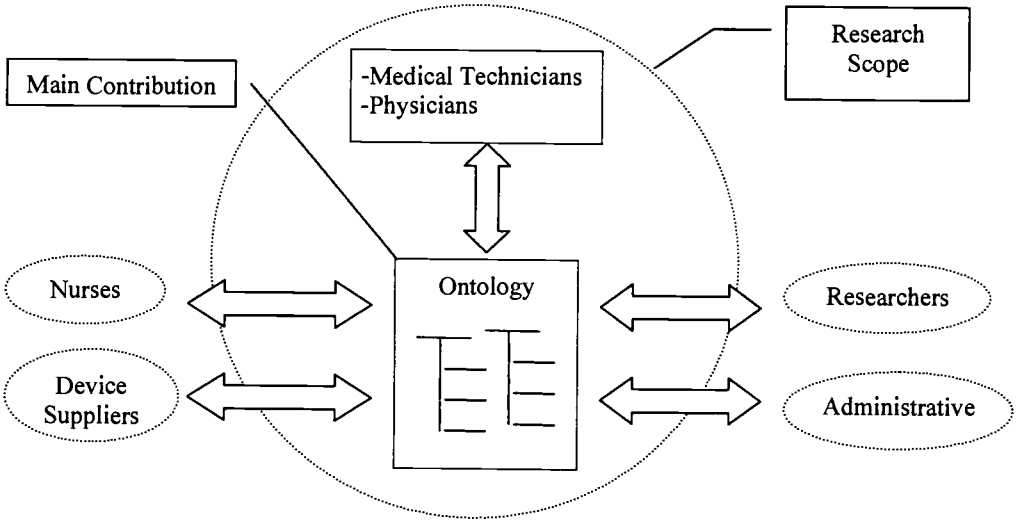


Figure 1: Relationships between Ontology and Different Domains.

With the Ontology, ECG data can then be shared and interpreted through different domains. For example, medical technicians/physicians can view and diagnose ECG data of patients while device suppliers and researchers can access the same data for different purposes without the interoperability problem.

Moreover, this research promotes knowledge-based rules for ECG diagnosis based on HL7 which will help the medical technicians/physicians highlight important alerts for decision-support of cardiac diseases. It is expected that this research will provide knowledge from the Ontology and experimental results that could be used to develop algorithms targeted to specific cardiac diseases for ECG interpretation.

2. LITERATURE REVIEW

This literature review summarizes the research and methods that have been developed in the related fields of this dissertation. This chapter is divided into five sections. First, a description of electrocardiogram (ECG) diagnosis is presented. Research in the field of ECG standards for interoperability and related work are discussed in the second section. The third section focuses on the literature about Ontology. Human factors concerns for medical devices are described in the forth section. The last section provides a summary of the literature review.

2.1 Electrocardiogram (ECG) Diagnosis

Two types of ECG diagnosis which are paper record and automated diagnoses are explained in the following sections.

2.1.1 Paper Record Diagnosis

In the area of ECG diagnosis, the most common method of storing an ECG of each patient is as a paper record. ECG data are often stored as graphical paper records printed by a chart recorder (Bhullar et al., 1992). Diagnostic information can be reflected in ECG recordings stored on paper (Day et al., 1990). An example of a standard 12-lead ECG stored on paper is shown in Figure 2.

Figure 3 illustrates the structure of ECG waves, intervals, standard time, and voltage measures on the ECG paper.

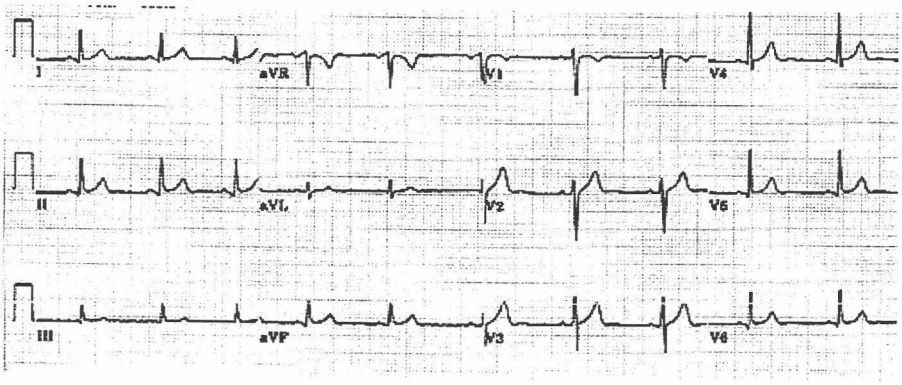


Figure 2: ECG Recordings on Paper (adapted from Yanowitz, 2005).

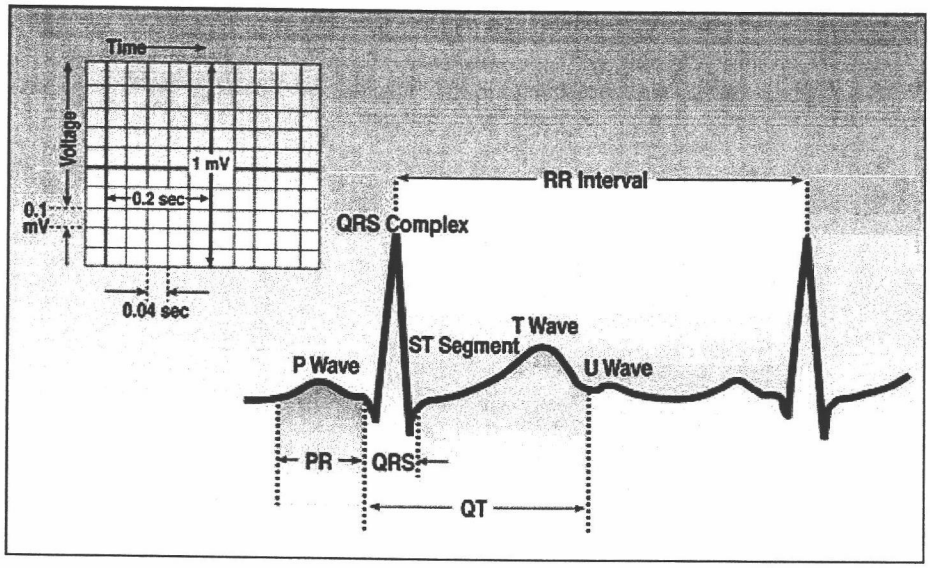


Figure 3: Standard ECG Paper and Wave Structure (adapted from Yanowitz, 2005).

From Figure 3, the P wave represents atrial activation. The PR interval is the time from onset of atrial activation to onset of ventricular activation. The QRS complex represents ventricular activation while the QRS duration is the duration of ventricular activation. The ST-T wave represents ventricular repolarization. The QT interval is the duration of ventricular activation and recovery. The U wave represents the time interval after depolarizations in the ventricles, and the start of the next P wave. An example of ECG diagnosis of a left bundle branch block, which is a common cardiac disease, is shown in Figure 4.

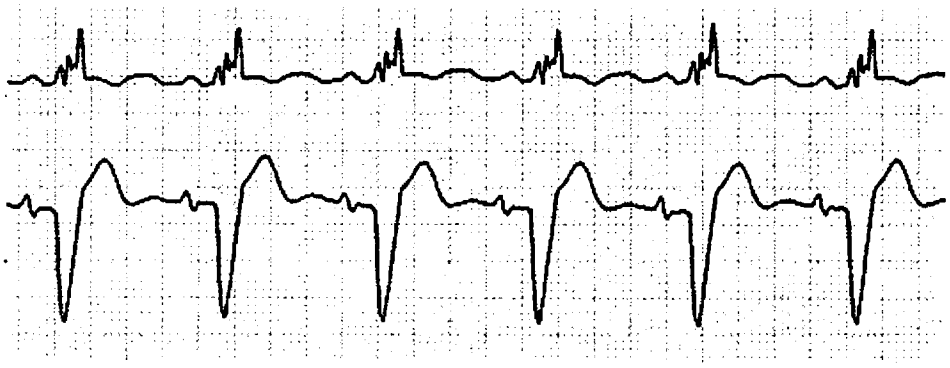


Figure 4: Left Bundle Branch Block (adapted from Yanowitz, 2005).

The above ECG has PR intervals ranging from 0.12 to 0.20 seconds, and QRS durations greater than 0.12 seconds. These are the conditions that typically indicate a left bundle branch block.

2.1.2 Automated ECG Diagnosis

Many health care providers now utilize machines and computers to record and diagnose ECG data. Useful measurements can be automated to make it more efficient in ECG diagnosis.

From the literature, automated interpretation of ECG has been done as decision support for less experienced physicians (Heden et al., 1997). By examining the ECG signal, a number of informative measurements can be derived from the characteristic ECG waveform. Most of the research focus has been on developing a method to detect specific ECG measurements for a specific cardiac disease. Methods for automated ECG diagnosis are summarized below.

Hughes et al., (2004) examined the use of hidden Markov and hidden semi-Markov models for automatically segmenting an ECG waveform into its waveform features. They developed an automated system for ECG interval analysis to detect prolongation of the QT interval (Long QT Syndrome) for the diagnosis of abnormal heart rhythm. This research was done to support the study of adverse effects which may be brought by new drugs such as Amiodarone. The ECG of the patient was used to provide information about the status of the patient's heart.

For the automated diagnoses of myocardial infarction, artificial neural networks were trained to detect acute myocardial infarction in the 12-lead ECG by Heden et al., (1997). Their results show that the networks can be used to improve automated ECG interpretation for acute myocardial infarction. They found that

their system performed better than an experienced cardiologist, indicating that the system may be useful as decision support even for the experienced ECG readers.

Porela et al., (1999) investigated the applicability of computerized electrocardiogram interpretation in classifying patients with suspected acute myocardial infarction. They found that computerized analysis of the 12-lead electrocardiogram can increase the consistency and reduce the workload of patient classification. They studied ECGs of 311 patients with suspected myocardial infarction and developed a new computerized coding system to detect electrocardiograhic myocardial infarction. In their work, the code allows interactive redefinition of criteria to meet user-defined needs. However, they concluded because of the weak relationship between elcetrocardiographic and biochemical criteria of myocardial injury, the role of ECG in the diagnostic classification of acute ischemic syndromes should be reevaluated.

Hiroki et al., (1988) developed criteria for the diagnosis of Right Ventricular Hypertrophy (RVH) using a point scoring system by analyzing standard 12-lead ECGs in 310 patients. ECGs were evaluated to identify criteria that provided at least 95% specificity. The criteria are (1) the R wave magnitude in V1 had to be greater than 0.7 mV; (2) the S wave magnitude in V6 had to be greater than 0.3 mV; (3) the S wave magnitude in V1 less than 0.5 mV; (4) the R wave magnitude in V1 plus the S wave magnitude in V6 minus the S wave magnitude in V1 must be greater than 0 mV; and (5) the degree of frontal QRS axis had to be greater than 90 degrees. By comparing sensitivity in patients with

existing criteria, the authors claim that the accuracy of their criteria was the highest among those criteria used in a point scoring system including the currently used automated ECG criteria for the diagnosis of RVH.

2.2 ECG Standards for Interoperability

Different approaches have been proposed to address the interoperability issue for sharing medical data among different formats and devices. The Standard Communications Protocol for Computer-Assisted Electrocardiography (SCP-ECG), which was proposed by the Project Team PT5-007 of CEN/TC 251 in 1993, provides specifications for the interchange format of ECG waveform data, patient information, and measurement results (European Committee for Standardization, 1993). However, the use of this standard was not successful due to some limitations, and therefore was never adopted by ECG product manufacturers. The standard leaves too many degrees of freedom in many areas such as details in data format with the result that it is difficult to produce generic SCP-based software (Chiarugi, 2001). Therefore, market-leader manufacturers still prefer a proprietary solution.

HL7 provides standards for the exchange and sharing of electronic health information (Health Level Seven, 2004). HL7 focuses on the interface requirements of the entire health care organization including clinical, financial, and

administrative information among heterogeneous computer systems. The standards enable healthcare information system interoperability and sharing of electronic clinical and relevant data.

The Lab Automation Committee, a special interest group of HL7, defines a set of standards for Point-of-Care medical device communication (Lab Automation Committee, 2004). It is intended to provide for open systems communications in healthcare applications between medical devices and patient care information systems for the acute care setting. The scope of the standard includes nomenclature architecture and a data dictionary for ECG and other clinical areas such as Vital Signs, Respiratory Measurements, and Common Blood Gas Measurements.

This research focuses on the ECG section of the HL7 standard which includes the data dictionary for ECG measurements and enumerations for ECG diagnostics (i.e., abnormal conditions) derived from ECG signals by an ECG machine. This HL7 standard was developed based on the SCP-ECG standard and is intended to supersede the previous use of the SCP-ECG.

Wang et al., (2004) proposed methods for managing ECG data by using XML for ECG representation. They developed tools to convert ECG from a specific database (MIT-BIH Arrhythmia) to data in XML format. This research initiates an XML-based approach to support ECG data storage. It provides hierarchical structure of ECG data representation. However, this research does not include ECG measurements and diagnosis approaches for decision support. It also

focuses on only representation of ECG data from a specific database. The developed tools cannot be directly applied to ECG data from other sources.

2.3 Ontology

Within the domain of Information Systems, an *Ontology* is "an explicit specification of a conceptualization" (Gruber, 1993), or a document or file that formally defines relations among terms (Berners-Lee et al., 2001). An Ontology offers a shared, structured, and common understanding of some domain or task that can be communicated across people and computers. The term *Ontology* was borrowed from philosophy where it means "Theory of existence" (Mizoguchi and Ikeda, 1996). It is the study of what exists.

Research on Ontology has become popular in the Information Systems community. Some of the reasons to develop an Ontology are to share a concept of the structure of information among people or software agents and enable reuse of domain knowledge (Musen, 1992; Gruber, 1993). Various applications in Information Systems apply the application of ontologies especially in the area of search and retrieval of information repositories (Guarino, 1998; McGuinness, 1998; Uschold and Jasper, 1999).

In this research, an Ontology for representation and diagnosis of ECG data was developed to standardize the ECG data processes. The standard Ontology integrates ECG waveform representation, measurements, and diagnosis based on

HL7. The Ontology also provides causative relationships among the ECG waveforms, measurements, and diagnostic conditions. In turn, the Ontology allows a machine readable format so that ECG diagnosis and data exchange can be done efficiently without the need of proprietary algorithms or software with the result of solving the interoperability issue.

2.4 Human Factors in Medical Devices and Site Usability

Human Factors Engineering (HFE), also known as Usability Engineering or Ergonomics is the study of interaction between humans and systems (Murff et al., 2001). Researchers in this area have provided principles concerning device and software program designs that allow for efficient usage (Murff et al., 2001; Sawyer, 1996). According to the United States Food and Drug Administration (FDA), between 1985 and 1989, almost half of all medical devices were recalled because of poor design including problems with software (Food and Drug Administration, 1998). In order to prevent user errors with electronic device, human factors design needs to be considered to ensure patient safety (Sawyer, 1996; Bogner, 1999).

HFE considerations relate directly to the user interface (Food and Drug Administration, 1998). There are numbers of medical devices and software products developed. The FDA provides guidance for device user interface characteristics. A well-designed user interface will facilitate correct actions and prevent actions that could result in hazards.

One of the objectives of this research was to develop a decision aid system for ECG diagnosis. Human Factors Engineering was considered in the design process of an efficient system for the users. The developed system is intended to provide ECG diagnosis which is medical information through interface via an Internet browser. Thus, site usability was also considered as a factor to build a system that meets user requirements and has a user-friendly interface.

With respect to site usability, Nielsen (1999) studied a real website and investigated factors that increase site usability. Some of these factors include the use of fewer words, making text scannable, and using appropriate words. He found that user performance can be improved by using appropriate coding such as headings, bold text, highlighted text, bullet lists, and graphics. Other principles for successful web interface design are found in the literature. Examples of these principles are simplicity, fast download time, and simple navigation systems.

2.5 Summary

From the literature, diagnosis of ECG has been done by using different approaches for different diagnosis of cardiac diseases. Various algorithms have been studied for properly identifying the diseases. While the literature provides contribution in the field of ECG diagnosis, the interoperability problem of ECG data diagnosis still exists as there is a lack of a rigorous diagnosis standard. Automated systems built based on this algorithm will only provide proprietary

solutions for ECG diagnosis. ECG data processes have been done with the need of proprietary software for a particular system. It is necessary to standardize the ECG processes for benefits of interoperability for diagnosis of cardiac diseases.

HL7 provides a standard for ECG measurements and enumerations (i.e., abnormal conditions). Both ECG measurements and enumerations are represented as simple listings with definitions. HL7 does not specify relationships between ECG measurements and abnormal conditions. Data description for each of these is listed separately without connection between each other. In other words, HL7 does not specify which ECG measurement is associated with diagnosis of a particular abnormal condition, and vice versa. There is no connection between data descriptions in the standard and actual waveform representation either.

In this research, an Ontology to standardize the ECG processes was developed based on the HL7 standard. Rules are included in the Ontology for diagnosis of abnormal conditions and cardiac diseases. Thus, the Ontology integrates ECG waveform representations with measurements and enumerations in HL7. ECG data can then be shared and diagnosed among different systems thus resolving interoperability issues.

3. PROBLEM STATEMENT

Effective medical systems must have a way of interaction and communication among several agents including physicians, nursing staff, technicians, patients, and computerized systems. There is a need to share data in the health care environment. There are many types and forms of data that will be used for multiple purposes. Medical information should be shared for the purposes of improving the quality of health care and proliferating the results from research. Sharing is possible only if interoperability exists.

ECG data, which is one type of medical data, are stored and analyzed in different formats, devices, and computer platforms. There is a need to have an independent platform to support ECG processes among different resources. Currently, ECG devices are proprietary. Devices from different companies cannot communicate with each other. It is crucial to have an open standard to manage ECG data for representation and diagnosis. HL7 is in the process of proposing a new standard of nomenclature of ECG measurements and diagnostics based on the SCP-ECG standard (Lab Automation Committee, 2004). However, this HL7 standard nomenclature consists only of a data dictionary that implicitly defines elements of the ECG waveform related to diagnosis of cardiac disease. HL7 does not represent the ECG waveform itself that is output from the medical device. In contrast, ECG output data from medical devices are stored solely as digital x,y

coordinates directly corresponding to the ECG waveform. In essence, there is a conceptual gap between the way ECG data is represented (digital data or waveform) and the HL7 ECG standard measurements and diagnosis (data dictionary).

HL7 does provide a data dictionary for both ECG measurements and enumerations (i.e., abnormal conditions). Both ECG measurements and enumerations are in a data dictionary format, and HL7 does not specify relationships between ECG measurements and the abnormal conditions. A Data description for each of these is listed separately without any type of connection between each other. In other words, HL7 does not specify which ECG measurement is associated with diagnosis of a particular abnormal condition and vice versa. Nor is there a connection between data descriptions in the standard and the actual waveform representation. These three events (i.e. digital waveform points, HL7 measurements, and HL7 diagnostics) are not directly related to each other in the standard. This lack of conceptual connectivity between ECG data presentation formats (waveform representation), HL7 diagnosis parameters (ECG measurements), and actual diagnostics (abnormal conditions) became a research opportunity, in that if a standard ontology is developed that integrates the three representation schemes, then both interoperability and ubiquitous diagnosis of ECG results can be done independent of device platform.

4. METHODOLOGY

This chapter describes the methodology to develop an Ontology-based system for representation and diagnosis of ECG data for the purpose of sharing ECG results. The following sections explain details of the research approach in steps including use case analysis, ontology creation, and the model development including examples to illustrate the processes.

4.1 Use Cases

In order to build an accurate and efficient system, *Use Cases* were used as a tool to capture requirements or options that a user can expect from the system. Use cases have become a widespread practice for capturing functional requirements from the users and are used to validate the software system architecture in the development process (Kulak and Guiney, 2004; Bittner and Spence, 2003). They help clarify the gap analysis by comparing system functionality to user requirements.

4.1.1 Users

The developed system is targeted to the use by medical technicians who do cardiac monitoring and interpret ECGs. Information of the ECG interpretation from medical technicians will be forwarded to the physicians who actually do the diagnosis of the patients.

4.1.2 Requirements of the System

In the design process of the system, requirements were captured from medical technicians and physicians from the EKG department in a hospital to ensure that the developed system will meet user requirements. System requirements are listed as follows:

- ECG data from different ECG devices shall be interpreted without the need of proprietary ECG software. Thus, a platform and software-independent system for ECG diagnosis is required.
- ECG measurements and diagnosis shall conform to a diagnosis standard.
- An automated ECG diagnostic system shall be provided with a list of diagnoses for decision support.
- The system shall be cost effective.

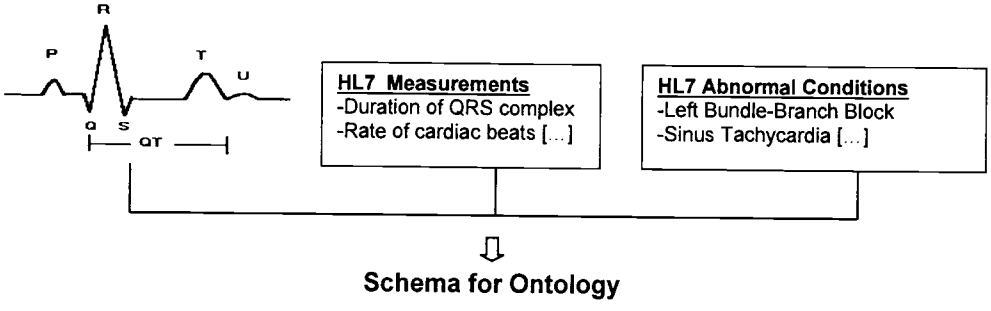
In the current system, ECG interpretation is cumbersome because it depends on manufacturer's software. Data cannot be shared among different ECG devices and software. Current devices do not have diagnoses conformed to any standard. Moreover, the proprietary system can be expensive. Table 1 summarizes the advantages that the developed system of Ontology-based will provide over the existing system.

Table 1: Comparison between the Current System and the Ontology-based System.

Characteristics	Current System	Ontology-based System
Interoperability	• Proprietary Software and Platform • Data cannot be interpreted on different computers without proprietary software. • ECG data cannot be transferred (e.g., when patients move, ECG diagnosis history cannot be transferred efficiently.)	✓Platform and software-independent system for ECG diagnosis in machine readable format. ✓Data from different ECG devices can be interpreted on different computers. ✓ECG data can be transferred efficiently (e.g., when patients move, ECG diagnosis history can be transferred electronically without interoperability problem.)
Standard	• Various outputs depending on companies. • No standard	✓Measurements and diagnosis conform to HL7 standard.
Diagnosis	• Some ECG devices do not provide automated diagnosis at all. They only provide graphics, and diagnosis is done by physicians. • Some ECG analysis software packages list a diagnosis. However, the diagnosis is not associated with any statement to say how the diagnosis was made. Need trained users. • List of diagnosis is not complete and they are not in a standard software language.	✓A decision aid system with complete diagnosis of cardiac diseases and abnormal conditions based on HL7. ✓Users can review the associated measurements according to a particular diagnosis. ✓For less experienced users: provide recommendations for disease diagnosis. ✓For more experienced users: save time spent in reading all the ECGs.
Cost	• Expensive	✓Cost effective

4.2 Ontology Development and Schema

An Ontology-based system representing structure for the presentation, measurement of ECG data, and criteria for diagnosis was developed. The structure of the Ontology for the representation, measurement, and diagnosis of ECG data was synthesized from existing standard formats and recommendations. This research integrates ECG data with the measurements and diagnosis described in the HL7 standard. Figure 5 depicts a schema for the developed Ontology presenting the relationships among ECG data and the HL7 standard. The Ontology integrates the ECG waveform data with textual measurement/diagnosis descriptions. The ECG Ontology was encoded by using XML Schema for rigorous vocabulary and structure, and diagnosis rules are included in a diagnosis system.



⇩

Schema for Ontology

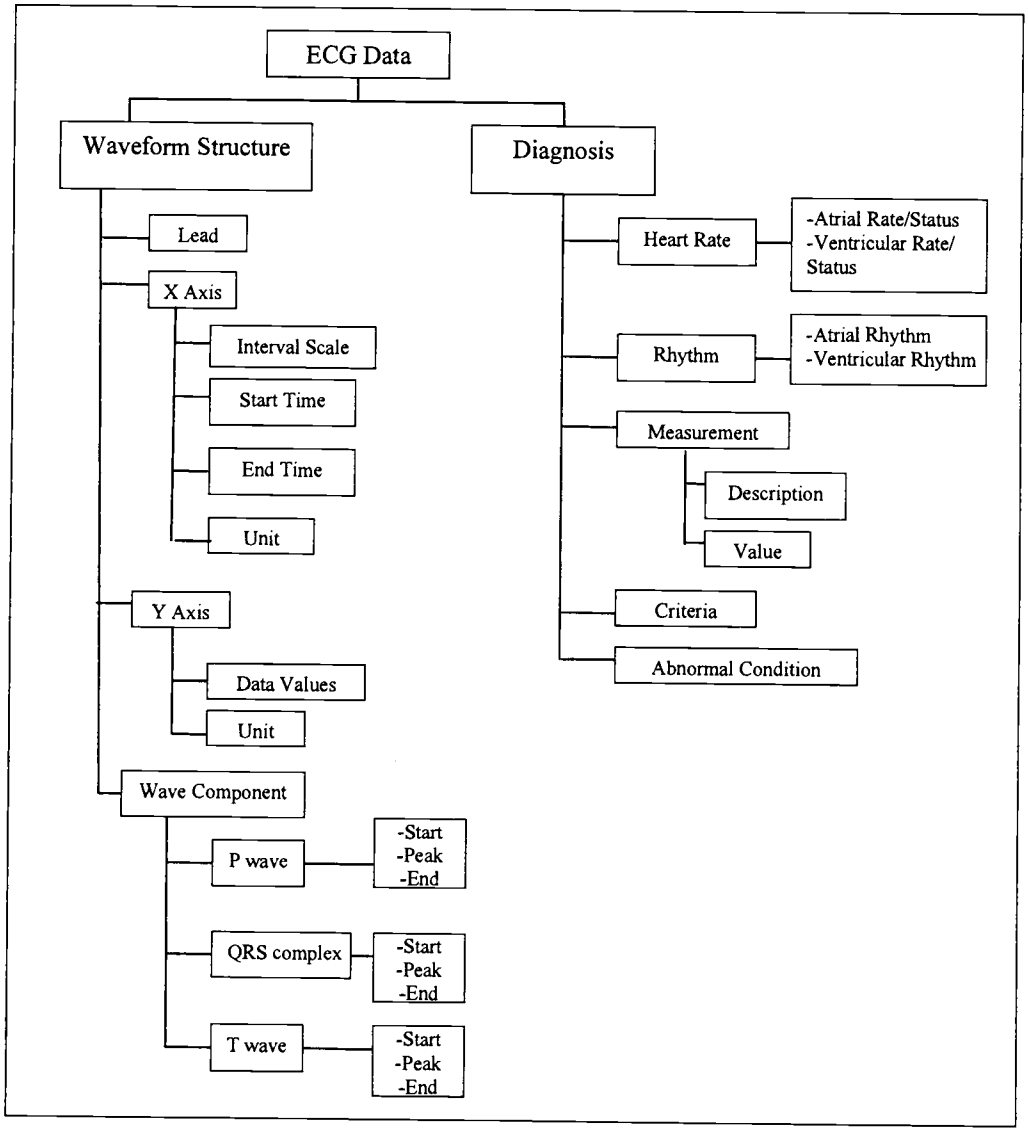


Figure 5: Schema for Ontology.

There are two categories for ECG data descriptions in the HL7 standard: ECG Measurements and Abnormal Conditions. However, there is no connection between ECG measurements and abnormal conditions in the standard. HL7 does not specify which ECG measurements lead to which abnormal condition. Moreover, there are no specific criteria for diagnosis in the HL7. The developed Ontology can improve the use of the HL7 standard by adding connections between ECG measurements and abnormal conditions. This research includes a comprehensive set of diagnosis rules that draw upon HL7 measurements. The Ontology integrates three different flat files (wave form, HL7 measurements, and HL7 abnormal conditions), add structure illustrating inter-relationships, and represent them through a neutral representation.

From Figure 5, schema for the Ontology consists of two categories which are waveform structure and diagnosis.

Waveform Structure

Waveform structure consists of necessary components for ECG plots and associated waves. The structure format was adapted from existing recommendations in the literature with the following components (Wang et al., 2004).

- Lead (Electrode Placement)
- *X-Axis*
    - Time Unit

  - Start Time
  - End Time
  - Interval Scale
- *Y-Axis*
  - Amplitude Unit
  - Digital Data
- Wave component (i.e., P wave, QRS complex, and T wave)
- Wave boundary
  - Start: indicating the sample number that starts the wave
  - Peak: indicating the sample number of peak point of the wave
  - End: indicating the sample number that ends the wave

Diagnosis

This section includes diagnosis rules which connect HL7 measurements and abnormal conditions along with diagnosis criteria. The diagnosis knowledge was collected from available rules (Lippincott Williams & Wilkins, 2005; Jenkins and Gerred, 1996; Yanowitz, 2005; Dubin, 1993; Marriott, 1987). An example diagnosis of sinus arrhythmia is described below including an ECG image in Figure 6. A complete list of ECG diagnosis rules is provided in Appendix A.

Abnormal Condition (HL7)

Sinus arrhythmia

General Descriptions

Sinus arrhythmia is a variation in rhythm of more than 0.16 second. Rate normally falls within normal limits. However, rhythm is irregular and varies with respiratory cycle. Treatment is not typically required unless symptomatic bradycardia is present.

ECG Measurements (HL7)

- Duration of the interval between two consecutive P waves of ECG
- Duration of the interval between P onset and QRS onset of ECG
- Duration of the interval between two consecutive QRS complexes
- Rate of cardiac beats

Criteria

- Sinus arrhythmia occurs when the longest PP or PR interval exceeds the shortest interval by 0.16 second.
- Normal P waves preceding each QRS complex
- Normal (Narrow) QRS complex, RR interval < 0.12 second
- Rate between 60 and 100 beats per minute (bpm)
- The rhythm varies: increasing on inspiration, decreasing on expiration.

ECG Image

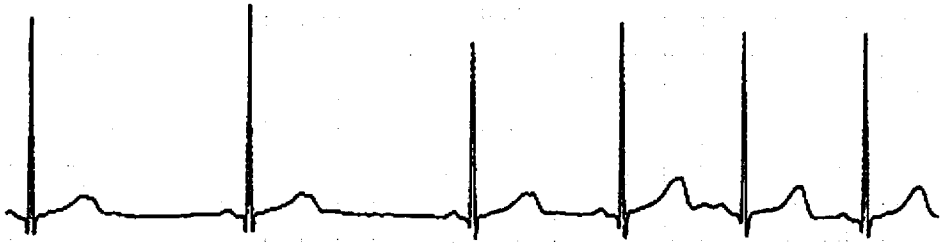


Figure 6: Sinus Arrhythmia (adapted from Yanowitz, 2005).

4.3 Model Development

This section describes the processes of model development. The development tasks are divided into three phases and explained in the following subsections. Figure 7 illustrates the overall framework of the model development.

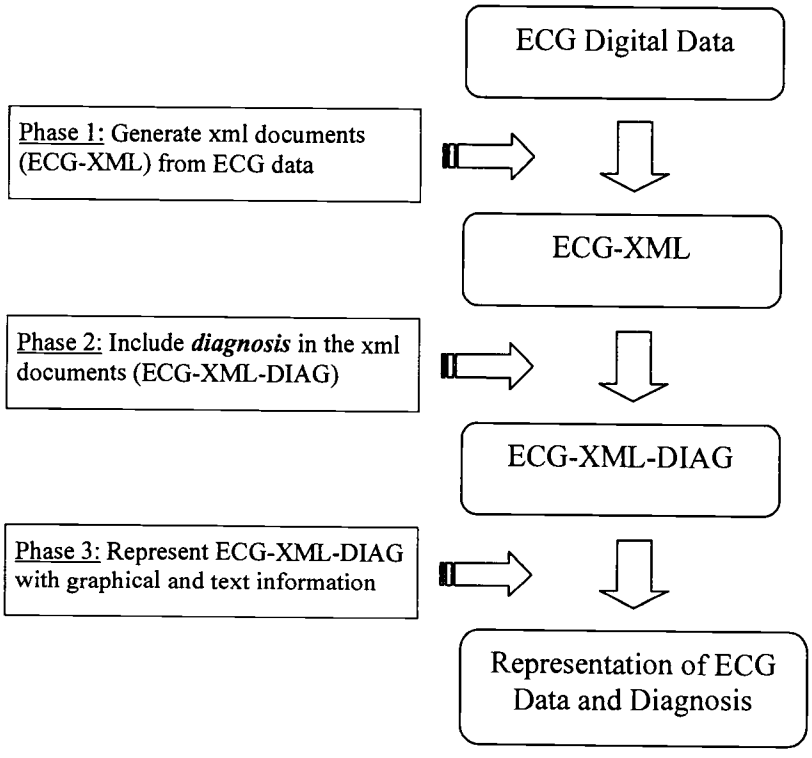


Figure 7: Model Development Framework.

4.3.1 Generation of XML Documents (ECG-XML) from ECG Data

ECG data has been traditionally recorded as a data file in a flat file format. No database is typically used to query this data, but it is stored in such a manner for easy access by the vendor's ECG software. In this first step of the process to create a heterogeneous file, XML documents were automatically created from ECG *x,y* coordinate data. XML Schema was used to restrict and validate ECG data instantiated into XML documents as shown in Figure 8. Waveform data and structure were encoded in XML Schema with the following information:

- Lead (Electrode Placement)
- Start time of the recording
- End time of the recording
- Time unit
- Interval scale (time interval between each sample)
- Digital data
- Unit of digital data
- Wave component (i.e., P wave, QRS complex, and T wave)
- Wave boundary
    - Start: indicating the sample number that starts the wave
    - Peak: indicating the sample number of peak point of the wave
    - End: indicating the sample number that ends the wave

This research applied the ecgpuwave software to detect ECG waves (i.e., P wave, QRS complexes, and T wave) and locate boundary of each wave (start, peak, and end) (Goldberger et al., 2000). The software analyzes ECG data based on the algorithm of Pan and Tompkins to detect the QRS complex with modifications for improvements (Goldberger et al., 2000; Pan and Tompkins, 1985).

The conversion process was implemented in an internet browser with programming codes written in PHP version 4.3.11-1.

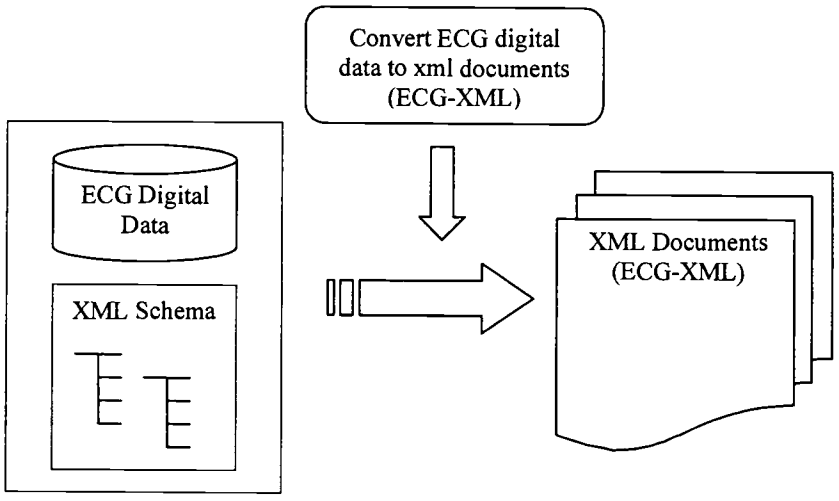


Figure 8: Generation of ECG-XML.

This following example illustrates the processes explained above by using real ECG data.

ECG Waveform Information

Lead: MLII

Start Time: 10 second

End Time: 20 second

Interval: 0.003 second

Digital Data: see Table 2

Table 2: Digital Data.

Sample #	Time (second)	Amplitude (mV)
1	0.000	-0.270
2	0.003	-0.255
3	0.009	-0.245
:	:	:
3333	20	-0.345

XML Schema

The XML Schema consists of structures of waveform which is a graphical representation of x and y coordinates. The X-axis represents time interval in seconds while the Y-axis represents amplitude in milli-volt (mV). From ECG digital data and the XML Schema, an ECG-XML document was created as shown in Figure 9. Figure 10 presents the XML Schema for waveform representation that was used to validate elements in the XML document.

```
<?xml version="1.0"?>
<ECG xmlns:xsi="http://www.w3.org/2001/XMLSchema-instance">
   <Lead>MLII</Lead>
   <GraphInfo>
      <XAxis>
            <IntervalScale>0.003</IntervalScale>
            <StartTime>10</StartTime>
            <EndTime>29.997</EndTime>
            <TimeUnit>Second</TimeUnit>
      </XAxis>
      <YAxis>
            <DigitalData>-0.27,-0.255,-0.245,-0.24,-0.24,-0.245,
-0.25,-0.235,-0.225,-0.235,-0.23,-0.245,-0.245,-0.24,-0.23,-0.225,
-0.22,-0.215,-0.205,-0.18,-0.155,-0.145,-0.145,-0.145,-0.165,
-0.14,-0.125,-0.115,-0.105,-0.125,-0.13,-0.13,-0.125,-0.135,
-0.155,-0.155,-0.16,-0.16,-0.155,-0.15,-0.13,-0.125,-0.13,-0.155,
 [..]
            </DigitalData>
            <AmpUnit>mV</AmpUnit>
      </YAxis>
   </GraphInfo>
   <WaveComponent>
      <Pwave>
            <Start>14</Start>
            <Peak>29</Peak>
            <End>53</End>
      </Pwave>
      <QRScomplex>
            <Start>70</Start>
            <Peak>89</Peak>
            <End>99</End>
      </QRScomplex>
      <Twave>
            <Start>188</Start>
            <Peak>214</Peak>
            <End>251</End>
      </Twave>
   </WaveComponent>

      [..]

</ECG>
```

Figure 9: ECG-XML Document.

```
<?xml version="1.0" encoding="UTF-8" standalone="yes"?>
<xs:schema xmlns:xs="http://www.w3.org/2001/XMLSchema"
elementFormDefault="qualified">
      <xs:element name="ECG">
            <xs:complexType>
                  <xs:sequence>
                        <xs:element ref="Lead"/>
                        <xs:element ref="GraphInfo"/>
                        <xs:element ref="WaveComponent"
maxOccurs="unbounded"/>
                  </xs:sequence>
            </xs:complexType>
      </xs:element>
      <xs:element name="Lead" type="xs:string"/>
      <xs:element name="GraphInfo">
            <xs:complexType>
                  <xs:sequence>
                        <xs:element ref="XAxis"/>
                        <xs:element ref="YAxis"/>
                  </xs:sequence>
            </xs:complexType>
      </xs:element>
      <xs:element name="WaveComponent">
            <xs:complexType>
                  <xs:sequence>
                        <xs:element ref="Pwave" minOccurs="0"/>
                        <xs:element ref="QRScomplex"
minOccurs="0"/>
                        <xs:element ref="Twave" minOccurs="0"/>
                  </xs:sequence>
            </xs:complexType>
      </xs:element>
      <xs:element name="XAxis">
            <xs:complexType>
                  <xs:sequence>
                        <xs:element ref="IntervalScale"/>
                        <xs:element ref="StartTime"/>
                        <xs:element ref="EndTime"/>
                        <xs:element ref="TimeUnit"/>
                  </xs:sequence>
            </xs:complexType>
      </xs:element>
      <xs:element name="IntervalScale" type="xs:float"/>
      <xs:element name="StartTime" type="xs:float"/>
      <xs:element name="EndTime" type="xs:float"/>
      <xs:element name="TimeUnit">
            <xs:simpleType>
                  <xs:restriction base="xs:string">
                        <xs:enumeration value="Second"/>
                  </xs:restriction>
            </xs:simpleType>
      </xs:element>
```

```
	<xs:element name="YAxis">
		<xs:complexType>
			<xs:sequence>
				<xs:element ref="DigitalData"/>
				<xs:element ref="AmpUnit"/>
			</xs:sequence>
		</xs:complexType>
	</xs:element>
	<xs:element name="DigitalData" type="xs:string"/>
	<xs:element name="AmpUnit">
		<xs:simpleType>
			<xs:restriction base="xs:string">
				<xs:enumeration value="mV"/>
			</xs:restriction>
		</xs:simpleType>
	</xs:element>
	<xs:element name="Pwave">
		<xs:complexType>
			<xs:sequence>
				<xs:element ref="Start"/>
				<xs:element ref="Peak"/>
				<xs:element ref="End"/>
			</xs:sequence>
		</xs:complexType>
	</xs:element>
	<xs:element name="QRScomplex">
		<xs:complexType>
			<xs:sequence>
				<xs:element ref="Start"/>
				<xs:element ref="Peak"/>
				<xs:element ref="End"/>
			</xs:sequence>
		</xs:complexType>
	</xs:element>
	<xs:element name="Twave">
		<xs:complexType>
			<xs:sequence>
				<xs:element ref="Start"/>
				<xs:element ref="Peak"
maxOccurs="unbounded"/>
				<xs:element ref="End"/>
			</xs:sequence>
		</xs:complexType>
	</xs:element>
	<xs:element name="Start" type="xs:string"/>
	<xs:element name="Peak" type="xs:string"/>
	<xs:element name="End" type="xs:string"/>
</xs:schema>
```

Figure 10: XML Schema for Waveform Representation.

4.3.2 Inclusion of Diagnosis in the XML Documents (ECG-XML-DIAG)

In this step, ECG data in XML format (ECG-XML) were diagnosed by using the diagnosis rules for each abnormal condition listed in HL7. Details of the diagnosis rules can be found in Appendix A. Table 3 shows examples of ECG measurements including duration, amplitude, and appropriate wave intervals.

Table 3: Examples of ECG Measurements.

Waves	*Measurements*
P wave	• Duration • Amplitude • P-P Interval
QRS complex	• Duration • Amplitude • R-R Interval • P-R Interval
T wave	• Duration • Amplitude • Q-T Interval

In order to properly identify abnormal conditions, information of rate and rhythm were calculated and included in the diagnosis rule as shown in Table 4.

Table 4: Rate and Rhythm.

Rate/Rhythm	*Measurements*
Rate	• Atrial Rate • Ventricular Rate • Status
Rhythm	• Atrial Rhythm • Ventricular Rhythm

The diagnosis rules were applied in order to convert ECG-XML to ECG-XML-DIAG in an internet browser with programming codes written in PHP version 4.3.11-1. The overall framework for this phase of this process is illustrated in Figure 11.

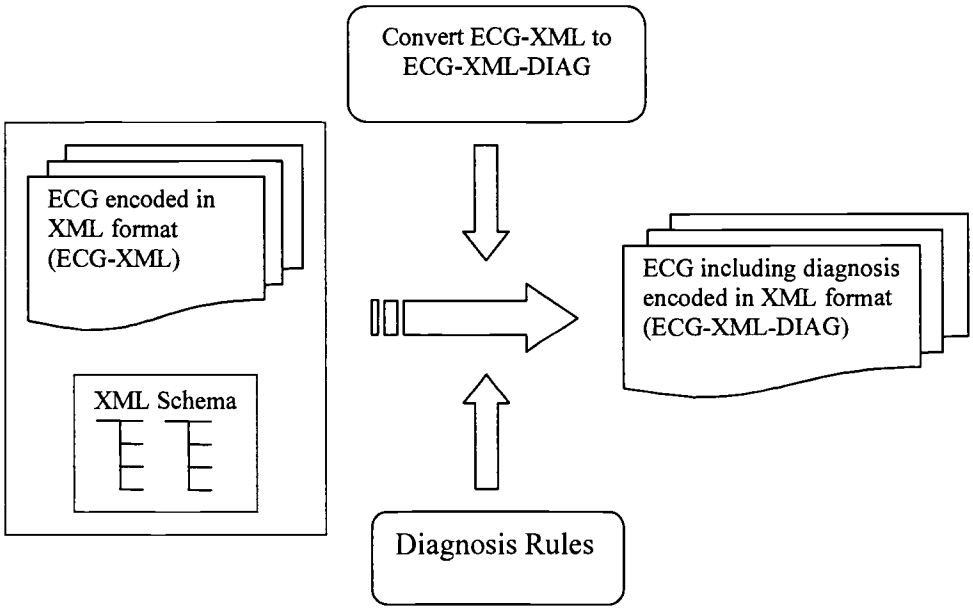


Figure 11: Generation of ECG-XML-DIAG.

Rules for diagnosis were added to the system as a decision-aid support tool for the medical technician or physician. These rules are not described in the standard and were synthesized from available recommendations gathered through the archived literature (Lippincott Williams & Wilkins, 2005; Jenkins and Gerred, 1996; Yanowitz, 2005; Dubin, 1993; Marriott, 1987). The following diagnosis presents some examples of abnormal conditions and measurement descriptions in the HL7 standard along with diagnosis rules from well-known recommendations outside the standard.

Abnormal Condition #1:

Irregular Rhythm

General Descriptions

Irregular rhythm is a condition of disturbances in the heart's rhythm.

ECG Measurements

- Duration of the interval between two consecutive QRS complexes
- Duration of the interval between two consecutive P waves of ECG

Criteria

- Irregular rhythm can be determined by accessing whether the RR intervals and PP intervals are regularly spaced.
- If the rhythm is irregular, determine if:
    - It is occasionally irregular
    - Regularly irregular (there is a pattern to the irregularity)

- Irregularly irregular (there is no pattern to the irregularity)

- Evaluate the waveform of the ECG in detail for additional clues.

Abnormal Condition #2:

Premature Ventricular Contraction

General Descriptions

Premature ventricular contractions (PVCs) are ectopic beats that originate in the ventricles, and occur earlier than expected. PVCs may occur in healthy people without being clinically significant. However, with underlying heart disease, PVCs may cause ventricular tachycardia and ventricular fibrillation.

ECG Measurements

- Rate of cardiac beats
- Duration of the QRS complex of ECG in <lead>
- Amplitude of the T negative wave of ECG in specified <lead>

Criteria

- Atrial and ventricular rhythms may be regular in underlying rhythm; irregular during PVCs.
- QRS premature
- QRS complex wide, usually > 0.12 second in premature beat
- T wave opposite direction to QRS complex

ECG-XML can be converted to ECG-XML-DIAG by applying rules from the corresponding XML schema and diagnosis rules from the Ontology. An example of an ECG-XML-DIAG document is shown in Figure 12. Figure 13 presents the XML Schema for ECG-XML-DIAG document. The ECG example in Figure 12 was diagnosed with two abnormal conditions which are irregular rhythm and premature ventricular contraction.

```
<?xml version="1.0"?>
<ECG xmlns:xsi="http://www.w3.org/2001/XMLSchema-instance">
   <Lead>MLII</Lead>
   <GraphInfo>
      <XAxis>
            <IntervalScale>0.003</IntervalScale>
            <StartTime>10</StartTime>
            <EndTime>29.997</EndTime>
            <TimeUnit>Second</TimeUnit>
      </XAxis>
      <YAxis>
            <DigitalData>-0.27,-0.255,-0.245,-0.24,-0.24,-0.245,
-0.25,-0.235,-0.225,-0.235,-0.23,-0.245,-0.245,-0.24,-0.23,-0.225,
-0.22,-0.215,-0.205,-0.18,-0.155,-0.145,-0.145,-0.145,-0.165,
-0.14,-0.125,-0.115,-0.105,-0.125,-0.13,-0.13,-0.125,-0.135,
-0.155,-0.155,-0.16,-0.16,-0.155,-0.15,-0.13,-0.125,-0.13,-0.155,
-0.17,-0.18,-0.19,-0.21,-0.245,-0.235,-0.23,-0.24,-0.255,-0.26,
-0.26,-0.265,-0.255,-0.25,-0.255,-0.27,-0.275,-0.275,-0.27,-0.255,
-0.265,-0.265,-0.275,-0.275,-0.27,-0.255,-0.26,-0.265,-0.29,-0.3,
-0.31,-0.36,-0.395,-0.415,-0.46,-0.49,-0.465,0.385,0.235,0.05,
0.125,0.36,0.665,0.94,1.13,1.22,1.155,0.9,0.47,0.015,-0.3,-0.385,
-0.345,-0.28,-0.245,-0.235,-0.245,-0.245,-0.27,-0.265,-0.255,
-0.255,-0.265,-0.29,-0.3,-0.295,-0.305,-0.31,-0.305,-0.305,-0.32,
-0.31,-0.3,-0.305,-0.31,-0.31,-0.325,-0.325,-0.31,-0.3,-0.305,
-0.305,-0.32,-0.31,-0.3,-0.29,-0.295,-0.3,-0.3,-0.305,-0.295,
-0.285,-0.295,-0.305,-0.31,-0.3,-0.305,-0.305,-0.305,-0.31,-0.32,
-0.32,-0.305,-0.3,-0.3,-0.31,-0.31,-0.32,-0.3,-0.295,-0.295,-0.3,
-0.305, [..]
            </DigitalData>
            <AmpUnit>mV</AmpUnit>
      </YAxis>
   </GraphInfo>

<WaveComponent>
      <Pwave>
```

```
            <Start>301</Start>
            <Peak>318</Peak>
            <End>343</End>
            <Duration>0.13</Duration>
            <Amplitude>0.16</Amplitude>
            <PPInterval>0.87</PPInterval>
            <Measurements>Normal</Measurements>
      </Pwave>
      <QRScomplex>
            <Start>365</Start>
            <Peak>383</Peak>
            <End>392</End>
            <Duration>0.08</Duration>
            <Amplitude>1.62</Amplitude>
            <RRInterval>0.88</RRInterval>
            <PRInterval>0.19</PRInterval>
            <Measurements>Normal</Measurements>
      </QRScomplex>
      <Twave>
            <Start>488</Start>
            <Peak>517</Peak>
            <End>562</End>
            <Duration>0.22</Duration>
            <Amplitude>0.13</Amplitude>
            <QTInterval>0.59</QTInterval>
            <Measurements>Normal</Measurements>
      </Twave>
</WaveComponent>
      [..]
<WaveComponent>
      [..]
</WaveComponent>
      [..]
<Rhythm>
      <AtrialRhythm>Irregular</AtrialRhythm>
      <VentricularRhythm>Irregular</VentricularRhythm>
</Rhythm>
<HeartRate>
      <Atrial>
            <AtrRate>46-120</AtrRate>
            <AtrStatus>Various Rates</AtrStatus>
      </Atrial>
      <Ventricular>
            <VenRate>49-104</VenRate>
            <VenStatus>Various Rates</VenStatus>
      </Ventricular>
</HeartRate>
      <Abnormality>Irregular Rhythm,Premature Ventricular
Contraction</Abnormality>
```

Figure 12: ECG-XML-DIAG Document.

```
<?xml version="1.0" encoding="UTF-8" standalone="yes"?>
<xs:schema xmlns:xs="http://www.w3.org/2001/XMLSchema"
elementFormDefault="qualified">
      <xs:element name="ECG">
            <xs:complexType>
                  <xs:sequence>
                        <xs:element ref="Lead"/>
                        <xs:element ref="GraphInfo"/>
                        <xs:element ref="WaveComponent"
maxOccurs="unbounded"/>
                        <xs:element ref="Rhythm"/>
                        <xs:element ref="HeartRate"/>
                        <xs:element ref="Abnormality"/>
                  </xs:sequence>
            </xs:complexType>
      </xs:element>
      <xs:element name="Lead" type="xs:string"/>
      <xs:element name="GraphInfo">
            <xs:complexType>
                  <xs:sequence>
                        <xs:element ref="XAxis"/>
                        <xs:element ref="YAxis"/>
                  </xs:sequence>
            </xs:complexType>
      </xs:element>
      <xs:element name="WaveComponent">
            <xs:complexType>
                  <xs:sequence>
                        <xs:element ref="Pwave" minOccurs="0"/>
                        <xs:element ref="QRScomplex"
minOccurs="0"/>
                        <xs:element ref="Twave" minOccurs="0"/>
                  </xs:sequence>
            </xs:complexType>
      </xs:element>
      <xs:element name="XAxis">
            <xs:complexType>
                  <xs:sequence>
                        <xs:element ref="IntervalScale"/>
                        <xs:element ref="StartTime"/>
                        <xs:element ref="EndTime"/>
                        <xs:element ref="TimeUnit"/>
                  </xs:sequence>
            </xs:complexType>
      </xs:element>
      <xs:element name="IntervalScale" type="xs:float"/>
      <xs:element name="StartTime" type="xs:float"/>
      <xs:element name="EndTime" type="xs:float"/>
      <xs:element name="TimeUnit">
            <xs:simpleType>
                  <xs:restriction base="xs:string">
                        <xs:enumeration value="Second"/>
```

```
                </xs:restriction>
            </xs:simpleType>
        </xs:element>
        <xs:element name="YAxis">
            <xs:complexType>
                <xs:sequence>
                    <xs:element ref="DigitalData"/>
                    <xs:element ref="AmpUnit"/>
                </xs:sequence>
            </xs:complexType>
        </xs:element>
        <xs:element name="DigitalData" type="xs:string"/>
        <xs:element name="AmpUnit">
            <xs:simpleType>
                <xs:restriction base="xs:string">
                    <xs:enumeration value="mV"/>
                </xs:restriction>
            </xs:simpleType>
        </xs:element>
        <xs:element name="Pwave">
            <xs:complexType>
                <xs:sequence>
                    <xs:element ref="Start"/>
                    <xs:element ref="Peak"/>
                    <xs:element ref="End"/>
                    <xs:element ref="Duration"/>
                    <xs:element ref="Amplitude"/>
                    <xs:element ref="PPInterval"
minOccurs="0"/>
                    <xs:element ref="Measurements"/>
                </xs:sequence>
            </xs:complexType>
        </xs:element>
        <xs:element name="QRScomplex">
            <xs:complexType>
                <xs:sequence>
                    <xs:element ref="Start"/>
                    <xs:element ref="Peak"/>
                    <xs:element ref="End"/>
                    <xs:element ref="Duration"/>
                    <xs:element ref="Amplitude"/>
                    <xs:element ref="RRInterval"
minOccurs="0"/>
                    <xs:element ref="PRInterval"/>
                    <xs:element ref="Measurements"/>
                </xs:sequence>
            </xs:complexType>
        </xs:element>
        <xs:element name="Twave">
            <xs:complexType>
                <xs:sequence>
                    <xs:element ref="Start"/>
```

```
                        <xs:element ref="Peak"
maxOccurs="unbounded"/>
                        <xs:element ref="End"/>
                        <xs:element ref="Duration"/>
                        <xs:element ref="Amplitude"/>
                        <xs:element ref="QTInterval"/>
                        <xs:element ref="Measurements"/>
                  </xs:sequence>
            </xs:complexType>
      </xs:element>

      <xs:element name="Start" type="xs:int"/>
      <xs:element name="Peak" type="xs:int"/>
      <xs:element name="End" type="xs:int"/>

      <xs:element name="Duration" type="xs:float"/>
      <xs:element name="Amplitude" type="xs:float"/>
      <xs:element name="PPInterval" type="xs:float"/>
      <xs:element name="RRInterval" type="xs:float"/>
      <xs:element name="PRInterval" type="xs:float"/>
      <xs:element name="QTInterval" type="xs:float"/>
      <xs:element name="Measurements" type="xs:string"/>

      <xs:element name="Rhythm">
            <xs:complexType>
                  <xs:sequence>
                        <xs:element ref="AtrialRhythm"/>
                        <xs:element ref="VentricularRhythm"/>
                  </xs:sequence>
            </xs:complexType>
      </xs:element>

      <xs:element name="AtrialRhythm">
            <xs:simpleType>
                  <xs:restriction base="xs:string">
                        <xs:enumeration value="Regular"/>
                        <xs:enumeration value="Irregular"/>
                  </xs:restriction>
            </xs:simpleType>
      </xs:element>

      <xs:element name="VentricularRhythm">
            <xs:simpleType>
                  <xs:restriction base="xs:string">
                        <xs:enumeration value="Regular"/>
                        <xs:enumeration value="Irregular"/>
                  </xs:restriction>
            </xs:simpleType>
      </xs:element>

      <xs:element name="HeartRate">
            <xs:complexType>
```

```
                <xs:sequence>
                    <xs:element ref="Atrial"/>
                    <xs:element ref="Ventricular"/>
                </xs:sequence>
            </xs:complexType>
        </xs:element>

        <xs:element name="Atrial">
            <xs:complexType>
                <xs:sequence>
                    <xs:element ref="AtrRate"/>
                    <xs:element ref="AtrStatus"/>
                </xs:sequence>
            </xs:complexType>
        </xs:element>

        <xs:element name="AtrRate" type="xs:string"/>
        <xs:element name="AtrStatus" type="xs:string"/>

        <xs:element name="Ventricular">
            <xs:complexType>
                <xs:sequence>
                    <xs:element ref="VenRate"/>
                    <xs:element ref="VenStatus"/>
                </xs:sequence>
            </xs:complexType>
        </xs:element>

        <xs:element name="VenRate" type="xs:string"/>
        <xs:element name="VenStatus" type="xs:string"/>
        <xs:element name="Abnormality" type="xs:string"/>

</xs:schema>
```

Figure 13: XML Schema for ECG-XML-DIAG.

4.3.3 Representation of ECG-XML-DIAG with Graphical and Text Information

"ECG-XML-DIAG" is ECG data encoded in xml format with diagnostic information included. ECG-XML-DIAG documents were converted to output in an internet browser for the presentation purposes as shown in Figure 14. Users will be able to see output consisting of an ECG image and appropriate diagnosis without the need of proprietary software. The presentation process was implemented in an internet browser by using Java Scripts, Java Applet, and PHP version 4.3.11-1 as computer programming language tools.

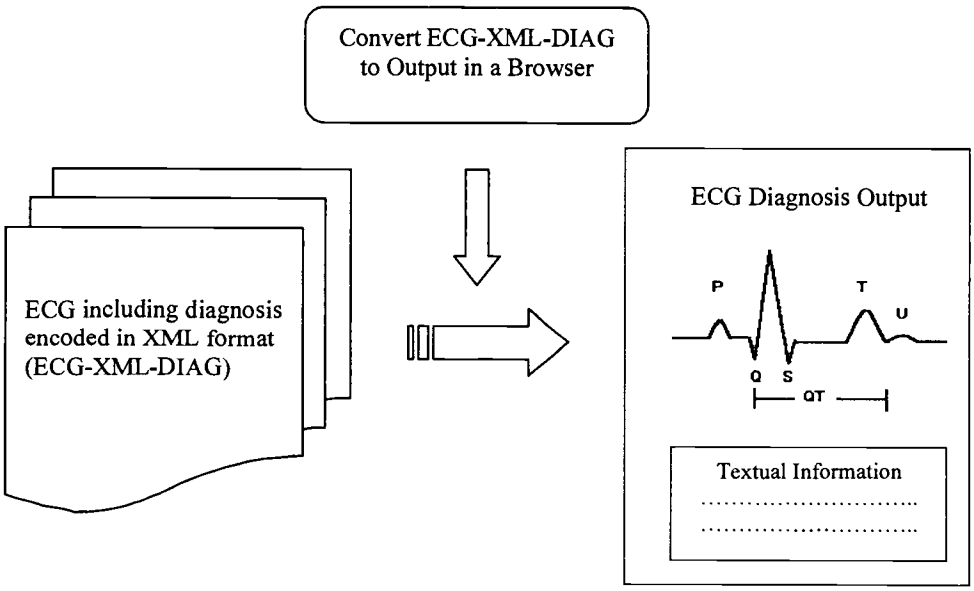


Figure 14: Representation of Output.

For user's output, both graphical and textual information are presented via a browser. Graphical information consists of an image of the ECG plot along with boundary and status of each wave. Textual information lists heart rates (both atrial and ventricular rates), rhythm status (both atrial and ventricular rhythms), abnormal ECG measurements, and possible findings (normal ECG or abnormal conditions found). Table 5 summarizes the user's output.

Table 5: User's Output.

Information of Output	*Details*
Graphical Information	• ECG plots • Wave Boundary • Wave Status
Textual Information	• Heart Rates (Atrial and Ventricular) • Rhythm Status (Atrial and Ventricular) • Abnormal ECG Measurements • Possible Findings

Color coding has been used for the design of output in the interface. Blue represents information under normal condition, while red represents abnormal status. Other coding such as headings, bold text, and bullet lists are also applied for a user-friendly interface which provides information that is easy to read and interpret. Figure 15 illustrates graphical output with a single beat of Premature Ventricular Contraction. Figure 16 presents output of textual information for this ECG data.

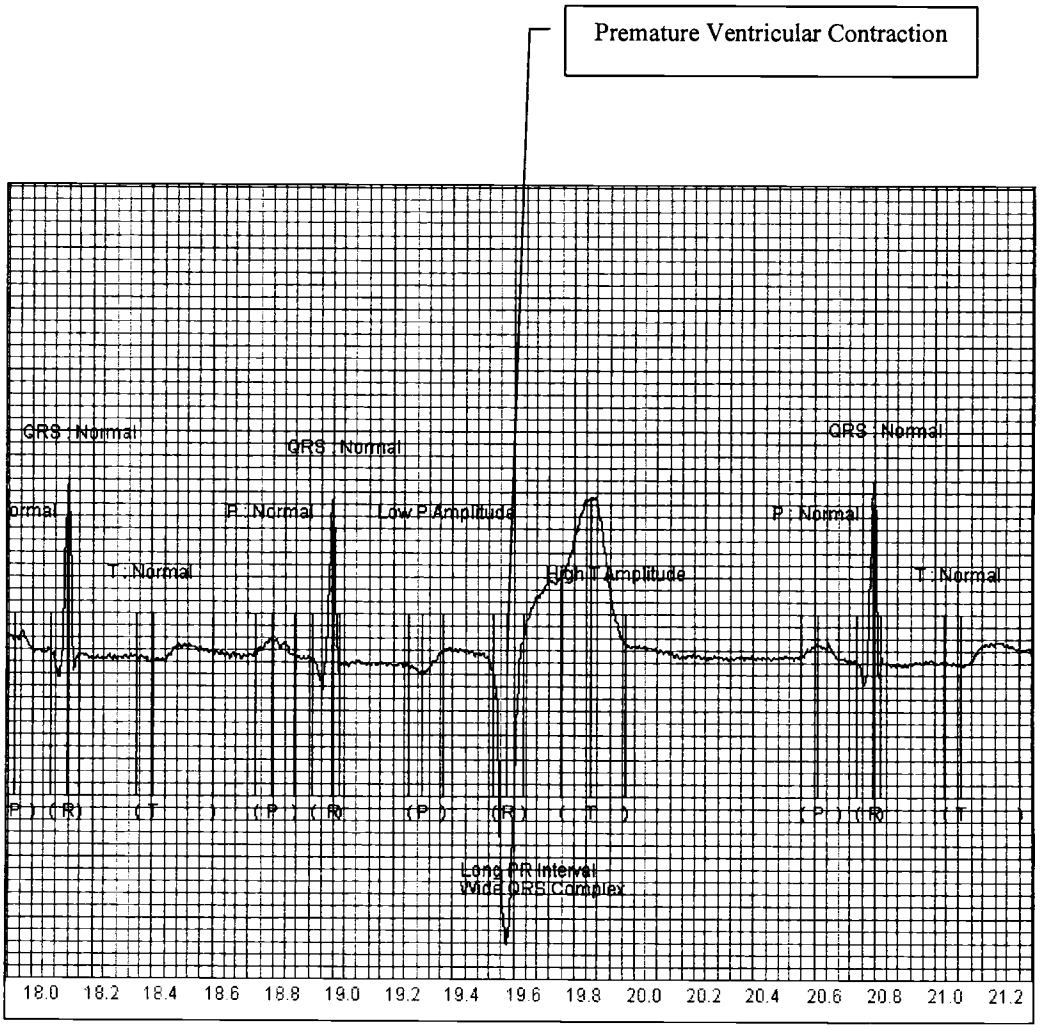


Figure 15: Graphical Output.

Lead: MLII

Summary of Findings

Heart Rates

Atrial Rate: 46-120 bpm Status: Various Rates
Ventricular Rate: 49-104 bpm Status: Various Rates

Rhythm

Atrial Rhythm: Irregular
Ventricular Rhythm: Irregular

Abnormal ECG Measurements

- Low P Amplitude
- Long PR Interval
- Wide QRS Complex
- High T Amplitude

Possible Findings

- Irregular Rhythm
- Premature Ventricular Contraction

Figure 16: Textual Output.

Another example of the diagnosis of a normal ECG is presented as follows:

ECG Waveform Information

Lead: signal 0

Start Time: 0.000 second

End Time: 7.992 second

Interval: 0.008 second

Digital Data: see Table 6

Table 6: Digital Data of a Normal ECG.

Sample #	Time (second)	Amplitude (mV)
1	0.000	-0.185
2	0.008	-0.215
3	0.024	-0.215
:	:	:
1000	7.992	-0.085

Figure 17 presents an ECG-XML-DIAG document which includes the diagnosis of this normal ECG by the model.

```
<?xml version="1.0"?>
<ECG xmlns:xsi="http://www.w3.org/2001/XMLSchema-instance">
   <Lead>signal 0</Lead>
   <GraphInfo>
      <XAxis>
            <IntervalScale>0.008</IntervalScale>
            <StartTime>0.000</StartTime>
            <EndTime>7.992</EndTime>
            <TimeUnit>Second</TimeUnit>
      </XAxis>
      <YAxis>
            <DigitalData>-0.185,-0.215,-0.215,-0.245,-0.205,-
0.195,-0.155,-0.165,-0.165,-0.175,-0.215,-0.185,-0.165,-0.165,-
0.165,-0.145,-0.155,-0.185,-0.215,-0.175,-0.165,-0.155,-0.155,-
0.155,-0.165,-0.185,-0.165,-0.175,-0.185,-0.165,-0.155,-0.165,-
0.165,-0.165,-0.165,-0.155,-0.175,-0.185, [..]
            </DigitalData>
            <AmpUnit>mV</AmpUnit>
      </YAxis>
   </GraphInfo>

<WaveComponent>
      <Pwave>
            <Start>53</Start>
            <Peak>60</Peak>
```

```
            <End>64</End>
            <Duration>0.088</Duration>
            <Amplitude>0.200</Amplitude>
            <Measurements>Normal</Measurements>
      </Pwave>
      <QRScomplex>
            <Start>68</Start>
            <Peak>73</Peak>
            <End>80</End>
            <Duration>0.096</Duration>
            <Amplitude>1.400</Amplitude>
            <PRInterval>0.120</PRInterval>
            <Measurements>Normal</Measurements>
      </QRScomplex>
      <Twave>
            <Start>0</Start>
            <Peak>0</Peak>
            <End>0</End>
            <Duration>0.000</Duration>
            <Amplitude>0.000</Amplitude>
            <QTInterval>0.000</QTInterval>
            <Measurements>Normal</Measurements>
      </Twave>
</WaveComponent>
      [..]
<WaveComponent>
      [..]
</WaveComponent>
      [..]
<Rhythm>
      <AtrialRhythm>Regular</AtrialRhythm>
      <VentricularRhythm>Regular</VentricularRhythm>
</Rhythm>
<HeartRate>
      <Atrial>
            <AtrRate>60</AtrRate>
            <AtrStatus>Normal</AtrStatus>
      </Atrial>
      <Ventricular>
            <VenRate>61</VenRate>
            <VenStatus>Normal</VenStatus>
      </Ventricular>
</HeartRate>
<Abnormality>Normal</Abnormality>
```

Figure 17: ECG-XML-DIAG Document of a Normal ECG.

A part of the graphical representation of this normal ECG in a browser is depicted in Figure 18 along with the textual descriptions shown in Figure 19.

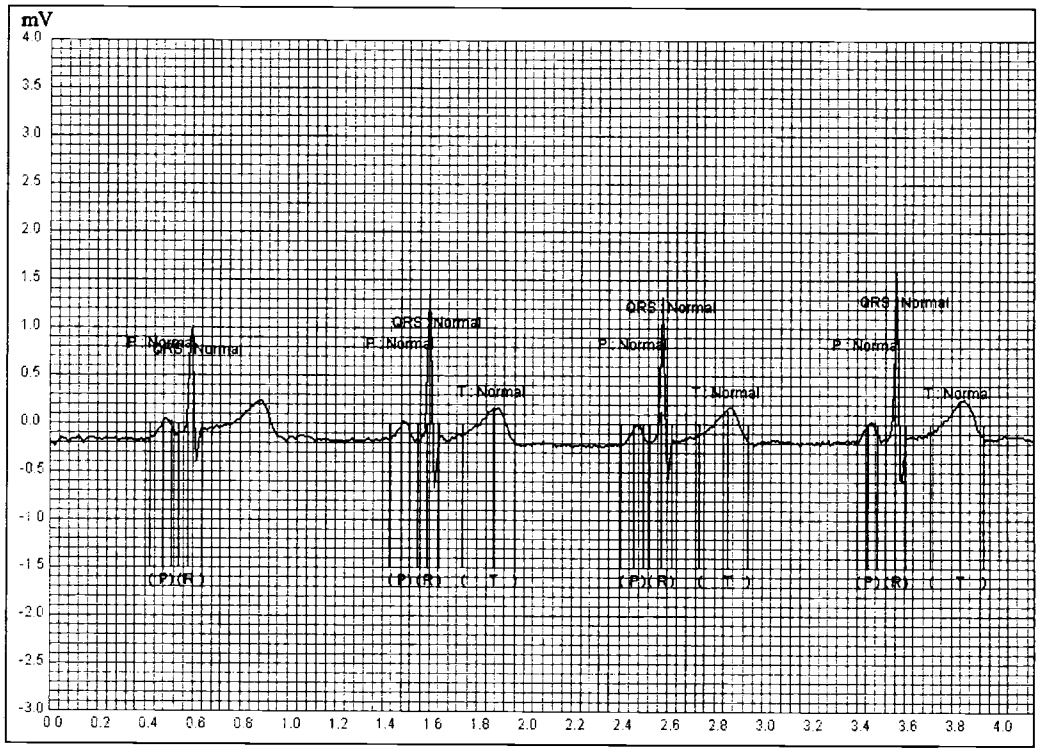


Figure 18: Graphical Output of a Normal ECG.

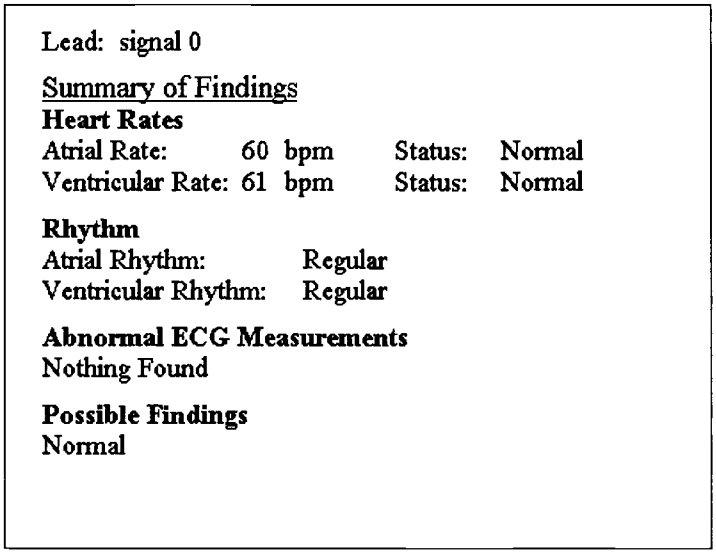


Figure 19: Textual Output of a Normal ECG.

Figure 20 presents a diagram that summarizes the overall process for the model.

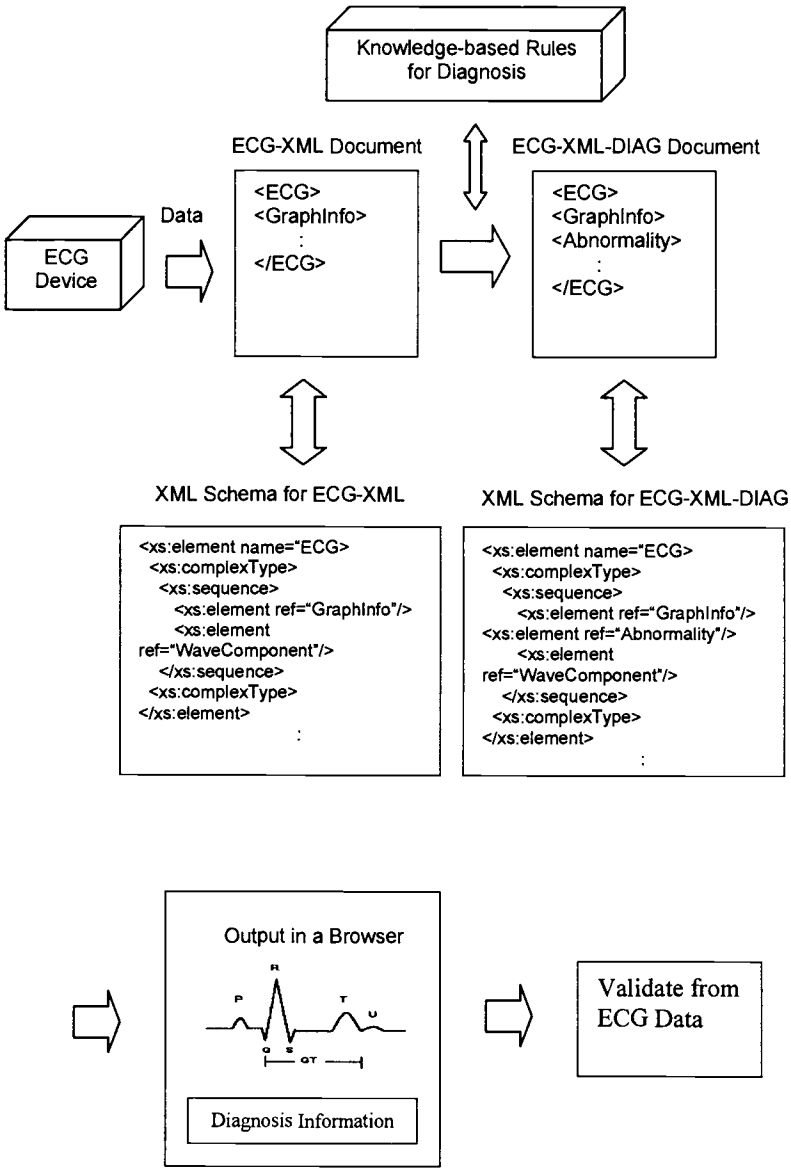


Figure 20: Model Development Diagram.

5. VALIDATION

5.1 Overview

This research was validated in two ways. First, to validate interoperability of the Ontology-based system, ECG data were obtained from different ECG instrument vendors, and the data were automatically translated and interpreted by the developed model according to the steps described in the previous chapter. Secondly, the system automatically detected HL7 abnormal conditions from input ECG data. Real ECG data with known heart diseases and normal ECGs were analyzed. Figure 21 illustrates an overall picture of the validation processes.

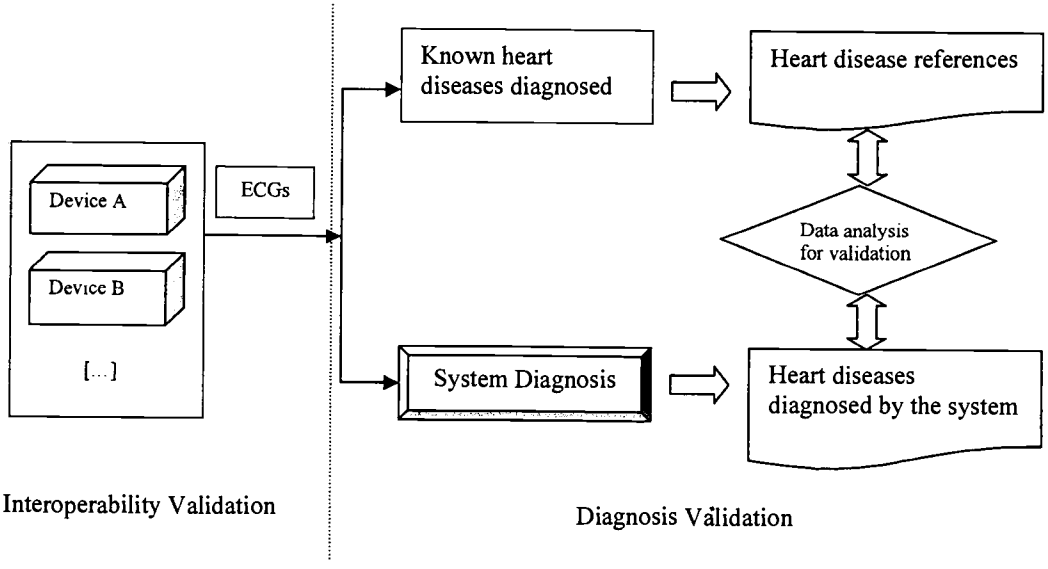


Figure 21: Overall Validation Process.

5.1.1 Interoperability Validation

ECG data from seven databases coming out of different devices were provided, and diagnosed by the system in order to demonstrate capability of interoperability of the Ontology. These ECGs from different sources were used as input to the system. The system then diagnosed for appropriate normal or abnormal condition of each ECG. This step illustrates the interoperable ability of the system in that ECGs from different devices can be diagnosed by using the standard Ontology. If users can access heterogeneous ECGs and diagnostic information by using a browser without the need of proprietary software, then the interoperability issue has been resolved.

5.1.2 Diagnosis Validation

This section involves validating the accuracy of the system in detecting abnormal conditions and interpreting normal ECGs. When ECG data from different devices are interpreted by the system, abnormal conditions will be listed. Table 7 illustrates some examples of ECG abnormal conditions listed in the HL7 standard. Discrete data analysis (Hayter, 1996) was used to find the percentage of accuracy of the model in diagnosing normal and abnormal conditions.

Table 7: HL7 Abnormal Conditions.

List No.	Abnormal Conditions
1	Irregular Rhythm
2	Sinus Arrhythmia
3	Sinus Rhythm
4	Left Bundle Branch Block
5	Right Bundle Branch Block
[...]	[...]

5.2 Experimental Design

This section explains the design of experiment in detail including data source, hypotheses, sample size determination, and tests for validation. There are three parts to validation. First, the validation was implemented to find the *sensitivity* rate or the accuracy of the model in detecting abnormal conditions when the abnormal conditions exist. Secondly, the experiment was done to find the *specificity* rate or the accuracy of the model in interpreting normal ECGs correctly when the data are normal. Finally, *overall accuracy* of the model can be determined from the results of the sensitivity and specificity tests.

Sensitivity and specificity are terms used in the medical literature. They are related to Type I and Type II errors which are more typical terms used in Statistics as shown in Table 8. True state of null hypothesis is physician's diagnosis.

Statistical decision is the model's diagnosis. Type I error occurs in the specificity test when normal ECGs are misdiagnosed with any abnormal condition by the model. The other names of type I error are false positive and false alarm error. Type II error occurs in the sensitivity test when the model cannot correctly identify the abnormal condition diagnosed by physicians. The other names of type II error are false negative and miss error.

Table 8: Type I and Type II Errors.

Statistical Decision *(Model's Diagnosis)*	**True State of Null Hypothesis** *(Physician's Diagnosis)*	
	Specificity Test	**Sensitivity Test**
	H_0 True *(Normal)*	H_0 False *(Abnormal)*
Reject H_0 *(Abnormal)*	**Type I error (α)** -False Positive -False Alarm Error	Correct
Do Not Reject H_0 *(Normal)*	Correct	**Type II error (β)** -False Negative -Miss Error

5.2.1 Data Source

ECG data for the experiment came from PhysioBank (Goldberger et al., 2000). PhysioBank is a source for digital recordings of physiologic signals including ECGs for use in research community. Real raw ECGs coming from different sources (machine, database, hospital) from time to time are available for

download. Physician's diagnosis is also provided. Two hundreds and seventy six ECG data from seven different databases provided by PhysioBank were input to the model to ensure that both interoperability and accuracy will be validated. Table 9 presents a sample size collected from each database. In this research, validation of the accuracy of the model was performed by using ECGs from different sources to ensure that the interoperability validation was also included in this process.

Table 9: Databases and Numbers of Samples.

No.	Database	Number of Samples
1	MIT-BIH Arrhythmia	72
2	European ST-T	7
3	Long-Term ST	23
4	MIT-BIH Noise Stress Test	12
5	Creighton University Ventricular Tachyarrhythmia	3
6	MIT-BIH Atrial Fibrillation	10
7	MIT-BIH Supraventricular Arrthymia	5
8	Normal Sinus Rhythm	144

5.2.2 Hypotheses and Sample Size Determination

Hypotheses

- H_0: Error Rate $\geq p_2$
- H_a: Error Rate $< p_2$

  p_2: Acceptable Error Rate

In this research, the acceptable error rate of 10% (p_2 = 0.10) has been determined from information about ECG decision support systems and algorithms for classifying cardiac diseases in the literature (Kaufman et al., 1997; Ayesta et al., 2001); and recommendations from three experienced cardiac physicians.

Sample Size Determination

Sample size that guarantees the two following probability requirements was determined from the acceptable error rate (Burstein, 1971).

- Probability [accept the model when error rate $\geq p_2$] $\leq \beta$ (accept bad lot)
- Probability [reject the model when error rate $\leq p_1$] $\leq \alpha$ (reject good lot)

The first inequality states that the sample size should be large enough so that if the error rate is greater than p_2, there is a very small chance (less than β) of not detecting it. The second inequality states that if the error rate is satisfactory (e.g., less than p_1), there is a low probability (less than α) of rejecting the model. Normally, p_1 ranges between 1%-5% while α and β range between 5%-10%. Table 10 shows the minimum required sample size for different values of the following parameters.

- p_2 (error rate) = 0.1 = 10%
- c = number of failures
- n = sample size

From Table 10, sampling plan #4 was selected for minimum required sample size in order to guarantee the two probability requirements with 95% confidence interval and in regards to data availability. Therefore, sample size (n) must be greater than or equal to 117.

Table 10: Minimum Required Sample Size for Different Values of Parameters.

Sampling Plan	p_1	p_2	α	β	c	n
1	0.04	0.10	0.05	0.01	16	274
2	0.04	0.10	0.05	0.05	11	186
3	0.05	0.10	0.05	0.05	20	285
4*	**0.03**	**0.10**	**0.05**	**0.05**	**6**	**117**
5	0.02	0.10	0.05	0.05	3	75
6	0.01	0.10	0.05	0.05	1	50
7	0.01	0.10	0.10	0.10	1	34

5.2.3 Sensitivity, Specificity, and Overall Accuracy Calculations

Accuracy of the model was validated in terms of its sensitivity, specificity, and overall accuracy. Sensitivity is the ability to predict positive results correctly when abnormal conditions exist. Specificity is the ability to predict negative results when the data are actually normal. Overall accuracy rate is the calculation when

combining sample size numbers and correct results from sensitivity and specificity tests to determine the overall rate of model accuracy.

276 ECGs were used to validate the interoperability and accuracy of the model. Each ECG was automatically interpreted with the following information.

- Heart Rates (Atrial and Ventricular Rates) in beats per minutes (bpm)
- Heart Rhythm (Atrial Rhythm and Ventricular Rhythm)
- Abnormal ECG Measurements e.g., long QRS duration, long PR interval, etc.
- Possible Findings e.g., Normal, Sinus Arrthymia, Premature Ventricular Contraction, etc.

5.2.3.1 Sensitivity Test

The accuracy of the model in detecting abnormal conditions was calculated. A sample size (*n*) of 132 ECGs with a variety of abnormal conditions diagnosed by physicians served as input to the model. These ECG data came from different ECG devices provided by PhysioBank (Goldberger et al., 2000). The system diagnosed each ECG with heart rates, heart rhythm, abnormal ECG measurements, and possible findings. Therefore, the system demonstrates interoperable capability because it can diagnose ECGs coming from different devices and present the diagnosis results in a browser. The list of abnormal conditions found for each ECG was compared with its diagnosis by the physicians.

Figure 22 illustrates the method to perform the experiment and calculate the sensitivity rate. 132 abnormal ECGs with various abnormal conditions were input to the model. These ECGs were diagnosed by physicians for specific abnormal conditions and to include one or more of the following abnormal conditions:

- Premature Ventricular Contraction
- Supraventricular Premature or Ectopic Beat
- Junctional Escape Beats
- Premature Atrial Contraction
- Ventricular Tachycardia
- Sinus Arrhythmia

- Left Bundle Branch Block
- Right Bundle Branch Block
- Atrial Fibrillation
- Atrial Flutter
- Sinus Bradycardia
- Irregular Atrial Escape Rhythm
- Ventricular Fibrillation

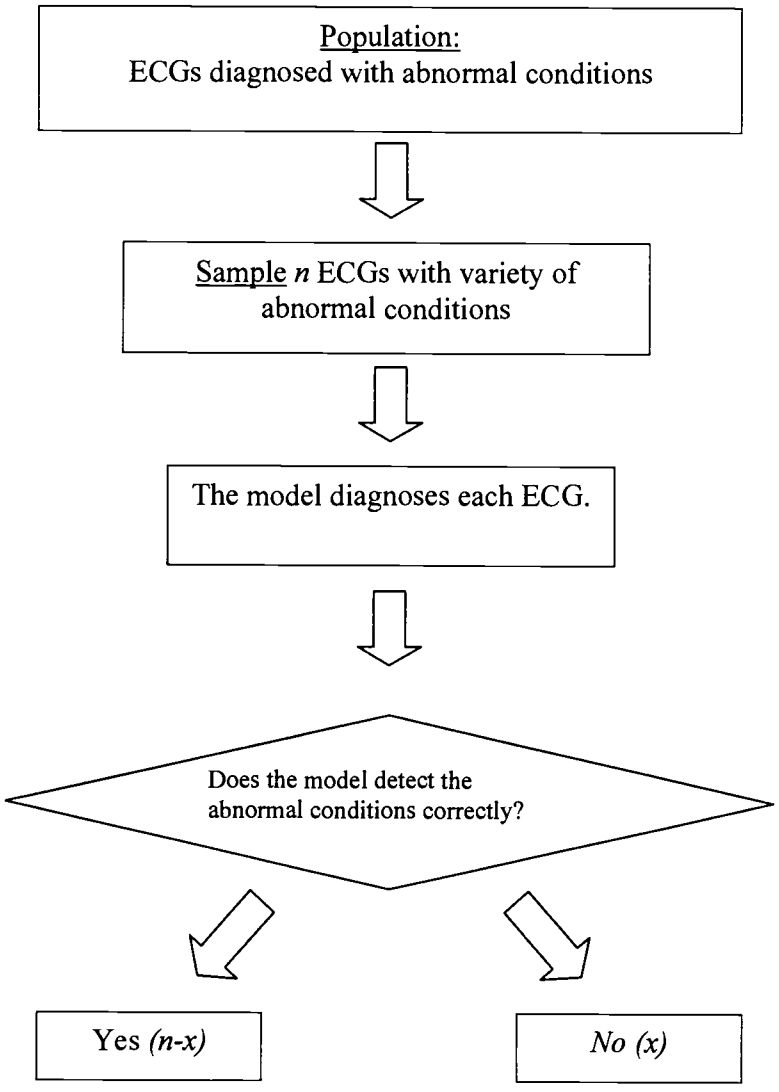


Figure 22: Sensitivity Test Experiment.

Inferences on the population probabilities of *discrete random variables* are considered. Figure 22 illustrates the overall framework where n is the number of samples which is obtained from the population. The variable x is the number of observations which possess the particular characteristics of interest which is the number of ECGs in which the model cannot accurately detect the abnormal conditions.

The cell probability or success probability p can be calculated by the sample proportion, $\hat{p} = x/n$. With appropriate number of n, the sample proportion can then be taken to approximately have the normal distribution.

$\hat{p}$ will be used to calculate the confidence interval of p as shown below.

$$p \in \left(0, \hat{p} + z_{\alpha} \sqrt{\frac{\hat{p}(1-\hat{p})}{n}} \right) \quad (1)$$

where 1-α is a one-sided level of confidence interval for p and z_{α} is the cumulative distribution function of the standard normal distribution.

Minimum Sensitivity Rate = (1- upper bound of p) x 100% (2)

Results and Conclusion for Sensitivity Test

From 132 ECGs with a variety of abnormal conditions, 125 ECGs were diagnosed correctly according to the physician's diagnosis. The model misdiagnosed 7 ECGs. Details of this data are provided in Appendix B.

The following equations illustrate the calculation of variables in Equation 1. From a sample size of 132 ECGs, the model could not diagnose 7 ECGs correctly. Thus,

$$n = 132, x = 7 \tag{3}$$

$$\hat{p} = x/n = 7/132 = 0.05 \tag{4}$$

Using the critical point $z_\alpha = z_{0.05} = 1.645$, a one-sided 95% confidence interval for the probability p of sensitivity error is as follows:

$$p \in \left(0, 0.05 + 1.645\sqrt{\left(\frac{(0.05)(1-0.05)}{132}\right)}\right) \tag{5}$$

$$p = (0, 0.09) \tag{6}$$

From equation 6, the *upper bound* on the probability p is 0.09 which can be used to obtain a lower bound on the complementary *1-p* (Hayter, 1996). Since 1-0.09 = 0.91, thus, the model has a sensitivity rate of *at least* 91%. Table 11 summarizes the calculation values.

Table 11: Sensitivity Calculation.

Variables	Values
Sample size (n)	132
Number of errors (x)	7
Number of correct diagnoses (n-x)	125
$\hat{p} = x/n.$	0.05
z_α ($\alpha = 0.05$)	1.645
Minimum error rate	0
Maximum error rate	0.09
Minimum Percentage of Sensitivity	**91%**
Maximum Percentage of Sensitivity	**100%**

Hypotheses

- H_0: Error Rate ≥ 0.10
- H_a: Error Rate < 0.10

Conclusion

From 132 ECGs, the acceptable error rate (p_2) = 0.10 does not fall in p = (0, 0.09). Thus, we reject the null hypothesis and conclude that the error rate for the sensitivity is acceptable based on 95% confidence interval. Consequently, based upon 132 observations with a 95% confidence, the proportion of ECGs with abnormal conditions that the model can detect correctly will be *at least* 91%.

5.2.3.2 Specificity Test

Specificity is the ability of the model in detecting negative results when the data are normal. 144 normal ECGs from different devices provided by PhysioBank (Goldberger et al., 2000) were input to the model. The system demonstrates the interoperable capability by being able to diagnose each ECG and present the results in a browser. These ECGs are considered as 'normal' by physicians. The accuracy of the model in interpreting normal ECG was calculated. Figure 23 illustrates the method to perform the experiment and calculates the specificity rate.

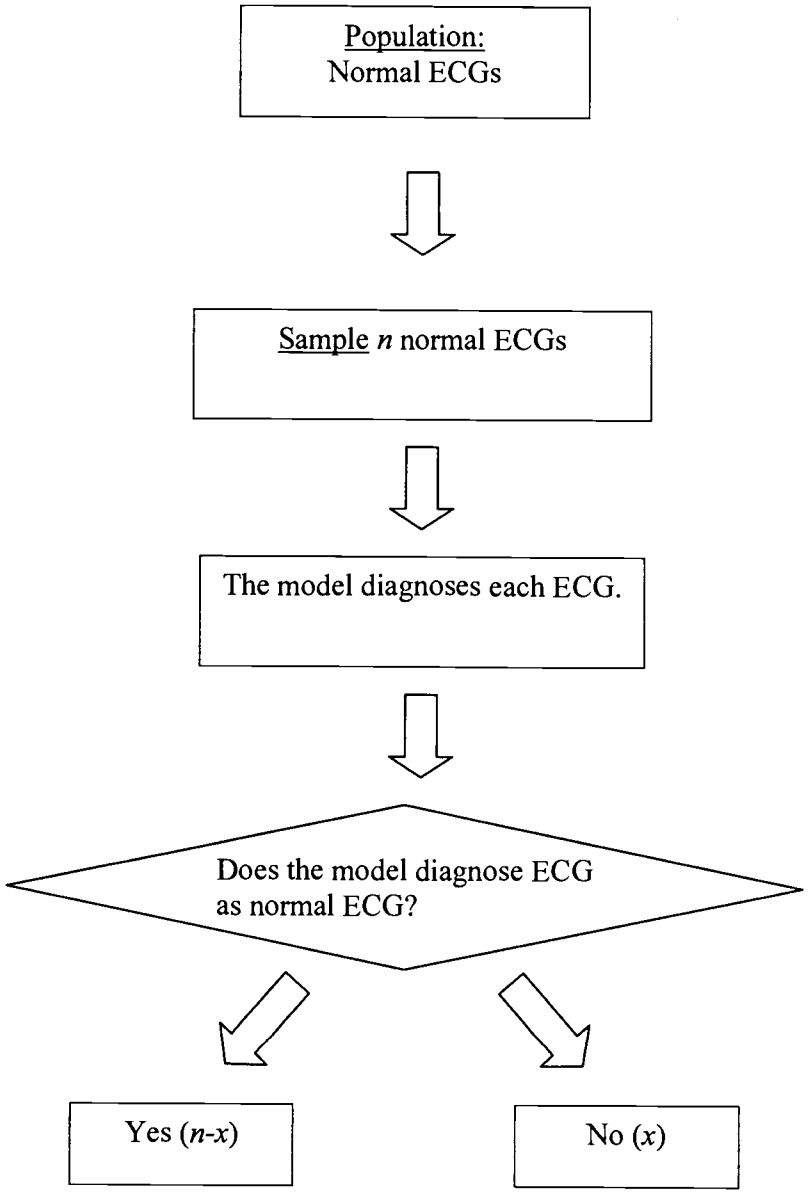


Figure 23: Specificity Test Experiment.

Results and Conclusion for Specificity Test

From 144 normal ECGs, 138 ECGs were diagnosed by the model as normal ECGs correctly without finding any abnormal conditions. The model misdiagnosed 6 ECGs. Details of data are provided in Appendix B. By using the method of calculation explained in the sensitivity section, values of variables can be calculated as follows:

From a sample size of 144 ECGs, the model misdiagnosed 6 ECGs. Thus,

$$n = 144, x = 6 \tag{7}$$

$$\hat{p} = x/n = 6/144 = 0.04 \tag{8}$$

Using the critical point $z_\alpha = z_{0.05} = 1.645$, a one-sided 95% confidence interval for the probability p of specificity error is as follows:

$$p \in \left(0, 0.04 + 1.645\sqrt{\left(\frac{(0.04)(1-0.04)}{144}\right)}\right) \tag{9}$$

$$p = (0, 0.07) \tag{10}$$

From Equation 10, the *upper bound* on the probability p is 0.07 which can be used to obtain a lower bound on the complementary *1-p* (Hayter, 1996). Since 1-0.07 = 0.93, thus, the model has a specificity rate *at least* 93%. Table 12 summarizes the calculation values.

Table 12: Specificity Calculation.

Variables	Values
Sample size (n)	144
Number of errors (x)	6
Number of correct diagnoses (n-x)	138
$\hat{p} = x/n.$	0.04
z_α ($\alpha = 0.05$)	1.645
Minimum error rate	0
Maximum error rate	0.07
Minimum Percentage of Sensitivity	**93%**
Maximum Percentage of Sensitivity	**100%**

Hypotheses

- H_0: Error Rate ≥ 0.10
- H_a: Error Rate < 0.10

Conclusion

From 144 normal ECGs, the acceptable error rate (p_2) = 0.10 does not fall in (0, 0.07). Thus, we reject the null hypothesis and conclude that the error rate for specificity is acceptable based on 95% confidence interval. Consequently, based upon 144 observations with a 95% confidence, the proportion of normal ECGs that the model can interpret correctly will be *at least* 93%.

5.2.3.3 Overall Accuracy Rate

The overall accuracy of the model was calculated by considering total number of samples and total number of errors from sensitivity and specificity tests. Table 13 presents the calculation of the accuracy rate.

Table 13: Overall Accuracy Calculation.

Variables	**Values**
Sample size (n)	276
Number of errors (x)	13
Number of correct diagnoses (n-x)	263
$\hat{p} = x/n.$	0.05
z_α ($\alpha = 0.05$)	1.645
Minimum error rate	0
Maximum error rate	0.07
Minimum Percentage of Overall Accuracy	**93%**
Maximum Percentage of Overall Accuracy	**100%**

Hypotheses

- H_0: Error Rate ≥ 0.10
- H_a: Error Rate < 0.10

Interval of overall error rate = $p = (0, 0.07)$

Conclusion

From 276 ECGs, the acceptable error rate (p_2) = 0.10 does not fall in (0, 0.07). Thus, we reject the null hypothesis and conclude that the error rate of the model is acceptable based on 95% confidence interval. Consequently, based upon 276 observations with a 95% confidence, the proportion of normal and abnormal ECGs that the model diagnoses correctly will be *at least* 93%.

6. CONCLUSIONS

This chapter discusses the Ontology-based system and the results obtained with regards to each of the objectives listed in chapter 1. In addition, a discussion of research is provided which could contribute to the accuracy of automated ECG diagnosis.

6.1 Conclusion from the Objectives and Results

The first objective of this dissertation was to create an Ontology for representation and diagnosis of ECG data. The developed Ontology represents structure for the representation, measurement of ECG data, and criteria for ECG diagnosis based on HL7. The Ontology integrates ECG data with the measurements and diagnosis described in the HL7 standard. The Ontology was encoded in XML vocabularies providing human and machine readable format. By using ECG digital data as inputs, diagnosis of ECG can be automatically implemented via an internet browser with textual and graphical information presented. Users are able to access the ECG data and information of diagnosis without the requirements of proprietary systems. Thus, the interoperability problem of ECG data share and diagnosis among different systems has been resolved.

The second objective was to create and evaluate a system for ECG measurements and diagnosis based on the HL7 standard. The Ontology developed in the first objective was encoded in XML formats for rigorous vocabulary and structure, and diagnosis rules are included in a diagnosis system. The Ontology-based system is able to diagnose ECG data coming from different devices. An experiment was conducted to validate the interoperability and the accuracy of the Ontology and diagnosis model. All ECG data in the experiment could be presented and diagnosed via an Internet browser even though data were from different ECG devices. This step demonstrates the interoperable ability of the Ontology-based system in storing, diagnosing, and presenting ECG data.

Medical statistics usually involve sensitivity and specificity tests. In this research, sensitivity and specificity rates were calculated using the results from the experiment. Sensitivity is the ability to correctly detect abnormal conditions when data are actually abnormal. Specificity is the ability to determine negative results (normal condition) when data are actually normal. The experiment includes both sensitivity and specificity tests. The results yield a 91% sensitivity rate (based on a sample size of 132) and 93% specificity rate (based on a sample size of 144). The overall accuracy or base rate of the model was also calculated from the results of both normal and abnormal ECG in sensitivity and specificity test. The overall accuracy of the model is 93% (based on a sample size of 276).

Thus, the model will diagnose an abnormal ECG condition with a 91% accuracy rate. For normal ECGs, the model is likely to diagnose it correctly 93%

of the time. The base rate which can be considered when referring to the overall accuracy is 93%. According to the accuracy rates, error rates for each type of tests can be calculated. 91% sensitivity, 93% specificity and 93% base rates yield 9%, 7%, and 7% error rates for sensitivity, specificity, and overall accuracy, respectively. The accuracy of the model is acceptable because the results yield less than 10% of the error rates which is considered to be an acceptable error rate in this research according to information about ECG decision support systems and algorithms for classifying cardiac diseases in the literature (Kaufman et al., 1997; Ayesta et al., 2001); and recommendations from three experienced cardiac physicians.

From the results of these experiments, the error rate of sensitivity is higher than that of the specificity. The explanation for this result is that it is more difficult to automatically diagnose an ECG that indicates abnormal conditions. If an obvious abnormal condition occurs, the model will diagnose it correctly. However, in some challenging records, when an abnormal condition is embedded within another abnormal condition in the same ECG strip, a misdiagnosis is likely to occur. For example, when an ECG strip has multiple beats of Left Bundle Branch Block, and there is a single beat of Premature Ventricular Contraction occurring between those Left Bundle Branch Block beats as shown in Figure 24, the model will detect Left Bundle Branch Block but may or may not detect the Premature Ventricular Contraction.

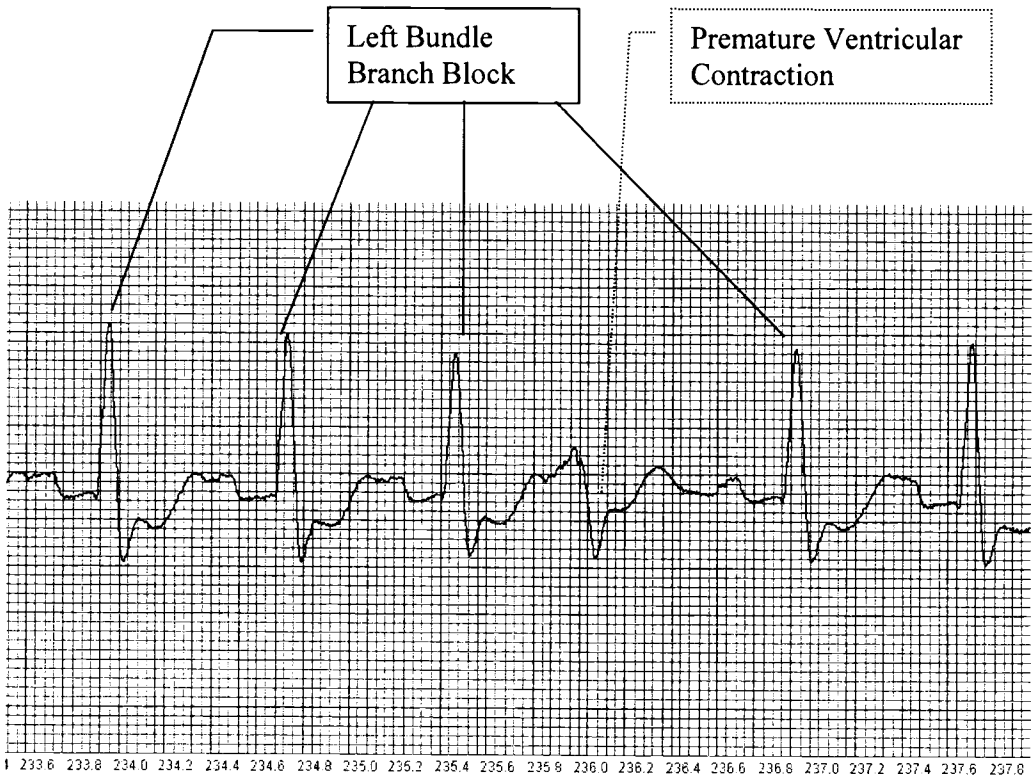
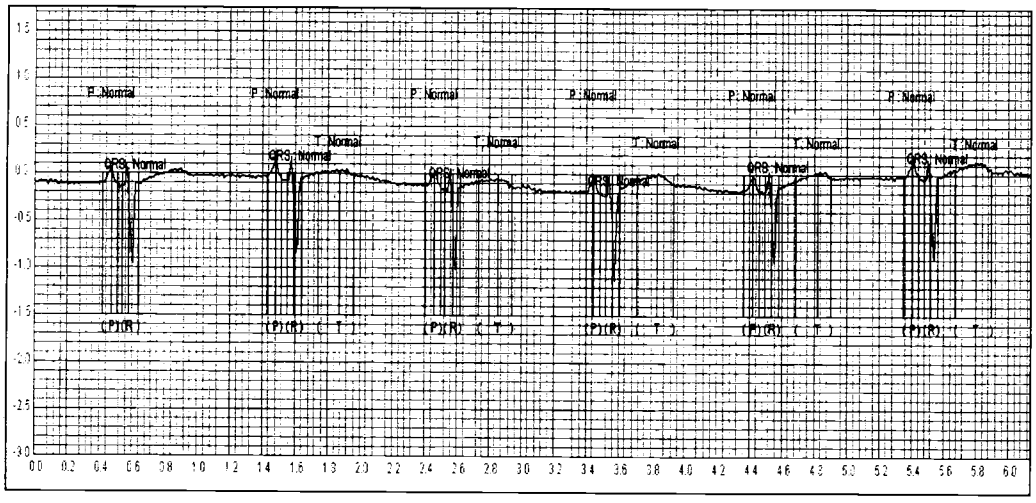


Figure 24: Left Bundle Branch Block Beats with Premature Ventricular Contraction.

In some records, physicians' diagnoses were different than the abnormal conditions diagnosed by the model. For example, the following ECG record in Figure 25 was diagnosed as a normal ECG by a physician. However, the model found 'Irregular Rhythm' in this ECG strip. The atrial rate which was measured by P-P duration has slightly various rates. The model diagnosed 'Irregular Rhythm' because it detected wide range of the atrial rates from 54 to 66 beats per minute.



Lead: signal 1

Summary of Findings

Heart Rates

Atrial Rate: 54-66 bpm Status: Various Rates
Ventricular Rate: 61 bpm Status: Normal

Rhythm

Atrial Rhythm: Irregular
Ventricular Rhythm: Regular

Abnormal ECG Measurements

Nothing Found

Possible Findings

- Irregular Rhythm

Figure 25: Normal ECG with Irregular Rhythm Detected by the Model.

It is important to note that the diagnosis model was revised several times, with improvement in accuracy occurring each time in order to achieve the accuracy reported in this research. However, there appears to be a tradeoff with any modifications that attempted to improve the model. If the sensitivity rate increases,

then the specificity tends to decrease. On the other hand, if the specificity increases, then the sensitivity tends to decrease. In other words, if one tries to increase the ability of the model algorithm to detect the abnormal conditions (higher sensitivity), the model tends to be more sensitive and increases the likelihood of interpreting normal ECGs as abnormal (lower specificity). In contrast, when the model is very good at correctly interpreting normal ECGs as normal (higher specificity), the model tends to be less sensitive to correctly detecting an abnormal condition when diagnosing abnormal ECGs (lower sensitivity). The results finally reported were attempts to compromise the error rates and ensure that they are all acceptable based on the available sample size. Table 14 illustrates number of errors for each test compared to maximum number of errors allowed for the acceptable error rate of 10% (90% accuracy rate). Numbers of errors from the experiment are less than the maximum numbers of allowable errors in every category (i.e., sensitivity, specificity, and overall accuracy). Therefore, the sensitivity, specificity, and overall accuracy rates were proven to be acceptable.

Table 14: Comparison for Number of Errors.

	Sample Size (n)	Number of Errors from the Experiment (x)	Maximum Number of Errors Allowed
Sensitivity Test	132	7	9
Specificity Test	144	6	10
Overall Accuracy Rate	276	13	21

In conclusion, this research provides an innovation of the Ontology-based system for ECG data representation and diagnosis conforming to the HL7 standard in order to standardize the ECG processes. The system is platform and software independent providing human and machine readable format. ECG data can then be shared and diagnosed across systems without the need of proprietary software, which in turns, reduce the cost of operating software. It also promotes the use of the HL7 standard and provides an automated ECG diagnosis system with acceptable accuracy rates which can be used as a decision-aid tool for ECG diagnosis.

6.2 Future Research

This section describes future research, which can be done in order to improve the understanding of ECG diagnosis and develop more accurate ECG diagnosis model.

6.2.1 Validating the Decision-support System with the Targeted User

In this research, the experiment has been done to validate the interoperability and accuracy of the model to address the second objective. A more practical model for users which are medical technicians/physicians could be obtained by performing further experiments. For example, validation for the user's requirements could be implemented to determine level of satisfaction of the system to the users. This research applied user's requirements in the design process. The validation for user's requirements can be done by having the groups of users use the system. Then, a survey tool and/or other appropriate methods may be implemented to ensure that the system actually present information according to what the users want and how they want it.

6.2.2 Increasing the Reliability of the Results by Validating the Accuracy Rates with More Variety of Data and Sample Size Number

In statistics, the larger the sample size, the greater the confidence in the statement of results. PhysioBank was the only available resource for ECG data used to validate this work. Although PhysioBank provides an adequate number of ECG records sufficient for this research, more data from a different resource, such as hospitals with a greater variety of abnormal conditions, could improve the robustness of the stated conclusions for both interoperability and accuracy of the model.

6.2.3 Improving the Accuracy of the Diagnosis Model

An example of methods to improve the accuracy rate of the model is to include ECG images as pattern recognition of knowledge for diagnosis. Besides rules for diagnosis, ECG images of particular conditions diagnosed by physicians may be included in the algorithm in order to define the abnormal conditions found for an input ECG. The added pattern recognition feature may lead to a more accurate ECG prediction algorithm because it has ECG image of a particular condition to compare. The ECG pattern recognition system can be a new area of research.

6.2.4 Improving the Methods and Interfaces to Analyze and Present ECG for Decision Support

In this research, an automated ECG diagnosis tool which can be used for decision support was developed. However, the research focuses on the Ontology and diagnosis rules. Future research may include improvement of methods for creating a user-friendly interface for ECG representation. An experiment for usability of a human-machine system could be conducted to ensure that the system conforms to accepted standards for usability.

6.2.5 Implementing ECG Data Management

A database of ECG data can be created to facilitate the users in querying specific abnormal cardiac conditions. Future work could focus on the design and implementation of advanced techniques for data entry, storing, searching, and presenting ECG information to the users.

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APPENDICES

APPENDIX A

Rules for ECG Diagnosis from HL7 and Existing Recommendations

Abnormal Condition

Irregular rhythm

General Descriptions

Irregular rhythm is a condition of disturbances in the heart's rhythm.

ECG Measurements

- Duration of the interval between two consecutive QRS complexes
- Duration of the interval between two consecutive P waves of ECG

Criteria

- Irregular rhythm can be determined by accessing whether the RR intervals and PP intervals are regularly spaced.
- If the rhythm is irregular, determine if:
  - It is occasionally irregular
  - Regularly irregular (there is a pattern to the irregularity)
  - Irregularly irregular (there is no pattern to the irregularity)
- Evaluate the waveform of the ECG in detail for additional clues.

Image

Figure A.1: Irregular Rhythm.

Abnormal Condition

Irregular atrial escape rhythm

General Descriptions

The normal pacemaker fails to elicit a stmulus for one or more cycles, so an impatient ectopic focus fires.

ECG Measurements

- Duration of the P wave of ECG
- Duration of the interval between two consecutive P waves of ECG
- Duration of the interval between P onset and QRS onset of ECG

Criteria

- Late P wave, abnormal P wave morphology
- PQ interval < 100 ms

Image

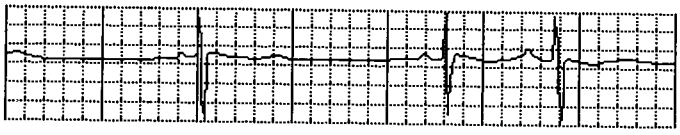

Figure A.2: Irregular Atrial Escape Rhythm.

Abnormal Condition

Sinus arrhythmia

General Descriptions

Sinus arrhythmia is a variation in rhythm of more than 0.16 second. Rate normally falls within normal limits. However, rhythm is irregular and varies with respiratory cycle. Treatment is not typically required unless symptomatic bradycardia is present.

ECG Measurements

- Duration of the interval between two consecutive P waves of ECG
- Duration of the interval between P onset and QRS onset of ECG
- Duration of the interval between two consecutive QRS complexes
- Rate of cardiac beats

Criteria

- Sinus arrhythmia occurs when the longest PP or PR interval exceeds the shortest interval by 0.16 second.
- Normal P waves preceding each QRS complex
- Normal (Narrow) QRS complex, RR interval < 0.12 second
- Rate between 60 and 100 beats per minute (bpm)
- The rhythm varies: increasing on inspiration, decreasing on expiration.

Images

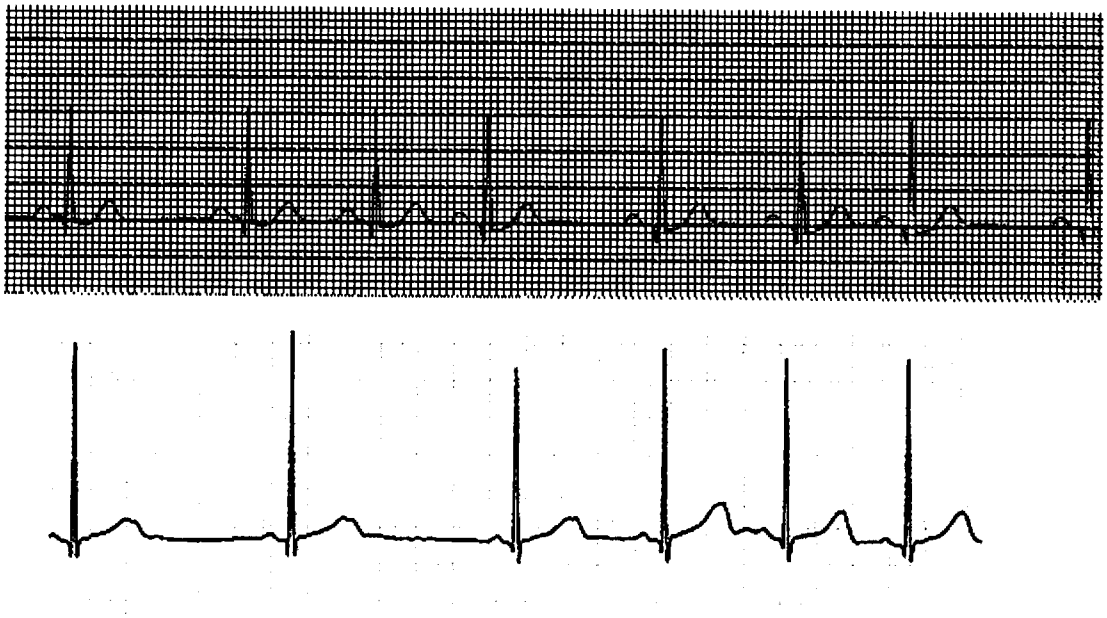

Figure A.3: Sinus Arrhythmia.

Abnormal Condition

Left bundle branch block

- Complete left bundle branch block
- Incomplete left bundle branch block

General Descriptions

Left bundle branch fails to conduct impulses normally. Left bundle branch block is usually caused by hypertensive heart diseases, aortic stenosis, degenerative changes of the conduction system.

ECG Measurements

- Duration of the QRS complex of ECG in <lead>
- Duration of the S1 wave of ECG in <lead>
- Duration of the S2 wave of ECG in <lead>
- Duration of the S3 wave of ECG in <lead>
- Amplitude of the T positive wave of ECG in specified <lead>
- Amplitude of the R1 wave of ECG in specified <lead>
- Amplitude of the R2 wave of ECG in specified <lead>
- Amplitude of the R3 wave of ECG in specified <lead>
- Duration of the R1 wave of ECG in <lead>
- Duration of the R2 wave of ECG in <lead>
- Duration of the R3 wave of ECG in <lead>
- Amplitude of the T negative wave of ECG in specified <lead>

Criteria

Complete left bundle branch block

- QRS complex will be greater than 0.12 second because the ventricles are activated sequentially, not simultaneously.
- Lead I
    - Depolarization spreads from right ventricle to left, producing wide S wave with a positive T wave
    - S wave may follow Q wave or small R wave.

- Lead V_6
    - No initial Q wave occurs
    - Tall, notched R wave appears as impulse spreads from right to left with negative T wave.

Incomplete left bundle branch block

- Incomplete left bundle branch block looks like LBBB but QRS duration is between 0.10 and 0.12s, with less ST-T change. This is often a progression of LVH (Left Ventricular Hypertrophy).

Image

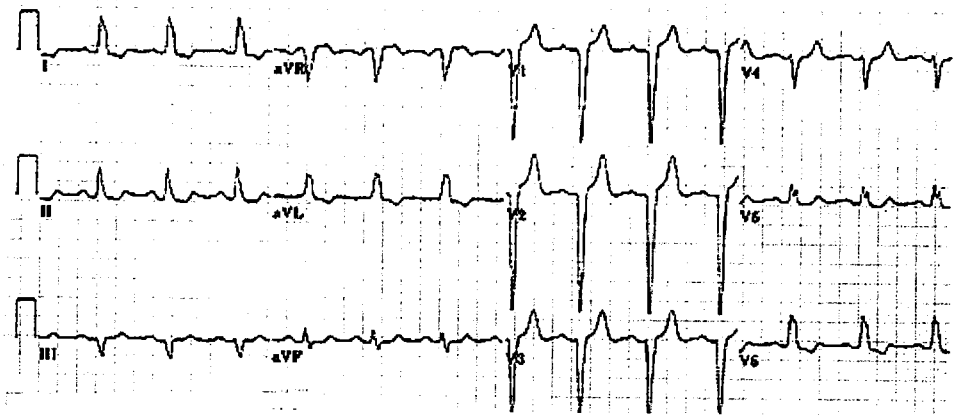

Figure A.4: Left Bundle Branch Block.

Abnormal Condition

Right bundle branch block

- Complete right bundle branch block
- Incomplete right bundle branch block

General Descriptions

Right bundle branch block occurs with conditions such as anterior wall myocardial infarction (MI), coronary cardiac disease (CAD), and pulmonary embolism. It may also occur without cardiac disease.

ECG Measurements

- Duration of the QRS complex of ECG in <lead>
- Duration of the S1 wave of ECG in <lead>
- Duration of the S2 wave of ECG in <lead>
- Duration of the S3 wave of ECG in <lead>
- Amplitude of the T positive wave of ECG in specified <lead>
- Amplitude of the R1 wave of ECG in specified <lead>
- Amplitude of the R2 wave of ECG in specified <lead>
- Amplitude of the R3 wave of ECG in specified <lead>
- Duration of the R1 wave of ECG in <lead>
- Duration of the R2 wave of ECG in <lead>
- Duration of the R3 wave of ECG in <lead>
- Amplitude of the T negative wave of ECG in specified <lead>

Criteria

Complete right bundle branch block

- QRS duration is greater than 0.12 second.
- Small R wave remains as septal depolarization unaffected.
- R wave then S wave (left ventricular depolarization) and tall R wave (late right ventricular depolarization)
- T wave is negative.

Incomplete right bundle branch block

- Incomplete right bundle branch block has a QRS duration of 0.10 - 0.12s with the same terminal QRS features.

Image

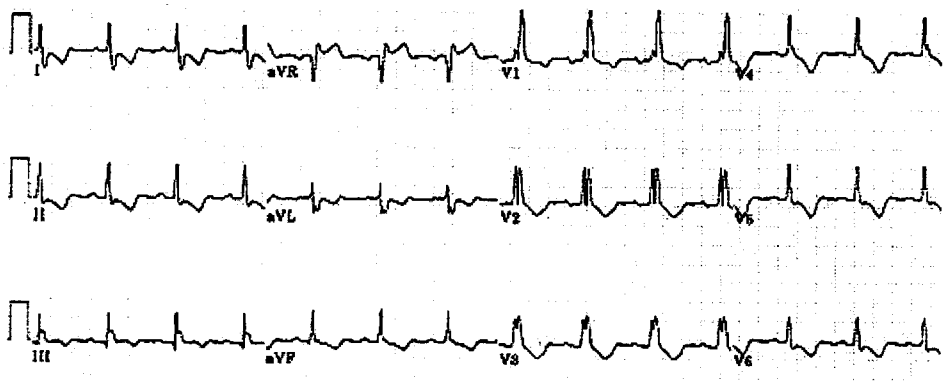

Figure A.5: Right Bundle Branch Block.

Abnormal Condition

Premature supraventricular contractions or premature atrial contractions (PACs)

General Descriptions

Premature beats or extra beats most often cause irregular heart rhythms. Those that start in the upper chambers are called premature atrial contractions (PACs). PACs originates in the atria, outside the sinoatrial (SA) node. They arrive from either a single ectopic focus or from multiple atrial foci that supersede the SA node as pacemaker for one or more beats. PACs are generally caused by enhanced automatically in the atrial tissue.

ECG Measurements

- Duration of the P wave of ECG in <lead>
- Duration of the interval between two consecutive QRS complexes

Criteria

- Premature, abnormal P waves (differ in configuration from normal P waves)
- QRS complexes after P waves, except in blocked PACs
- P wave often buried or identified in preceding T wave

Image

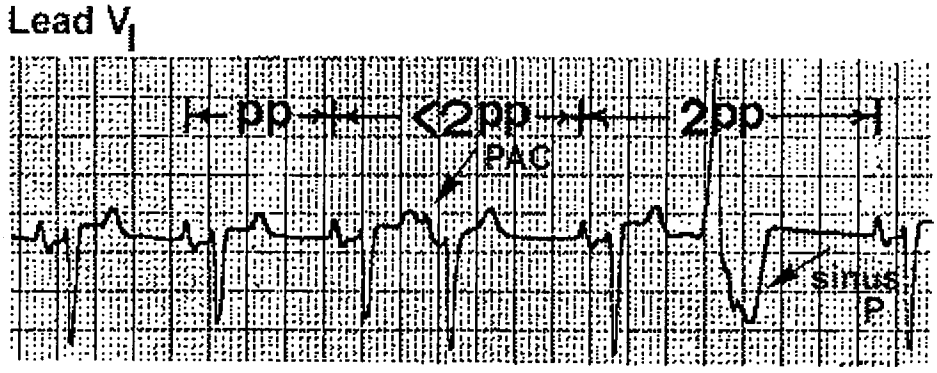

Figure A.6: Premature Supraventricular Contractions or Premature Atrial Contractions (PACs).

Abnormal Condition

Frequent PVC's (premature ventricular contractions)

General Descriptions

Premature ventricular contractions (PVCs) are ectopic beats that originate in the ventricles, occur earlier than expected. PVCs may occur in healthy people without being clinically significant. However, with underlying heart disease, PVCs may cause ventricular tachycardia and ventricular fibrillation.

ECG Measurements

- Rate of cardiac beats
- Duration of the QRS complex of ECG in <lead>
- Amplitude of the T negative wave of ECG in specified <lead>

Criteria

- Atrial and ventricular rhythms may be regular in underlying rhythm; irregular during PVCs.
- QRS premature
- QRS complex wide, usually > 0.12 second in premature beat
- T wave opposite direction to QRS complex

Image

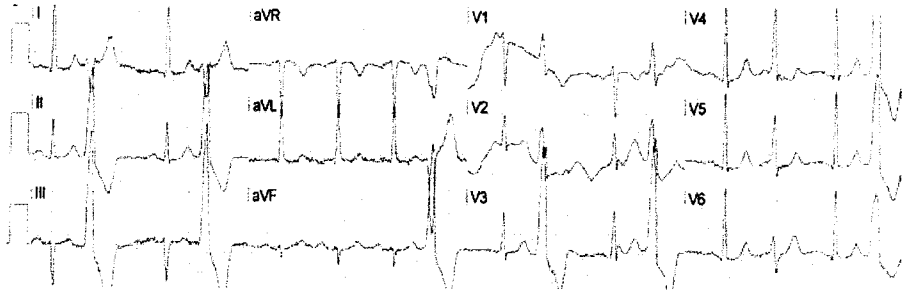

Figure A.7: Frequent PVC's (Premature Ventricular Contractions).

Abnormal Condition

Multiformed PVC's (polyformed) (premature ventricular contractions)

General Descriptions

Multiformed PVC's is one type of PVCs that are more dangerous than others. Mutliformed PVCs arise from different sites or from the same site with abnormal conduction. It may indicate severe heart disease or digoxin toxicity.

ECG Measurements

- Rate of cardiac beats
- Duration of the QRS complex of ECG in <lead>
- Amplitude of the T negative wave of ECG in specified <lead>

Criteria

- Atrial and ventricular rhythms may be regular in underlying rhythm; irregular during PVCs.
- QRS premature
- QRS complex wide, usually > 0.12 second in premature beat
- T wave opposite direction to QRS complex

Image

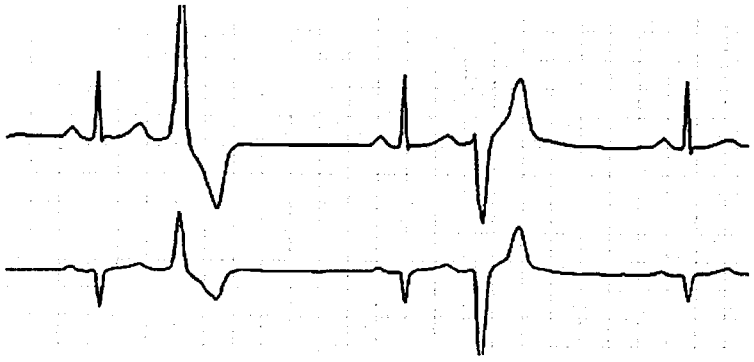

Figure A.8: Multiformed PVC's (polyformed) (Premature Ventricular Contractions).

Abnormal Condition

PVC's (premature ventricular contractions) R-on-T

General Descriptions

PVC R-on-T is one type of PVCs that are more dangerous than others. In R-on-T phenomenon, a PVC occurs so early that it falls on the T wave of the preceding beat. Because the cells have not fully repolarized, ventricular fibrillation can result.

ECG Measurements

- Rate of cardiac beats
- Duration of the QRS complex of ECG in <lead>
- Amplitude of the T negative wave of ECG in specified <lead>

Criteria

- Atrial and ventricular rhythms may be regular in underlying rhythm; irregular during PVCs.
- QRS premature
- QRS complex wide, usually > 0.12 second in premature beat
- T wave opposite direction to QRS complex

Image

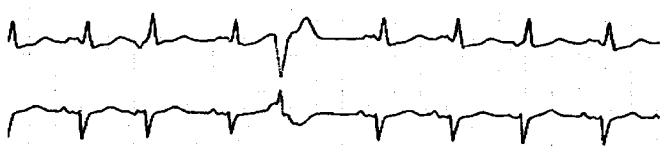

Figure A.9: PVC's (Premature Ventricular Contractions) R-on-T.

Abnormal Condition

Junctional escape beats

General Descriptions

Junctional escape beats (rhythms) is an arrhythmia originating in the atrioventricular (AV) junction. The AV junction performs pacemaker duty when a higher pacemaker site in the atria fails as the heart's dominant pacemaker. It can be either a beat, or when repeating, a rhythm.

ECG Measurements

- Rate of cardiac beats
- Duration of the QRS complex of ECG in <lead>
- Area of the P wave of ECG in sepcified <lead> (mVolt x msec) by integrating absolute values
- Duration of the P wave of ECG in <lead>

Criteria

- Rhythm is regular
- Heart rate is slow (40-55 beats per minute).
- P waves before, hidden in or after QRS complex; inverted if visible.
- If the P wave appears before QRS complex, PR interval is less than 0.12 second, otherwise absent.
- QRS complex is normal (duration < 0.12 second)

Image

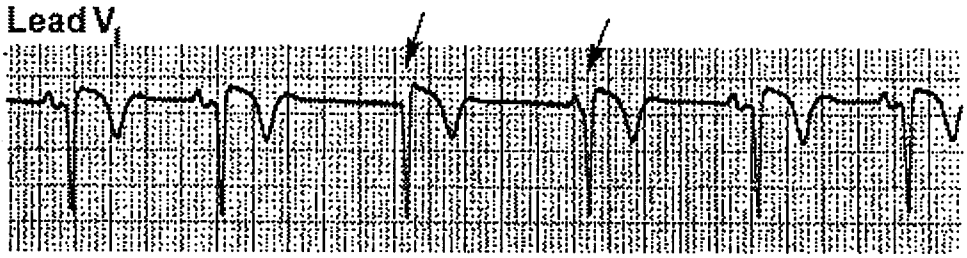

Figure A.10: Junctional Escape Beats.

Abnormal Condition

Left ventricular hypertrophy

General Descriptions

In left ventricular hypertrophy (LVH), the left ventricular wall thickens. LVH usually results from conditions that cause chronic increases in pressures within the ventricle.

ECG Measurements

- Amplitude of the R1 wave of ECG in specified <lead>
- Amplitude of the R2 wave of ECG in specified <lead>
- Amplitude of the R3 wave of ECG in specified <lead>
- Amplitude of the S1 wave of ECG in specified <lead>
- Amplitude of the S2 wave of ECG in specified <lead>
- Amplitude of the S3 wave of ECG in specified <lead>
- Duration of the QRS complex of ECG in <lead>
- Amplitude of the T negative wave of ECG in specified <lead>

Criteria

- QRS complex is prolonged or widened with increased amplitude.
- R wave in lead I is >= 2.5 mV, R wave in lead V5 is >= 3.5 mV, R wave in lead V6 is >= 3.5 mV
- S wave in lead III is >= 2.5 mV, S wave in lead V1 is >= 3.5 mV, S wave in lead V2 is >= 3.5 mV
- ST segment is possibly depressed in precordial leads if associated with T-wave inversion.
- T wave is possibly inverted in lead V_5 and V_6 (depending on extent of hypertrophy).
- Axis is usually normal. Left axis deviation may be present.
- There is a large S in V1 and a large R in V5

Image

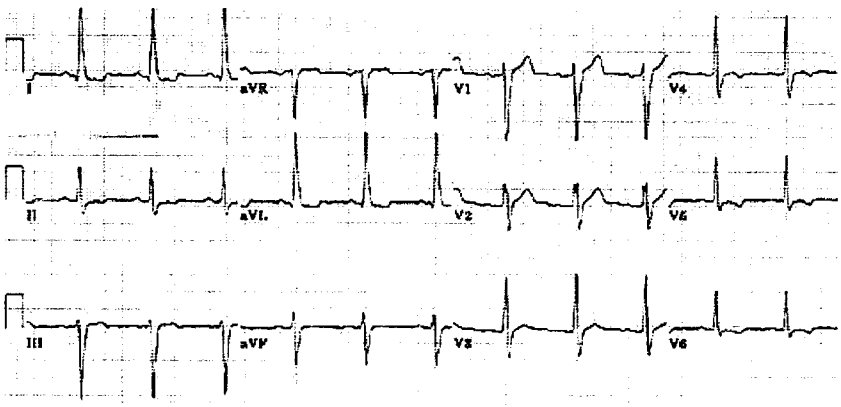

Figure A.11: Left Ventricular Hypertrophy.

Abnormal Condition

Right ventricular hypertrophy (RVH)

General Descriptions

With right ventricular hypertrophy, the wall of the right ventricle is very thick, so there is much more (positive) depolarization (and more vectors) toward the (positive) V_1 electrode. Therefore, QRS complex in lead V_1 is expected to be more positive (upward) than usual.

ECG Measurements

- Amplitude of the R1 wave of ECG in specified <lead>
- Amplitude of the R2 wave of ECG in specified <lead>
- Amplitude of the R3 wave of ECG in specified <lead>
- Amplitude of the S1 wave of ECG in specified <lead>
- Amplitude of the S2 wave of ECG in specified <lead>
- Amplitude of the S3 wave of ECG in specified <lead>

Criteria

- Large R wave in lead V_1; Amplitude >= 0.7 mV
- S wave in lead V_1 is smaller than the R wave. Without RVH, S wave is normally larger than the R wave in V_1.
- Large R wave of V_1 gets progressively smaller in V_2, V_3, V_4, etc.
- Right Axis Deviation (of the Mean QRS Vector) is often found because the enlarged right ventricle adds more vectors toward the right side.

Image

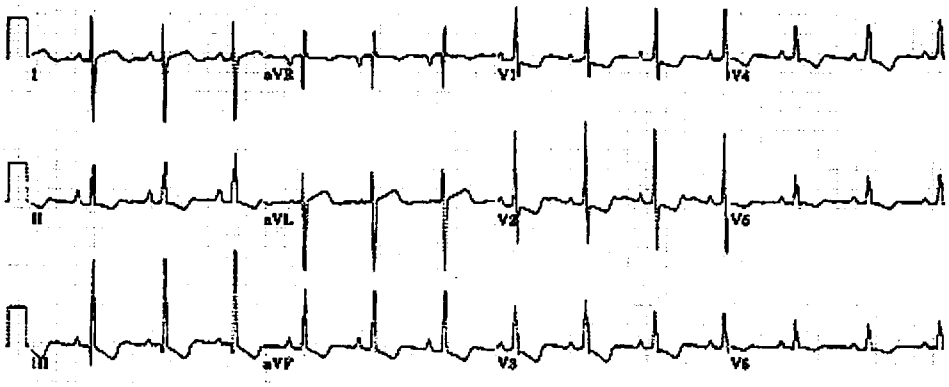

Figure A.12: Right Ventricular Hypertrophy (RVH).

Abnormal Condition

Infarction

- Anterior Infarction
- Inferior Infarction
- Lateral Infarction

General Descriptions

Each type of myocardial infarction causes characteristic ECG changes which are localized to the leads overlying the infarction site.

- Anterior Infarction

An anterior wall MI occurs when the left anterior descending artery becomes occluded.

- Inferior Infarction

Inferior infarction is usually caused by occlusion of the right coronary artery and produces characteristic ECG changes in the inferior leads II, III, and aV_F and reciprocal changes in the lateral leads I and aV_L.

- Lateral Infarction

Lateral infarction is usually caused by a blockage in the left circumflex artery and shows characteristic changes in the left lateral leads I, aV_L, V_5 and V_6. The reciprocal leads for a lateral wall infarction are leads V_1 and V_2.

ECG Measurements

- Area of the ST-T segment computed between J point and the beginning of the T wave of ECG in specified <lead> (mVolt x msec) by integrating absolut values
- Duration of the Q wave of ECG in <lead>
- Amplitude of the Q wave of ECG in specified <lead>

Criteria

- Anterior Infarction
    - Q, QS, or QRS complexes in leads V1, V2, V3, V4
    - Evolving ST-T changes
    - ST elevation, abnormal Q waves in lead V2, V3, V4
    - Reciprocal Changes in lead II, III, Avf

- Inferior Infarction
    - Pathologic Q waves and evolving ST-T changes in leads II, III, aVF
    - Q waves usually largest in lead III, next largest in lead aVF, and smallest in lead II
    - ST elevation, abnormal Q waves in lead I, aVL, V3, V4, V5, V6
    - Reciprocal Changes in lead II, III, aVF
- Lateral Infarction
    - High Lateral MI (typical MI features seen in leads I and/or aVL)
    - Slight U-wave inversion in leads II, III, aVF, V4-6, a strong marker for coronary disease
    - ST elevation, abnormal Q waves in lead I, aVL, V5, V6
    - Reciprocal Changes in lead II, III, aVF

Images

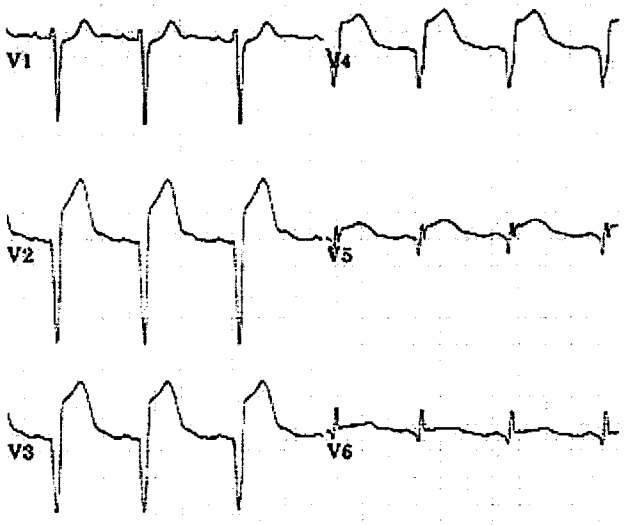

Figure A.13: Anterior Infarction.

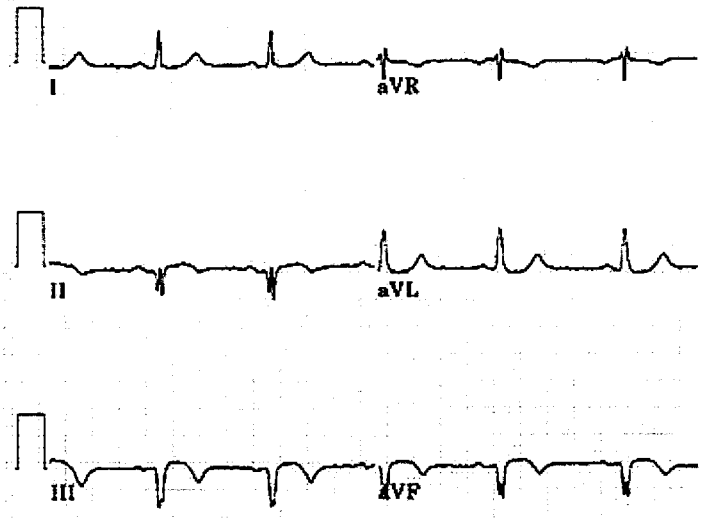

Figure A.14: Inferior Infarction.

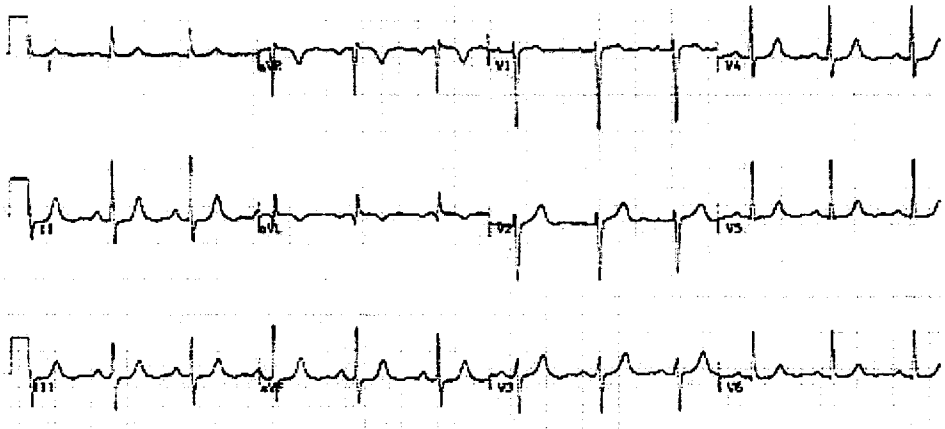

Figure A.15: Lateral Infarction.

Abnormal Condition

Intraventricular conduction defect

General Descriptions

This abnormality is frequently seen with previous myocardial infarction and scar formation. Prolonged QRS duration without a specific bundle branch block pattern can also occur due to intramyocardial conduction slowing from anti-arrhythmic drugs, left ventricular hypertrophy and hyperkalemia.

ECG Measurements

- Duration of the QRS complex of ECG in <lead>
- Duration of the interval between P offset and QRS onset of ECG in <lead>

Criteria

- QRS duration is greater than 0.12 second.
- Normal PR interval (not greater than 0.12 second)

Image

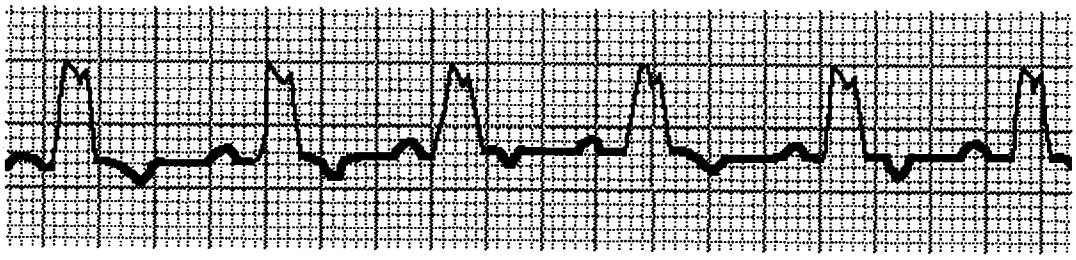

Figure A.16: Intraventricular Conduction Defect (Lead I).

Abnormal Condition

Atrial Enlargement

- Right Atrial Enlargement
- Left Atrial Enlargement

General Descriptions

- Right atrial enlargement (RAE)

RAE is diagnosed by the presence of a P wave 2.5 millimeters or greater in height. The P wave often has a sharp, peaked appearance. This increased voltage is caused by hypertrophy or acute strain of right atrial tissue. The lead most likely to show the right atrial enlargement is lead II.

- Left Atrial Enlargement (LAE)

Dilation or hypertrophy of the left atrium may increase the duration of the P wave. The long or abnormally shaped P wave occurs because of delay in electrical activation of the enlarged left atrium, as electricity moves leftward from the SA node. A P wave longer than 0.12 second is diagnostic of left atrial enlargement.

ECG Measurements

- Right Atrial Enlargement
    - Amplitude level of first extremum of the P wave of ECG in specified <lead> (mostly maximum of P, depends on morphology)
    - Duration of the QRS complex of ECG in <lead>

- Maximum amplitude of R wave of ECG in specified <lead>

- Left Atrial Enlargement
  - Duration of the P wave of ECG in <lead>
  - Amplitude level of first extremum of the P wave of ECG in specified <lead> (mostly maximum of P, depends on morphology)

Criteria

- Right Atrial Enlargement
  - P wave amplitude >2.5 mm in II and/or >1.5 mm in V1 (these criteria are not very specific or sensitive)
  - Better criteria can be derived from the QRS complex; these QRS changes are due to both the high incidence of RVH when RAE is present, and the RV displacement by an enlarged right atrium.
  - QR, Qr, qR, or qRs morphology in lead V1 (in absence of coronary heart disease)
  - QRS voltage in V1 is <5 mm and V2/V1 voltage ratio is >6 (Sensitivity = 50%; Specificity = 90%).
- Left Atrial Enlargement
  - P wave duration > 0.12s in frontal plane (usually lead II)
  - Notched P wave in limb leads with the inter-peak duration > 0.04s
  - Terminal P negativity in lead V1 (i.e., "P-terminal force") duration > 0.04s, depth >1 mm
  - Sensitivity = 50%; Specificity = 90%

Images

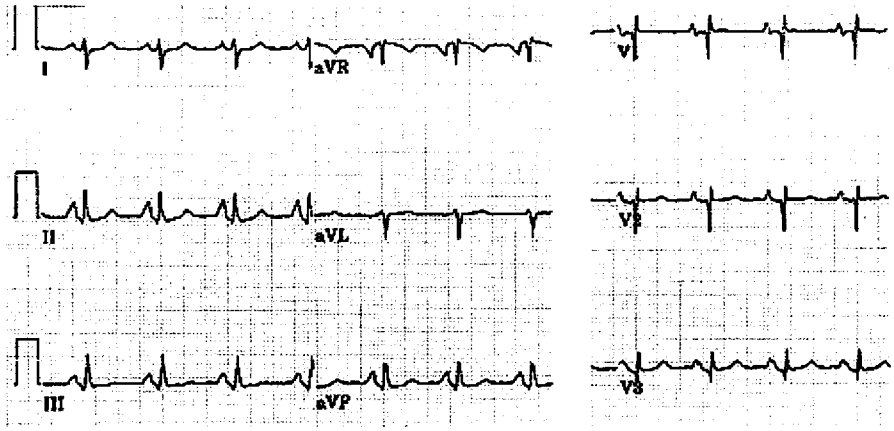

Figure A.17: Right Atrial Enlargement.

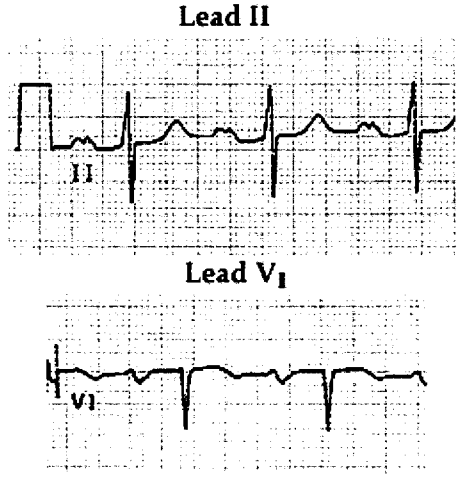

Figure A.18: Left Atrial Enlargement.

Abnormal Condition

Atrial tachycardia

General Descriptions

Atrial tachycardia is a supraventricular tachycardia which has an atrial rate from 150 to 250 beats/minute. The rapid rate shortens diastole, resulting in a loss of atrial kick, reduced cardiac output, and the potential of myocardial ischemia. Patients with a normal heart may have atrial tachycardia which is related to excessive use of caffeine or other stimulants. However, typically, atrial tachycardia is associated with primary or secondary cardiac disorders.

ECG Measurements

- Rate of cardiac beats
- Duration of the P wave of ECG in <lead>

Criteria

- Atrial rate: 150-250 bpm
- P wave may be aberrant (deviating from normal appearance)

Image

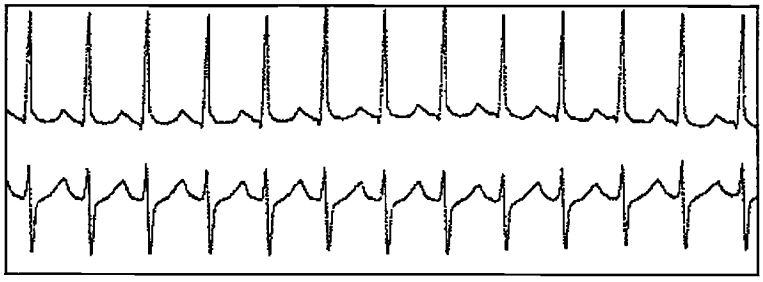

Figure A.19: Atrial Tachycardia.

Abnormal Condition

2:1 AV block

General Descriptions

This is a second degree AV block, when it takes 2 atrial impulses to stimulate the ventricular (QRS) complex. It can be either type I or type II second-degree AV block.

ECG Measurements

- Duration of the interval between two consecutive P waves of ECG
- Duration of the interval between P offset and QRS onset of ECG in <lead>
- Duration of the QRS complex of ECG in <lead>

Criteria

- P:QRS ratio is 2:1. Two P waves appears before each QRS on the ECG tracing.
- PR interval is normal (< 0.20 second).
- QRS duration is normal (< 0.12 second).

Image

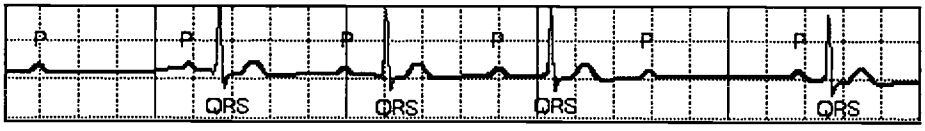

Figure A.20: 2:1 AV Block (Lead II).

Abnormal Condition

3:1 AV block

General Descriptions

This is a second degree AV block, when it takes 3 atrial impulses to stimulate the ventricular (QRS) complex.

ECG Measurements

- Duration of the interval between two consecutive P waves of ECG
- Duration of the interval between P offset and QRS onset of ECG in <lead>
- Duration of the QRS complex of ECG in <lead>

Criteria

- P:QRS ratio is 3:1. Threee P waves appears before each QRS on the ECG tracing.
- PR interval is normal (< 0.20 second).
- QRS duration is normal (< 0.12 second).

Image

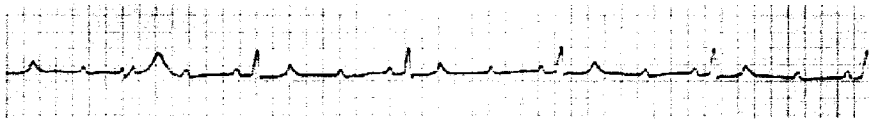

Figure A.21: 3:1 AV Block.

Abnormal Condition

4:1 AV block

General Descriptions

This is a second degree AV block, when it takes 4 atrial impulses to stimulate the ventricular (QRS) complex.

ECG Measurements

- Duration of the interval between two consecutive P waves of ECG
- Duration of the interval between P offset and QRS onset of ECG in <lead>
- Duration of the QRS complex of ECG in <lead>

Criteria

- P:QRS ratio is 4:1. Three P waves appears before each QRS on the ECG tracing.
- PR interval is normal (< 0.20 second).
- QRS duration is normal (< 0.12 second).

Image

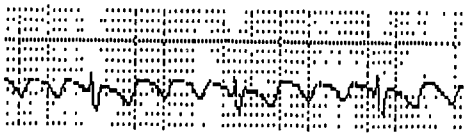

Figure A.22: 4:1 AV Block.

Abnormal Condition

AV block 1 degree

General Descriptions

First-degree atrioventricular (AV) block occurs when there's a delay in the conduction of electrical impulses from the atria to the ventricles. The delay normally occurs at the level of the AV node.

ECG Measurements

- Duration of the interval between P offset and QRS onset of ECG in <lead>
- Duration of the QRS complex of ECG in <lead>
- Duration of the interval between two consecutive P waves of ECG
- Duration of the interval between two consecutive QRS complexes

Criteria

- P-wave precedes each QRS complex but PR interval is greater than 0.2 second.
- Normal QRS, QRS duration < 0.12 second
- Normal atrial and ventricular rate
- P-QRS-T sequence is normal but the PR interval is prolonged.

Image

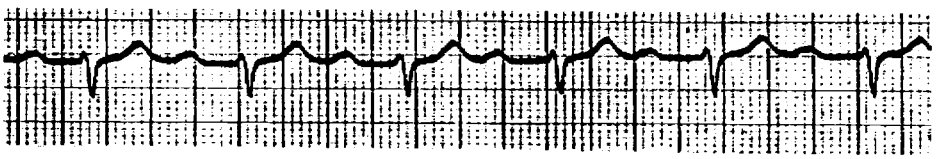

Figure A.23: AV Block 1 Degree.

Abnormal Condition

AV block 2 degree

General Descriptions

Second-degree atrioventricular (AV) block occurs when some of the electrical impulses from the AV node are blocked and some are conducted through normal conduction pathways. Second-degree AV block can be categorized to type I second-degree AV block and type II second-degree AV block.

- Type I second-degree AV block (Wenckebach) occurs when the P-R interval becomes progressively longer until the AV node is not stimulated (no QRS)
- Type II second-degree AV block (Mobitz) occurs when occasional ventricular depolarization is missed after a normal P wave and generally uniform PR intervals in the preceding cycle. It is less common than type I, but more serious.

ECG Measurements

- Duration of the interval between P onset and QRS onset of ECG
- Rate of cardiac beats
- Duration of the interval between two consecutive P waves of ECG
- Duration of the interval between P offset and QRS onset of ECG in <lead>
- Duration of the interval between two consecutive QRS complexes
- Duration of the QRS complex of ECG in <lead>

Criteria

Type I second-degree AV block (Wenckebach)

- Atrial rhythm is regular while ventricular rhythm is irregular due to skipped QRS complex.
- Atrial rate is faster than ventricular rate, usually within normal range (60-100 bpm)
- P waves are normal but some P waves are not followed by a QRS complex.
- PR interval is prolonged (> 0.2 second) with each cycle until P wave is not followed by a QRS complex.
- QRS complex is normal, but occasionally absent.

Type II second-degree AV block (Mobitz II block)

- Atrial rhythm is regular; ventricular rhythm is varied.
- Atrial rate is normal while ventricular rate is slower than atrial rate (< 60 bpm).
- P waves are normal but some of them are not followed by a QRS complex.
- PR interval is normal (< 0.2 second).
- QRS complex is occasionally absent.

Images

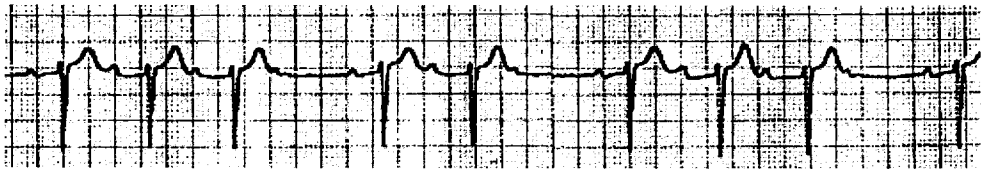

Figure A.24: Type I Second-degree AV Block (Wenckebach, Lead V_1).

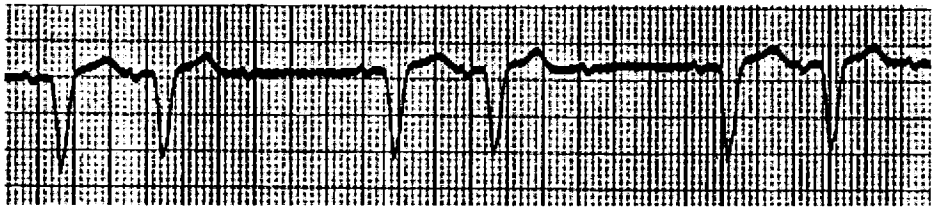

Figure A.25: Type II Second-degree AV Block (Mobitz II Block, Lead V_1).

Abnormal Condition

AV block 3 degree

General Descriptions

Third-degree atrioventricular block (complete heart block) indicates the complete absence of impulse conduction between the atria and ventricles resulting in A-V dissociation. Ventricles depolarize via an escape mechanism. The atrial rate is generally faster than the ventricular rate.

ECG Measurements

- Duration of the interval between two consecutive P waves of ECG
- Duration of the interval between two consecutive QRS complexes
- Rate of cardiac beats

- Duration of the interval between P offset and QRS onset of ECG in <lead>
- Duration of the QRS complex of ECG in <lead>

Criteria

- Atrial and ventricular rhythms are usually regular.
- Atrial rate is normal (60-100 bpm). Ventricular rate is slower than atrial rate (if junctional pacemaker, 40-60 bpm; if ventricular pacemaker, 20-40 bpm).
- P waves are normal but they have no relationship to QRS complexes.
- No PR interval.
- If junctional pacemaker, QRS duration is narrow (< 0.12 second). If ventricular pacemaker, QRS duration is wide (> 0.12 second).

Image

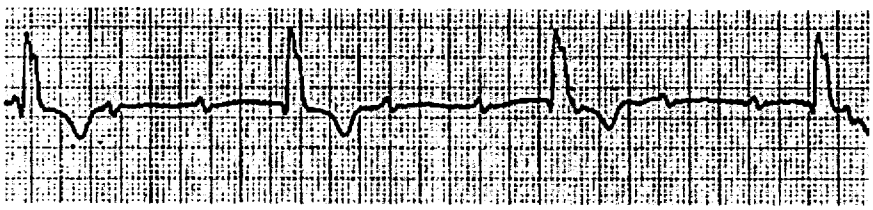

Figure A.26: AV Block 3 Degree (Lead V_1).

Abnormal Condition

Sinus bradycardia

General Descriptions

Sinus bradycardia is characterized by a normal sinus rhythm with a rate below 60 beats/minute. This arrhythmia's significance depends on the symptoms and the underlying cause. No treatment is necessary unless the patient show symptoms of decreased cardiac output.

ECG Measurements

- Rate of cardiac beats
- Duration of the P wave of ECG in <lead>
- Duration of the interval between P offset and QRS onset of ECG in <lead>
- Duration of the QRS complex of ECG in <lead>

Criteria

- Rate is less than 60 beats per min (bpm) with regular rhythm.
- Normal P Wave (before each QRS and identical)
- Normal P-R interval (between 0.12 and 0.2 second)
- Normal QRS complex (duration less than 0.12 second)

Image

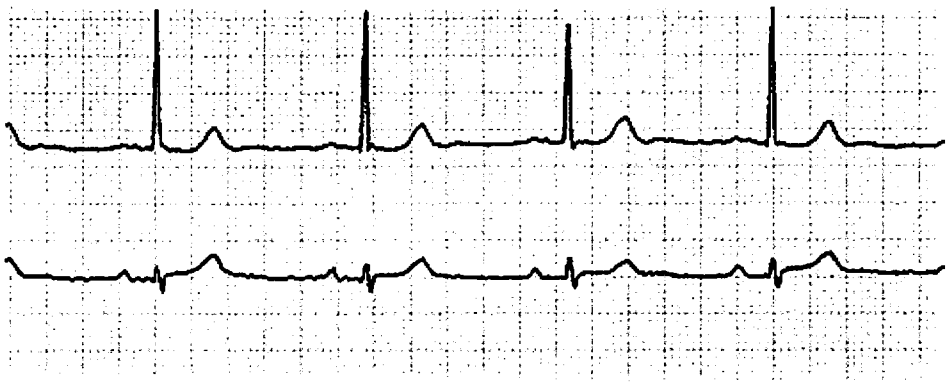

Figure A.27: Sinus Bradycardia.

Abnormal Condition

Atrial fibrillation

General Descriptions

Atrial fibrillation (AFib) is defined as chaotic, asynchronous, electrical activity in atrial issue. It is characterized by the absence of P waves and an irregularly irregular ventricular response.

ECG Measurements

- Duration of the interval between two consecutive P waves of ECG
- Duration of the interval between two consecutive QRS complexes
- Rate of cardiac beats
- Duration of the P wave of ECG in <lead>
- Duration of the interval between P offset and QRS onset of ECG in <lead>

- Duration of the QRS complex of ECG in <lead>

Criteria

- Atrial and ventricular rhythm are irregular.
- Atrial rate > 400 bpm; ventricular rate varies.
- No P waves.
- No PR interval.
- QRS complexes < 0.12 second; uniform in configuration and duration.

Image

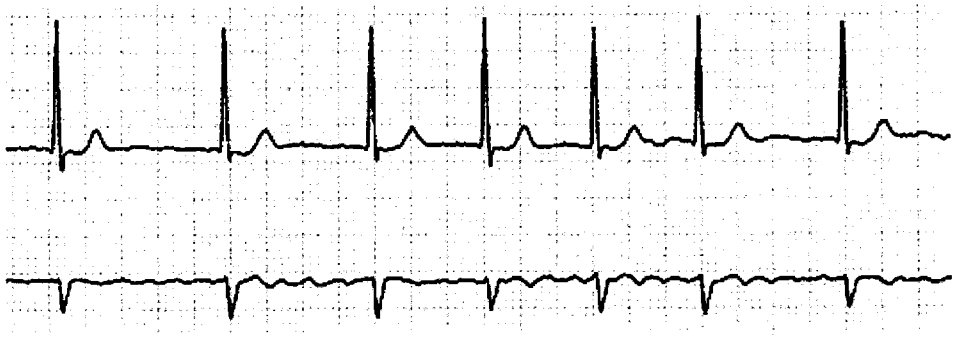

Figure A.28: Atrial Fibrillation.

Abnormal Condition

Ventricular fibrillation

General Descriptions

Ventricular fibrillation (V-fib, VF) is defined by a chaotic, disorganized pattern of electrical activity in the ventricles.

ECG Measurements

- Duration of the QRS complex of ECG in <lead>
- Duration of the interval between two consecutive QRS complexes

Criteria

- Heart rate: 300-600 bpm
- Ventricular rhythm is rapid and chaotic.
- No visible P waves, QRS complexes, or T waves
- Fine or coarse fibrillatory waves

Image

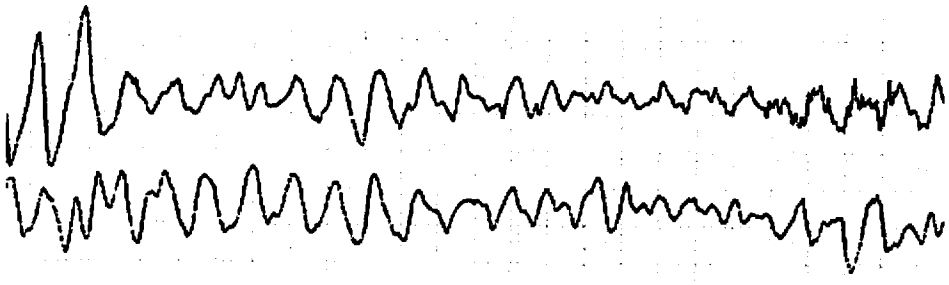

Figure A.29: Ventricular Fibrillation.

Abnormal Condition

Atrial flutter

General Descriptions

Atrial flutter is characterized by a rapid atrial rate of 250 to 400 beats/minute with the average of 300 beats/minute. On an ECG, P waves do not

appear normal due to the rapid atrial rate. The shape of P waves is in a sawtooth configuration called *flutter waves* or *F waves*.

ECG Measurements

- Duration of the interval between two consecutive P waves of ECG
- Duration of the interval between two consecutive QRS complexes
- Rate of cardiac beats
- Duration of the P wave of ECG in <lead>
- Duration of the QRS complex of ECG in <lead>

Criteria

- Atrial rhythm is regular.
- Ventricular rhythm is regular or irregular, depening on degree of AV block.
- Atrial rate 250 to 400 bpm; ventricular rate depends on degree of AV block.
- Sawtooth P-wave configuration
- QRS complexes uniform in shape and duration < 0.12 second.

Image

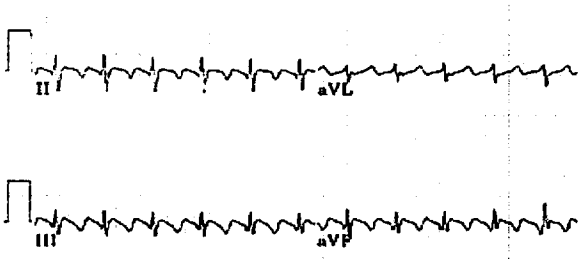

Figure A.30: Atrial Flutter with 2:1 AV Block.

Abnormal Condition

Junctional escape rhythm

General Descriptions

A junctional escape rhythm is an arrhythmia originating in the atrioventricular (AV) junction. The AV junction performs pacemaker duty when a higher pacemaker fails.

ECG Measurements

- Rate of cardiac beats
- Duration of the P wave of ECG in <lead>
- Duration of the interval between P offset and QRS onset of ECG in <lead>
- Duration of the QRS complex of ECG in <lead>

Criteria

- Heart rate is 40-60 bpm.
- P wave: inverted, absent, before or after QRS
- PR is short (< 0.12 second), if P Wave appears before QRS.
- QRS interval is normal (< 0.12 second).

Image

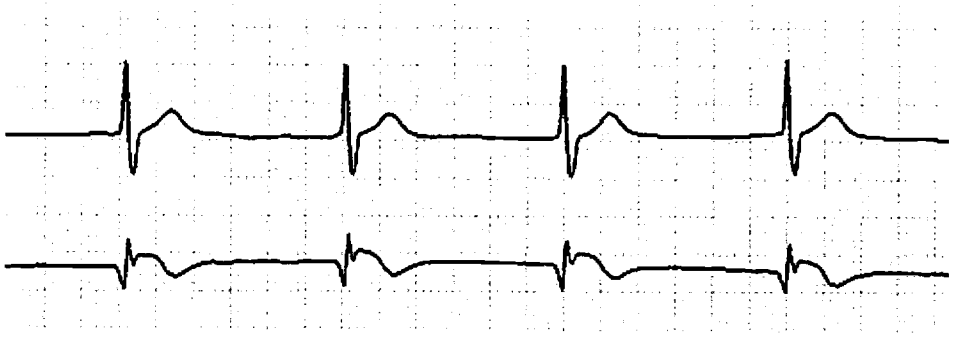

Figure A.31: Junctional Escape Rhythm.

Abnormal Condition

Junctional tachycardia

General Descriptions

In junctional tachycardia, three or more premature junctional contractions (PJCs) occur in a row. This usually begins as an accelerated junctional rhythm but the heart rate gradually increases to >100 bpm.

ECG Measurements

- Rate of cardiac beats
- Duration of the P wave of ECG in <lead>
- Duration of the interval between P offset and QRS onset of ECG in <lead>
- Duration of the QRS complex of ECG in <lead>

Criteria

- Heart rate > 100 bpm, usually < 200 bpm

- P wave: inverted, absent, before, during, or after QRS
- PR interval between 0.12 and 0.2 second, if P Wave appears before QRS.
- QRS interval is normal (< 0.12 second).

Image

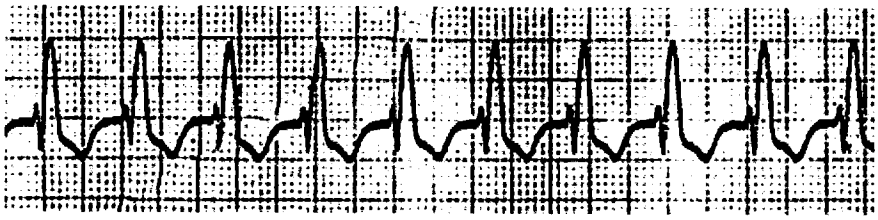

Figure A.32: Junctional Tachycardia.

Abnormal Condition

Paroxysmal supraventricular tachycardia

General Descriptions

Paroxysmal supraventricular tachycardia (PSVT) is a rapid heart rate, which occurs from time to time (paroxysmal). PSVT starts with events taking place above the ventricles. It can be initiated in the SA node; in the atria or the atrial conduction pathways; or in the AV node. It occurs most often in young people and infants.

ECG Measurements

- Duration of the P wave of ECG in <lead>
- Duration of the QRS complex of ECG in <lead>

- Rate of cardiac beats

Criteria

- P waves may be flattened, notched, or hidden in T wave.
- QRS interval is normal (< 0.12 second).
- Rate is between 150 and 250 bpm

Image

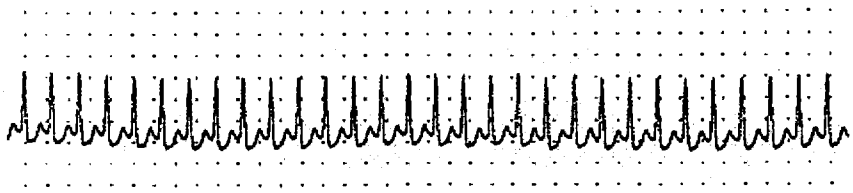

Figure A.33: Paroxysmal Supraventricular Tachycardia.

Abnormal Condition

Sinus tachycardia

General Descriptions

Sinus tachycardia is an acceleration of the firing of the sinoatrial node beyond its normal rate. The rate in an adult is characterized by a sinus rate of more than 100 beats/minute. It rarely exceeds 180 beats/minute except during heavy exercise.

ECG Measurements

- Rate of cardiac beats
- Duration of the P wave of ECG in <lead>

- Duration of the interval between P offset and QRS onset of ECG in <lead>
- Duration of the QRS complex of ECG in <lead>

Criteria

- Rate is greater than 100 beats per min (bpm).
- Normal P waves
- Normal P-R interval (between 0.12 and 0.2 second)
- QRS is normal (0.12 second).

Image

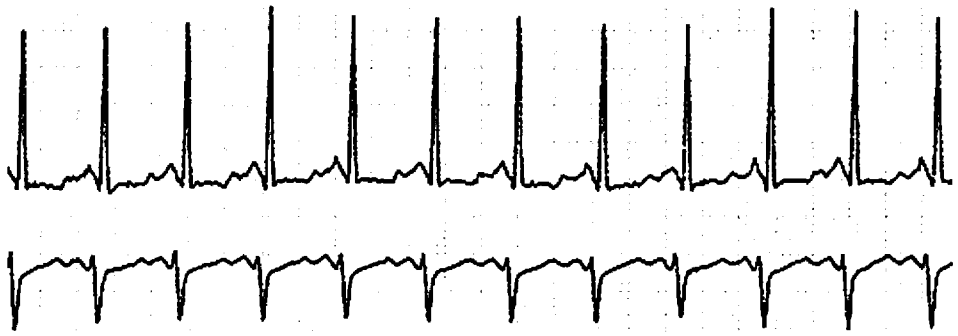

Figure A.34: Sinus Tachycardia.

Abnormal Condition

Ventricular tachycardia

General Descriptions

Ventricular tachycardia occurs when three or more premature ventricular contractions (PVCs) strike in a row and the ventricular rate exceeds 100 beats/minute.

ECG Measurements

- Rate of cardiac beats
- Duration of the interval between two consecutive P waves of ECG
- Duration of the interval between two consecutive QRS complexes
- Duration of the P wave of ECG in <lead>
- Duration of the QRS complex of ECG in <lead>

Criteria

- Atrial rate is unmeasurable; ventricular rate: 100-250 bpm.
- Atrial rhythm cannot be determined.
- Ventricular rhythm is usually regular (but may be slightly irregular).
- P waves are present or absent.
- QRS complex is wide (> 0.12 second).

Image

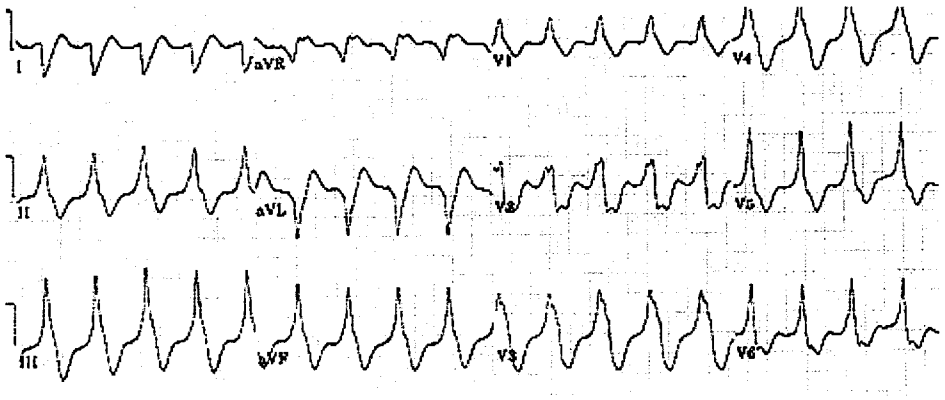

Figure A.35: Ventricular Tachycardia.

Abnormal Condition

Trifascicular block

General Descriptions

Trifasicular block is the combination of right bundle branch block, left anterior hemiblock and long PR interval. It implies that conduction is delayed in the third fascicle (in this case the left posterior fascicle) and a permanent pacemaker may be needed.

ECG Measurements

- Duration of the QRS complex of ECG in <lead>
- Duration of the S1 wave of ECG in <lead>
- Duration of the S2 wave of ECG in <lead>
- Duration of the S3 wave of ECG in <lead>
- Amplitude of the T positive wave of ECG in specified <lead>
- Amplitude of the R1 wave of ECG in specified <lead>
- Amplitude of the R2 wave of ECG in specified <lead>
- Amplitude of the R3 wave of ECG in specified <lead>
- Duration of the R1 wave of ECG in <lead>
- Duration of the R2 wave of ECG in <lead>
- Duration of the R3 wave of ECG in <lead>
- Amplitude of the T negative wave of ECG in specified <lead>
- Duration of the interval between P offset and QRS onset of ECG in <lead>

Criteria

- QRS duration is greater than 0.12 second.
- Small R wave remains as septal depolarization unaffected.
- R wave then S wave (left ventricular depolarization) and tall R wave (late right ventricular depolarization).
- T wave is negative.

Image

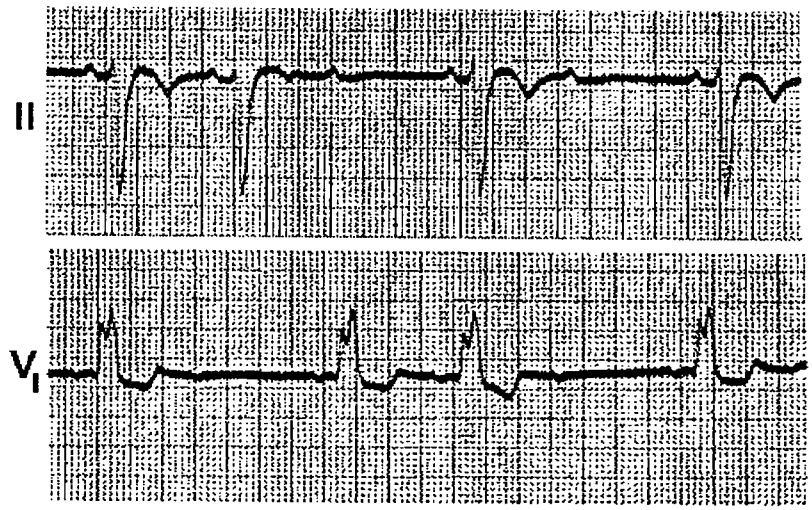

Figure A.36: Trifascicular Block.

Abnormal Condition

Wolf-Parkinson-White Syndrome

General Descriptions

Wolf-Parkinson-White syndrome is a common type of preexcitation syndrome. It occurs when electrical impulses enter the ventricles from the atria by

using an accessory pathway that bypasses the atrioventricular (AV) junction. This results in a short PR interval and a wide QRS complex.

ECG Measurements

- Duration of the QRS complex of ECG in <lead>
- Duration of the interval between P offset and QRS onset of ECG in <lead>

Criteria

- QRS duration is greater than 0.12 second.
- The P-R interval is short (< 0.12 second).
- A delta wave occurs at the beginning of the QRS complex.
- Secondary ST-T changes due to the altered ventricular activation sequence.

Image

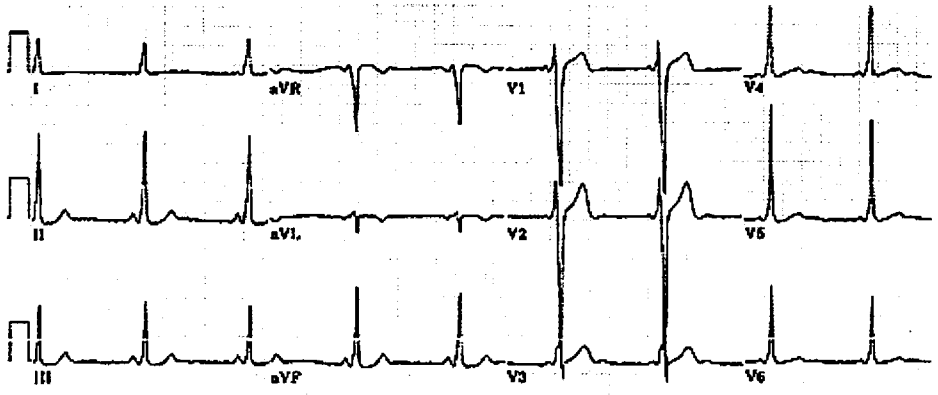

Figure A.37: Wolf-Parkinson-White Syndrome.

APPENDIX B

Data and Results for Sensitivity and Specificity Tests

Table B.1: Data and Results for Sensitivity Test.

Record	Database	Physician Diagnosis	Model Diagnosis	Result
1	MIT-BIH Arrhythmia	Premature Atrial Contraction	Irregular Rhythm, Premature Atrial Contraction	Correct
2	MIT-BIH Arrhythmia	Premature Ventricular Contraction	Irregular Rhythm, Premature Ventricular Contraction	Correct
3	MIT-BIH Arrhythmia	Premature Ventricular Contraction, Ventricular Tachycardia	Irregular Rhythm, Premature Ventricular Contraction, Ventricular Tachycardia	Correct
4	MIT-BIH Arrhythmia	Premature Atrial Contraction	Irregular Rhythm, Premature Atrial Contraction	Correct
5	MIT-BIH Arrhythmia	Premature Ventricular Contraction	Irregular Rhythm, Premature Ventricular Contraction	Correct
6	MIT-BIH Arrhythmia	Premature Atrial Contraction	Irregular Rhythm, Premature Atrial Contraction	Correct
7	MIT-BIH Arrhythmia	Premature Ventricular Contraction	Irregular Rhythm, Premature Ventricular Contraction	Correct
8	MIT-BIH Arrhythmia	Premature Ventricular Contraction	Irregular Rhythm, Premature Ventricular Contraction	Correct
9	MIT-BIH Arrhythmia	Premature Ventricular Contraction	Irregular Rhythm, Premature Ventricular Contraction	Correct
10	MIT-BIH Arrhythmia	Premature Ventricular Contraction	Irregular Rhythm, Premature Ventricular Contraction	Correct
11	MIT-BIH Arrhythmia	Premature Ventricular Contraction	Irregular Rhythm, Premature Ventricular Contraction	Correct
12	MIT-BIH Arrhythmia	Premature Ventricular Contraction	Irregular Rhythm, Premature Ventricular Contraction	Correct
13	MIT-BIH Arrhythmia	Premature Ventricular Contraction	Irregular Rhythm, Premature Ventricular Contraction	Correct
14	MIT-BIH Arrhythmia	Premature Atrial Contraction	Irregular Rhythm, Premature Atrial Contraction	Correct
15	MIT-BIH Arrhythmia	Premature Atrial Contraction	Irregular Rhythm, Premature Atrial Contraction	Correct

Record	Database	Physician Diagnosis	Model Diagnosis	Result
16	MIT-BIH Arrhythmia	Sinus Arrhythmia	Irregular Rhythm, Sinus Arrthythmia	Correct
17	MIT-BIH Arrhythmia	Premature Ventricular Contraction	Irregular Rhythm, Premature Ventricular Contraction	Correct
18	MIT-BIH Arrhythmia	Sinus Arrhythmia	Irregular Rhythm, Sinus Arrthythmia	Correct
19	MIT-BIH Arrhythmia	Premature Ventricular Contraction	Irregular Rhythm, Premature Ventricular Contraction	Correct
20	MIT-BIH Arrhythmia	Premature Atrial Contraction	Irregular Rhythm, Premature Atrial Contraction	Correct
21	MIT-BIH Arrhythmia	Right Bundle Branch Block	Right Bundle Branch Block	Correct
22	MIT-BIH Arrhythmia	Right Bundle Branch Block	Right Bundle Branch Block	Correct
23	MIT-BIH Arrhythmia	Premature Atrial Contraction	Irregular Rhythm, Premature Atrial Contraction	Correct
24	MIT-BIH Arrhythmia	Premature Ventricular Contraction	Irregular Rhythm, Premature Ventricular Contraction	Correct
25*	MIT-BIH Arrhythmia	Premature Atrial Contraction (PAC), Premature Ventricular Contraction	Irregular Rhythm, Premature Ventricular Contraction	Missing PAC
26	MIT-BIH Arrhythmia	Irregular Rhythm	Irregular Rhythm	Correct
27	MIT-BIH Arrhythmia	Premature Ventricular Contraction	Irregular Rhythm, Premature Ventricular Contraction	Correct
28*	MIT-BIH Arrhythmia	Right Bundle Branch Block, Premature Ventricular Contraction, Junctional Escape Beats (JEB)	Irregular Rhythm, Right Bundle Branch Block, Premature Ventricular Contraction	Missing JEB
29	MIT-BIH Arrhythmia	Right Bundle Branch Block	Right Bundle Branch Block	Correct
30	MIT-BIH Arrhythmia	Ventricular Tachycardia	Ventricular Tachycardia	Correct
31	MIT-BIH Arrhythmia	Premature Atrial Contraction	Irregular Rhythm, Premature Atrial Contraction	Correct
32	MIT-BIH Arrhythmia	Junctional Escape Beat	Junctional Escape Beat	Correct
33	MIT-BIH Arrhythmia	Atrial Fibrillation	Atrial Fibrillation	Correct
34	MIT-BIH Arrhythmia	Premature Ventricular Contraction	Irregular Rhythm, Premature Ventricular Contraction	Correct

Record	Database	Physician Diagnosis	Model Diagnosis	Result
35	MIT-BIH Arrhythmia	Junctional Escape Rhythm	Junctional Escape Rhythm	Correct
36	MIT-BIH Arrhythmia	Atrial Flutter, Atrial Fibrillation	Atrial Flutter, Atrial Fibrillation	Correct
37	MIT-BIH Arrhythmia	Ventricular Tachycardia	Ventricular Tachycardia	Correct
38	MIT-BIH Arrhythmia	Atrial Fibrillation	Atrial Fibrillation	Correct
39	MIT-BIH Arrhythmia	Premature Ventricular Contraction	Irregular Rhythm, Premature Ventricular Contraction	Correct
40	MIT-BIH Arrhythmia	Ventricular Tachycardia, Premature Ventricular Contraction	Ventricular Tachycardia, Premature Ventricular Contraction	Correct
41	MIT-BIH Arrhythmia	Ventricular Tachycardia	Ventricular Tachycardia	Correct
42	MIT-BIH Arrhythmia	Left Bundle Branch Block	Left Bundle Branch Block	Correct
43	MIT-BIH Arrhythmia	Left Bundle Branch Block	Left Bundle Branch Block	Correct
44	MIT-BIH Arrhythmia	Premature Ventricular Contraction	Irregular Rhythm, Premature Ventricular Contraction	Correct
45	MIT-BIH Arrhythmia	Premature Atrial Contraction	Irregular Rhythm, Premature Atrial Contraction	Correct
46	MIT-BIH Arrhythmia	Premature Ventricular Contraction	Irregular Rhythm, Premature Ventricular Contraction	Correct
47	MIT-BIH Arrhythmia	Ventricular Tachycardia	Ventricular Tachycardia	Correct
48	MIT-BIH Arrhythmia	Premature Ventricular Contraction	Irregular Rhythm, Premature Ventricular Contraction	Correct
49	MIT-BIH Arrhythmia	Right Bundle Branch Block	Right Bundle Branch Block	Correct
50	MIT-BIH Arrhythmia	Sinus Arrhythmia	Sinus Arrhythmia	Correct
51	MIT-BIH Arrhythmia	Ventricular Tachycardia	Ventricular Tachycardia	Correct
52	MIT-BIH Arrhythmia	Premature Ventricular Contraction	Irregular Rhythm, Premature Ventricular Contraction	Correct
53*	MIT-BIH Arrhythmia	Left Bundle Branch Block, Premature Ventricular Contraction (PVC)	Left Bundle Branch Block	Missing PVC
54	MIT-BIH Arrhythmia	Ventricular Tachycardia	Ventricular Tachycardia	Correct

Record	Database	Physician Diagnosis	Model Diagnosis	Result
55*	MIT-BIH Arrhythmia	Premature Ventricular Contraction, Premature Atrial Contraction (PAC)	Irregular Rhythm, Premature Ventricular Contraction	Missing PAC
56	MIT-BIH Arrhythmia	Premature Ventricular Contraction, Atrial Fibrillation	Irregular Rhythm, Premature Ventricular Contraction, Atrial Fibrillation	Correct
57	MIT-BIH Arrhythmia	Ventricular Tachycardia	Ventricular Tachycardia	Correct
58	MIT-BIH Arrhythmia	Premature Ventricular Contraction	Irregular Rhythm, Premature Ventricular Contraction	Correct
59	MIT-BIH Arrhythmia	Atrial Fibrillation	Atrial Fibrillation	Correct
60	MIT-BIH Arrhythmia	Premature Atrial Contraction	Irregular Rhythm, Premature Atrial Contraction	Correct
61	MIT-BIH Arrhythmia	Atrial Fibrillation, Premature Ventricular Contraction	Atrial Fibrillation, Premature Ventricular Contraction	Correct
62*	MIT-BIH Arrhythmia	Atrial Fibrillation (AF)	Irregular Rhythm, Sinus Arrthythmia	Missing AF
63	MIT-BIH Arrhythmia	Ventricular Tachycardia	Irregular Rhythm, Ventricular Tachycardia	Correct
64	MIT-BIH Arrhythmia	Irregular Atrial Escape Rhythm	Irregular Rhythm, Irregular Atrial Escape Rhythm	Correct
65	MIT-BIH Arrhythmia	Premature Ventricular Contraction	Irregular Rhythm, Premature Ventricular Contraction	Correct
66	MIT-BIH Arrhythmia	Premature Ventricular Contraction	Irregular Rhythm, Premature Ventricular Contraction	Correct
67	MIT-BIH Arrhythmia	Right Bundle Branch Block	Right Bundle Branch Block	Correct
68	MIT-BIH Arrhythmia	Sinus Bradycardia	Sinus Bradycardia	Correct
69	MIT-BIH Arrhythmia	Premature Ventricular Contraction	Irregular Rhythm, Premature Ventricular Contraction	Correct
70	MIT-BIH Arrhythmia	Ventricular Tachycardia	Irregular Rhythm, Ventricular Tachycardia	Correct
71*	MIT-BIH Arrhythmia	Premature Atrial Contraction (PAC), Premature Ventricular Contraction	Irregular Rhythm, Premature Ventricular Contraction	Missing PAC
72	MIT-BIH Arrhythmia	Premature Ventricular Contraction	Irregular Rhythm, Premature Ventricular Contraction	Correct
73	European ST-T	Premature Ventricular Contraction	Irregular Rhythm, Premature Ventricular Contraction	Correct

Record	Database	Physician Diagnosis	Model Diagnosis	Result
74	European ST-T	Ventricular Tachycardia	Irregular Rhythm, Ventricular Tachycardia	Correct
75	European ST-T	Premature Ventricular Contraction	Irregular Rhythm, Premature Ventricular Contraction	Correct
76	European ST-T	Premature Ventricular Contraction	Irregular Rhythm, Premature Ventricular Contraction	Correct
77	European ST-T	Premature Ventricular Contraction	Irregular Rhythm, Premature Ventricular Contraction	Correct
78	European ST-T	Premature Ventricular Contraction	Irregular Rhythm, Premature Ventricular Contraction	Correct
79	European ST-T	Ventricular Tachycardia	Irregular Rhythm, Ventricular Tachycardia	Correct
80	Long-Term ST	Premature Ventricular Contraction	Irregular Rhythm, Premature Ventricular Contraction	Correct
81	Long-Term ST	Supraventricular premature or ectopic beats	Irregular Rhythm, Supraventricular premature or ectopic beats	Correct
82	Long-Term ST	Premature Ventricular Contraction	Irregular Rhythm, Premature Ventricular Contraction	Correct
83	Long-Term ST	Supraventricular premature or ectopic beats	Irregular Rhythm, Supraventricular premature or ectopic beats	Correct
84	Long-Term ST	Premature Ventricular Contraction	Irregular Rhythm, Premature Ventricular Contraction	Correct
85	Long-Term ST	Supraventricular premature or ectopic beats	Irregular Rhythm, Supraventricular premature or ectopic beats	Correct
86	Long-Term ST	Premature Ventricular Contraction	Irregular Rhythm, Premature Ventricular Contraction	Correct
87	Long-Term ST	Supraventricular premature or ectopic beats	Irregular Rhythm, Supraventricular premature or ectopic beats	Correct
88	Long-Term ST	Premature Ventricular Contraction	Irregular Rhythm, Premature Ventricular Contraction	Correct
89	Long-Term ST	Supraventricular premature or ectopic beats	Irregular Rhythm, Supraventricular premature or ectopic beats	Correct
90	Long-Term ST	Premature Ventricular Contraction	Irregular Rhythm, Premature Ventricular Contraction	Correct

Record	Database	Physician Diagnosis	Model Diagnosis	Result
91	Long-Term ST	Supraventricular premature or ectopic beats	Irregular Rhythm, Supraventricular premature or ectopic beats	Correct
92	Long-Term ST	Premature Ventricular Contraction	Irregular Rhythm, Premature Ventricular Contraction	Correct
93	Long-Term ST	Supraventricular premature or ectopic beats	Irregular Rhythm, Supraventricular premature or ectopic beats	Correct
94	Long-Term ST	Premature Ventricular Contraction	Irregular Rhythm, Premature Ventricular Contraction	Correct
95	Long-Term ST	Premature Ventricular Contraction	Irregular Rhythm, Premature Ventricular Contraction	Correct
96	Long-Term ST	Supraventricular premature or ectopic beats	Irregular Rhythm, Supraventricular premature or ectopic beats	Correct
97	Long-Term ST	Premature Ventricular Contraction	Irregular Rhythm, Premature Ventricular Contraction	Correct
98	Long-Term ST	Supraventricular premature or ectopic beats	Irregular Rhythm, Supraventricular premature or ectopic beats	Correct
99	Long-Term ST	Premature Ventricular Contraction	Irregular Rhythm, Premature Ventricular Contraction	Correct
100	Long-Term ST	Supraventricular premature or ectopic beats	Irregular Rhythm, Supraventricular premature or ectopic beats	Correct
101	Long-Term ST	Premature Ventricular Contraction	Irregular Rhythm, Premature Ventricular Contraction	Correct
102	Long-Term ST	Supraventricular premature or ectopic beats	Irregular Rhythm, Supraventricular premature or ectopic beats	Correct
103	MIT-BIH Noise Stress Test	Right Bundle Branch Block	Right Bundle Branch Block	Correct
104	MIT-BIH Noise Stress Test	Right Bundle Branch Block	Right Bundle Branch Block	Correct
105	MIT-BIH Noise Stress Test	Right Bundle Branch Block	Right Bundle Branch Block	Correct
106	MIT-BIH Noise Stress Test	Right Bundle Branch Block	Right Bundle Branch Block	Correct
107	MIT-BIH Noise Stress Test	Right Bundle Branch Block	Right Bundle Branch Block	Correct
108	MIT-BIH Noise Stress Test	Right Bundle Branch Block	Right Bundle Branch Block	Correct

Record	Database	Physician Diagnosis	Model Diagnosis	Result
109	MIT-BIH Noise Stress Test	Premature Ventricular Contraction	Irregular Rhythm, Premature Ventricular Contraction	Correct
110	MIT-BIH Noise Stress Test	Premature Ventricular Contraction	Irregular Rhythm, Premature Ventricular Contraction	Correct
111	MIT-BIH Noise Stress Test	Premature Ventricular Contraction	Irregular Rhythm, Premature Ventricular Contraction	Correct
112	MIT-BIH Noise Stress Test	Premature Ventricular Contraction	Irregular Rhythm, Premature Ventricular Contraction	Correct
113	MIT-BIH Noise Stress Test	Premature Ventricular Contraction	Irregular Rhythm, Premature Ventricular Contraction	Correct
114	MIT-BIH Noise Stress Test	Premature Ventricular Contraction	Irregular Rhythm, Premature Ventricular Contraction	Correct
115	Creighton University Ventricular Tachyarrhythmia	Ventricular Fibrillation	Irregular Rhythm, Ventricular Fibrillation	Correct
116	Creighton University Ventricular Tachyarrhythmia	Ventricular Fibrillation	Irregular Rhythm, Ventricular Fibrillation	Correct
117	Creighton University Ventricular Tachyarrhythmia	Ventricular Fibrillation	Irregular Rhythm, Ventricular Fibrillation	Correct
118	MIT-BIH Atrial Fibrillation	Atrial Fibrillation	Irregular Rhythm, Atrial Fibrillation	Correct
119	MIT-BIH Atrial Fibrillation	Atrial Fibrillation	Irregular Rhythm, Atrial Fibrillation	Correct
120	MIT-BIH Atrial Fibrillation	Atrial Fibrillation	Irregular Rhythm, Atrial Fibrillation	Correct
121	MIT-BIH Atrial Fibrillation	Atrial Fibrillation	Irregular Rhythm, Atrial Fibrillation	Correct
122	MIT-BIH Atrial Fibrillation	Atrial Fibrillation	Irregular Rhythm, Atrial Fibrillation	Correct
123	MIT-BIH Atrial Fibrillation	Atrial Fibrillation	Irregular Rhythm, Atrial Fibrillation	Correct
124	MIT-BIH Atrial Fibrillation	Atrial Fibrillation	Irregular Rhythm, Atrial Fibrillation	Correct
125	MIT-BIH Atrial Fibrillation	Atrial Fibrillation	Irregular Rhythm, Atrial Fibrillation	Correct
126	MIT-BIH Atrial Fibrillation	Atrial Fibrillation	Irregular Rhythm, Atrial Fibrillation	Correct
127	MIT-BIH Atrial Fibrillation	Atrial Fibrillation	Irregular Rhythm, Atrial Fibrillation	Correct

Record	Database	Physician Diagnosis	Model Diagnosis	Result
128*	MIT-BIH Supraventricular Arrthymia	Premature Ventricular Contraction (PVC), Supraventricular premature or ectopic beats	Irregular Rhythm, Supraventricular premature or ectopic beats	Missing PVC
129	MIT-BIH Supraventricular Arrthymia	Premature Ventricular Contraction	Irregular Rhythm, Premature Ventricular Contraction	Correct
130	MIT-BIH Supraventricular Arrthymia	Premature Ventricular Contraction	Irregular Rhythm, Premature Ventricular Contraction	Correct
131	MIT-BIH Supraventricular Arrthymia	Premature Ventricular Contraction	Irregular Rhythm, Premature Ventricular Contraction	Correct
132	MIT-BIH Supraventricular Arrthymia	Premature Ventricular Contraction	Irregular Rhythm, Premature Ventricular Contraction	Correct

Table B.2: Data and Results for Specificity Test.

Record	Database	Physician Diagnosis	Model Diagnosis	Result
1	Normal Sinus Rhythm	Normal	Normal	Correct
2	Normal Sinus Rhythm	Normal	Normal	Correct
3	Normal Sinus Rhythm	Normal	Normal	Correct
4	Normal Sinus Rhythm	Normal	Normal	Correct
5	Normal Sinus Rhythm	Normal	Normal	Correct
6	Normal Sinus Rhythm	Normal	Normal	Correct
7	Normal Sinus Rhythm	Normal	Normal	Correct
8	Normal Sinus Rhythm	Normal	Normal	Correct
9	Normal Sinus Rhythm	Normal	Normal	Correct
10	Normal Sinus Rhythm	Normal	Normal	Correct
11	Normal Sinus Rhythm	Normal	Normal	Correct
12	Normal Sinus Rhythm	Normal	Normal	Correct
13	Normal Sinus Rhythm	Normal	Normal	Correct
14	Normal Sinus Rhythm	Normal	Normal	Correct
15	Normal Sinus Rhythm	Normal	Normal	Correct
16	Normal Sinus Rhythm	Normal	Normal	Correct
17	Normal Sinus Rhythm	Normal	Normal	Correct
18	Normal Sinus Rhythm	Normal	Normal	Correct
19	Normal Sinus Rhythm	Normal	Normal	Correct
20	Normal Sinus Rhythm	Normal	Normal	Correct
21	Normal Sinus Rhythm	Normal	Normal	Correct
22	Normal Sinus Rhythm	Normal	Normal	Correct
23*	Normal Sinus Rhythm	Normal	Sinus Tachycardia	Incorrectly Found Sinus Tachycardia
24	Normal Sinus Rhythm	Normal	Normal	Correct
25	Normal Sinus Rhythm	Normal	Normal	Correct
26	Normal Sinus Rhythm	Normal	Normal	Correct
27	Normal Sinus Rhythm	Normal	Normal	Correct
28	Normal Sinus Rhythm	Normal	Normal	Correct
29	Normal Sinus Rhythm	Normal	Normal	Correct
30	Normal Sinus Rhythm	Normal	Normal	Correct
31	Normal Sinus Rhythm	Normal	Normal	Correct
32	Normal Sinus Rhythm	Normal	Normal	Correct
33	Normal Sinus Rhythm	Normal	Normal	Correct
34	Normal Sinus Rhythm	Normal	Normal	Correct
35	Normal Sinus Rhythm	Normal	Normal	Correct
36	Normal Sinus Rhythm	Normal	Normal	Correct

Record	Database	Physician Diagnosis	Model Diagnosis	Result
37*	Normal Sinus Rhythm	Normal	Irregular Rhythm	Incorrectly Found Irregular Rhythm
38	Normal Sinus Rhythm	Normal	Normal	Correct
39	Normal Sinus Rhythm	Normal	Normal	Correct
40	Normal Sinus Rhythm	Normal	Normal	Correct
41	Normal Sinus Rhythm	Normal	Normal	Correct
42	Normal Sinus Rhythm	Normal	Normal	Correct
43	Normal Sinus Rhythm	Normal	Normal	Correct
44	Normal Sinus Rhythm	Normal	Normal	Correct
45	Normal Sinus Rhythm	Normal	Normal	Correct
46	Normal Sinus Rhythm	Normal	Normal	Correct
47	Normal Sinus Rhythm	Normal	Normal	Correct
48	Normal Sinus Rhythm	Normal	Normal	Correct
49	Normal Sinus Rhythm	Normal	Normal	Correct
50	Normal Sinus Rhythm	Normal	Normal	Correct
51	Normal Sinus Rhythm	Normal	Normal	Correct
52	Normal Sinus Rhythm	Normal	Normal	Correct
53	Normal Sinus Rhythm	Normal	Normal	Correct
54	Normal Sinus Rhythm	Normal	Normal	Correct
55	Normal Sinus Rhythm	Normal	Normal	Correct
56	Normal Sinus Rhythm	Normal	Normal	Correct
57	Normal Sinus Rhythm	Normal	Normal	Correct
58	Normal Sinus Rhythm	Normal	Normal	Correct
59	Normal Sinus Rhythm	Normal	Normal	Correct
60	Normal Sinus Rhythm	Normal	Normal	Correct
61	Normal Sinus Rhythm	Normal	Normal	Correct
62*	Normal Sinus Rhythm	Normal	Sinus Bradycardia	Incorrectly Found Sinus Bradycardia
63	Normal Sinus Rhythm	Normal	Normal	Correct
64	Normal Sinus Rhythm	Normal	Normal	Correct
65	Normal Sinus Rhythm	Normal	Normal	Correct
66	Normal Sinus Rhythm	Normal	Normal	Correct
67	Normal Sinus Rhythm	Normal	Normal	Correct
68	Normal Sinus Rhythm	Normal	Normal	Correct
69	Normal Sinus Rhythm	Normal	Normal	Correct
70	Normal Sinus Rhythm	Normal	Normal	Correct
71	Normal Sinus Rhythm	Normal	Normal	Correct
72	Normal Sinus Rhythm	Normal	Normal	Correct
73	Normal Sinus Rhythm	Normal	Normal	Correct
74*	Normal Sinus Rhythm	Normal	Irregular Rhythm	Incorrectly Found Irregular Rhythm

Record	Database	Physician Diagnosis	Model Diagnosis	Result
75	Normal Sinus Rhythm	Normal	Normal	Correct
76	Normal Sinus Rhythm	Normal	Normal	Correct
77	Normal Sinus Rhythm	Normal	Normal	Correct
78	Normal Sinus Rhythm	Normal	Normal	Correct
79	Normal Sinus Rhythm	Normal	Normal	Correct
80	Normal Sinus Rhythm	Normal	Normal	Correct
81	Normal Sinus Rhythm	Normal	Normal	Correct
82	Normal Sinus Rhythm	Normal	Normal	Correct
83	Normal Sinus Rhythm	Normal	Normal	Correct
84*	Normal Sinus Rhythm	Normal	Irregular Rhythm	Incorrectly Found Irregular Rhythm
85	Normal Sinus Rhythm	Normal	Normal	Correct
86	Normal Sinus Rhythm	Normal	Normal	Correct
87	Normal Sinus Rhythm	Normal	Normal	Correct
88	Normal Sinus Rhythm	Normal	Normal	Correct
89	Normal Sinus Rhythm	Normal	Normal	Correct
90	Normal Sinus Rhythm	Normal	Normal	Correct
91	Normal Sinus Rhythm	Normal	Normal	Correct
92	Normal Sinus Rhythm	Normal	Normal	Correct
93	Normal Sinus Rhythm	Normal	Normal	Correct
94	Normal Sinus Rhythm	Normal	Normal	Correct
95	Normal Sinus Rhythm	Normal	Normal	Correct
96	Normal Sinus Rhythm	Normal	Normal	Correct
97	Normal Sinus Rhythm	Normal	Normal	Correct
98	Normal Sinus Rhythm	Normal	Normal	Correct
99	Normal Sinus Rhythm	Normal	Normal	Correct
100	Normal Sinus Rhythm	Normal	Normal	Correct
101	Normal Sinus Rhythm	Normal	Normal	Correct
102	Normal Sinus Rhythm	Normal	Normal	Correct
103	Normal Sinus Rhythm	Normal	Normal	Correct
104	Normal Sinus Rhythm	Normal	Normal	Correct
105	Normal Sinus Rhythm	Normal	Normal	Correct
106	Normal Sinus Rhythm	Normal	Normal	Correct
107	Normal Sinus Rhythm	Normal	Normal	Correct
108	Normal Sinus Rhythm	Normal	Normal	Correct
109	Normal Sinus Rhythm	Normal	Normal	Correct
110	Normal Sinus Rhythm	Normal	Normal	Correct
111	Normal Sinus Rhythm	Normal	Normal	Correct
112	Normal Sinus Rhythm	Normal	Normal	Correct
113	Normal Sinus Rhythm	Normal	Normal	Correct
114	Normal Sinus Rhythm	Normal	Normal	Correct
115	Normal Sinus Rhythm	Normal	Normal	Correct

Record	Database	Physician Diagnosis	Model Diagnosis	Result
116	Normal Sinus Rhythm	Normal	Normal	Correct
117	Normal Sinus Rhythm	Normal	Normal	Correct
118	Normal Sinus Rhythm	Normal	Normal	Correct
119	Normal Sinus Rhythm	Normal	Normal	Correct
120	Normal Sinus Rhythm	Normal	Normal	Correct
121	Normal Sinus Rhythm	Normal	Normal	Correct
122	Normal Sinus Rhythm	Normal	Normal	Correct
123	Normal Sinus Rhythm	Normal	Normal	Correct
124	Normal Sinus Rhythm	Normal	Normal	Correct
125	Normal Sinus Rhythm	Normal	Normal	Correct
126	Normal Sinus Rhythm	Normal	Normal	Correct
127	Normal Sinus Rhythm	Normal	Normal	Correct
128	Normal Sinus Rhythm	Normal	Normal	Correct
129*	Normal Sinus Rhythm	Normal	Irregular Rhythm	Incorrectly Found Irregular Rhythm
130	Normal Sinus Rhythm	Normal	Normal	Correct
131	Normal Sinus Rhythm	Normal	Normal	Correct
132	Normal Sinus Rhythm	Normal	Normal	Correct
133	Normal Sinus Rhythm	Normal	Normal	Correct
134	Normal Sinus Rhythm	Normal	Normal	Correct
135	Normal Sinus Rhythm	Normal	Normal	Correct
136	Normal Sinus Rhythm	Normal	Normal	Correct
137	Normal Sinus Rhythm	Normal	Normal	Correct
138	Normal Sinus Rhythm	Normal	Normal	Correct
139	Normal Sinus Rhythm	Normal	Normal	Correct
140	Normal Sinus Rhythm	Normal	Normal	Correct
141	Normal Sinus Rhythm	Normal	Normal	Correct
142	Normal Sinus Rhythm	Normal	Normal	Correct
143	Normal Sinus Rhythm	Normal	Normal	Correct
144	Normal Sinus Rhythm	Normal	Normal	Correct