UNDERSTANDING AND IMPLEMENTING DIFFERENT MODES OF PACEMAKER

By

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Abstract

The Heart is a specialized muscle that contracts regularly and continuously, pumping blood to the body and the lungs. Heart's natural Pacemaker, the SA node is responsible for this pumping action by causing a flow of electricity through the heart. These electrical impulses cause the atria and ventricles to contract and thereby pump the blood to different parts of the body. Malfunction of the SA node leads to a disturbance in the heart's rhythm in which heart beats lower than 60 times a minute ending up with Bradycardia. It also leads to ventricular arrhythmia which disrupts the ability of the ventricles to pump blood effectively to the body. This can cause a loss of all blood pressure leading to cardiac arrest and eventually death. In order to restore the heart's natural healthy rhythm, an artificial pacemaker is necessary. A Pacemaker adapts to the present condition of the heart and responds to the heart by either pacing or just sensing it. It paces whenever there is some problem in the heart's electrical activity and inhibits the pace when there is a proper intrinsic beat. There are various modes in which Pacemaker can operate based on the condition of the heart. Ventricles and atria are individually paced in few modes such as VOO, VVT, VVI, AOO, AAT, and AAI and paced together in some modes such as DVI, DI, DDD, DDDR as per the requirement of the heart. The main goal of this report is to understand the various modes, their nomenclature, working strategy, developing the pseudo code and implementing different modes namely VOO, AOO, VVI, AAI, VVT and AAT modes using an academic, dual chamber pacemaker.

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I would like to express my appreciation to my committee members, **Dr. Mitchell Neilsen** and **Dr. Robby** for accepting to serve on my committee. It was a privilege to be able to take courses under you, which provided me with more practical guidance and experience.

I am grateful to **Brian Larson,** for his constant support through his suggestions and ideas throughout my project.

Dedication

To God, my parents and my friends. Without you, this would not have been possible.

God, you have given me the will power to handle any situation in the life. Thank you.

Mom and Dad, you are my role models. Without, you I would not be able to make it.

Special Thanks to my friends, Ravi Teja, Monica Kishore, Navya Deepthi, Marrapu Surya.

Chapter 1 - Introduction

The heart, one of the most significant organs in the human body, is nothing but a muscular pump, which pumps blood throughout the body. The heart beats approximately 72 times per minute, and pumps blood, carrying vital nutrients required by the body. A normal resting heart rate ranges from 60 to 100 beats a minute. Heart’s electrical system makes the atria and ventricles to contract by which the blood is pumped to various parts of the body. If there is some problem with the heart’s electrical system, the heart beats lower than 60 times per minute which leads to death. This brings an artificial Pacemaker into the picture. A Pacemaker is a medical device that uses electrical impulses, delivered by electrodes contacting the heart muscles, to regulate the beating of the heart. So, if the heart does not generate a pulse with in every defined time interval, pacemaker generates an electrical pulse which helps the aria and ventricles to contract and pump the blood. This pacemaker is operated using different modes based on the requirement for the patient. If the patient is suffering from Bradycardia or arrhythmia, the patient’s heart should be operated by a pacemaker.

The rest of the paper discusses about the heart and its functionality in Chapter 2; then pacemaker and its components in Chapter 3; Different operating modes of pacemaker in Chapter 4 then followed by implementation of these modes in Chapter 5; followed by conclusion and future work of the project in chapter 6.

1.1 Goal:

The principle goal of this project is to understand the necessity of pacemaker, its various operating modes and simulate the VOO, VVT and VVI modes by using the pacemaker board, Pickit 2 Debugger/ Programmer and NI USB-6008.

1.2 Motivation:

Electronic pacemakers play a vital role in today's society, providing approximately half a million people with a better quality and prolonged life. Numerous advancements have been made in pacemaker technology over the last fifty years, making current pacemakers highly sophisticated cardiac rhythm managers capable of correcting a myriad of complex heart abnormalities. The primary function of a typical pacemaker is to sense a person's heartbeat, and pace the heart via electric stimulation when irregularities are detected. There has been good research on implementing different pacemakers initially on a simulation mode and then expanding them to the real world. This motivated me to work on this project.

1.3 Challenges:

The main challenge was to understand how to setup the hardware, sensing and pacing circuits, acquiring signals and generating output. For doing this, I had to go through different tutorials of MPLAB IDE, Pickit 2, Pacemaker Specification, NI Lab view Signal Express, NI USB-6008. To implement the code, I had to study about the working methodology of PIC Microcontroller, Pickit 2 debugger/programmer, MCC compiler, External and Timer Interrupts in PIC18. Understanding the various timing cycles in modes operating on dual chambers was also a difficult task.

Chapter 2 - Heart and its Background

The human heart is a muscular organ that provides a continuous blood circulation through the cardiac cycle and is one of the most vital organs in the human body. The human heart resembles the shape of an upside down pear, weighing between 7-15 ounces, and is little larger than the size of the fist. It is located between the lungs that are in the middle of the chest, behind and slightly to the left of the sternum or breast bone. The heart beats approximately 72 times per minute, and pumps blood, carrying vital nutrients required by the body. The pumped blood also removes waste products from the body. It usually beats from 60 to 100 times per minute, but can go much faster when necessary. It beats about 100,000 times a day, more than 30 million times per year, and about 2.5 billion times in a 70-year lifetime.

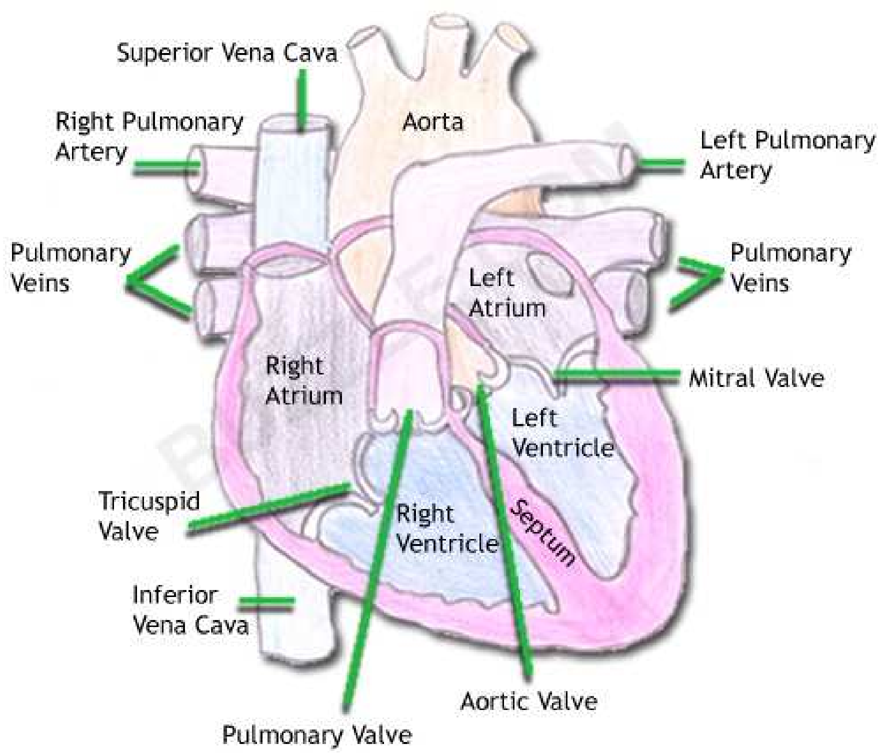

Figure2.1 A Labeled Diagram of the Human Heart

(www.buzzle.com)

The heart comprises four chambers. The two upper chambers are called the left and the right atria, and the two lower chambers are known as the left and the right ventricles. The two atria and ventricles are separated from each other by a muscle wall called 'Septum'. The right atrium is larger than the left one, and has thinner walls as compared to the left atrium. The left ventricle on the other hand is the strongest and largest chamber in the heart. The tricuspid valve separates the right atrium from the right ventricle, and the mitral valve separates the left atrium and the left ventricle.

After the body organs and tissues have used the oxygen in your blood, the superior and inferior vena cava carry the oxygen-poor blood back to the right atrium of your heart. The oxygen-poor blood from the vena cava flows into your heart's right atrium and then on to the right ventricle. From the right ventricle, the blood is pumped through the right and left pulmonary arteries to your lungs. There, through many small, thin blood vessels called capillaries, the blood picks up more oxygen. Oxygen-rich blood from your lungs passes through the pulmonary veins. It enters the left atrium and is pumped into the left ventricle. From the left ventricle, the oxygen-rich blood is pumped to the rest of your body through the aorta. Your blood carries the oxygen and nutrients that your organs need to work normally. Again the oxygen poor blood is collected by the vena cava and is carried back to the right atrium of the heart. The entire process repeats again and again.

2.1 Electrical System of Heart:

Heart's electrical system includes three important parts:

- **S-A node (sinoatrial node)** — known as the heart's natural pacemaker, the S-A node has special cells that create the electricity that makes your heart beat.
- **A-V node (atrioventricular node)** — the A-V node is the bridge between the atria and ventricles. Electrical signals pass from the atria down to the ventricles through the A-V node.
- **His-Purkinje system** — the His-Purkinje system carries the electrical signals throughout the ventricles to make them contract. The parts of the His-Purkinje system include:
  - His Bundle (the start of the system)
  - Right bundle branch
  - Left bundle branch
  - Purkinje fibers (the end of the system)

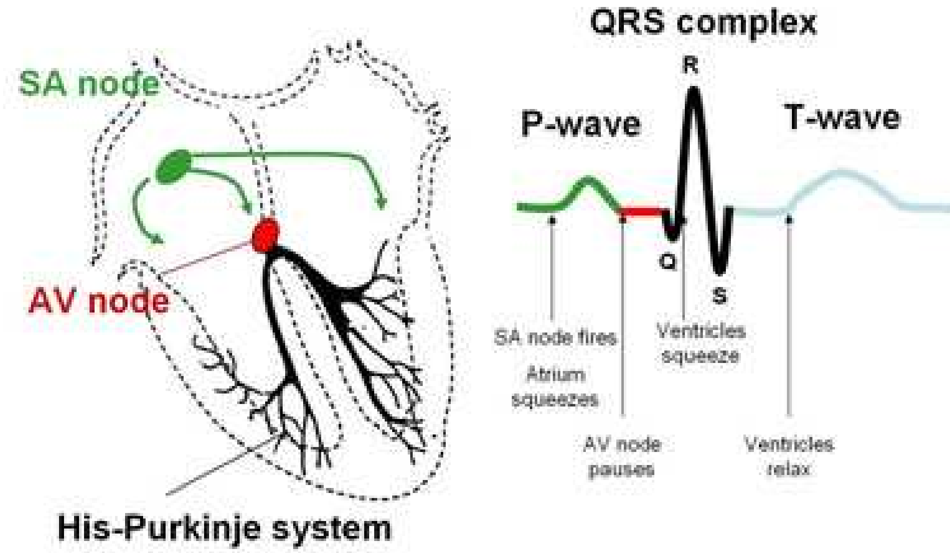

Figure2.2 Electrical system and corresponding ECG

(Boston Scientific)

The signal in SA node is generated as the two vena cava fill your heart's right atrium with blood from other parts of your body. This signal causes the atria to contract. This action pushes blood through the open valves from the atria into both ventricles. The P wave on the ECG marks the contraction of your heart’s atria. The signal arrives at the AV node near the ventricles. It slows for an instant to allow your heart's right and left ventricles to fill with blood. On an ECG, this interval is represented by the start of the line segment between the P and Q wave. The signal is released and moves along a pathway called the bundle of His, which is located in the walls of your heart's ventricles. From the bundle of His, the signal fibers divide into left and right bundle branches through the Purkinje fibers that connect directly to the cells in the walls of your heart's left and right ventricles. On the ECG, this is represented by the Q wave. The signal spreads across the cells of your ventricle walls, and both ventricles contract. On ECG, the R wave marks the contraction of left ventricle and S wave represents the contraction of right ventricle. The contraction of left ventricle pushes blood into the aortic valve, then to aorta and to all the parts of the body. The contraction of right ventricle pushes the blood into the pulmonary valve, then to pulmonary arteries and to the lungs. On the ECG, the T wave marks the point at which your heart’s ventricles are relaxing. Now the deoxygenated blood is brought back by the vena cava to the right atrium and again the SA node is ready to generate an electrical impulse.

In a normal, healthy heart, each beat begins with a signal from the SA node. This is why the SA node is sometimes called your heart's natural pacemaker. Your pulse, or heart rate, is the number of signals the SA node produces per minute. Heart’s conduction system senses need for oxygen and responds with the proper heart rate. A problem in your heart's electrical system can disrupt your heart's normal rhythm. Any kind of abnormal rhythm or heart rate is called an arrhythmia. Any disease of the heart (cardio) and blood vessels (vascular) is called cardiovascular disease (CVD). Many of these problems have similar names, like heart failure and heart attack, Bradycardia and tachycardia.

2.2 Necessity of a pacemaker:

Heart has a natural pacemaker (SA node) which may not work at times. Generally heart beats between 60 and 100 times a minute. Heart beat fewer than 60 times a minute is Bradycardia. Pacemaker comes into existence when a person is suffering from Bradycardia. As a result, your heart may not pump enough blood to meet your body's needs, and you may feel tired or dizzy.

Normally, the SA node automatically maintains a heart rate adequate for your body’s needs - for example, heart rate decreases during sleep and increases during exercise to match your body’s need for oxygen. But there are conditions which cause heart to pump slowly. They are:

- Sinus Bradycardia: The signals coming from the SA node may be too slow.
- Sick Sinus Syndrome: The signals coming from SA node may alter between being too fast and too slow.
- Sinus pause or Sinus arrest: The signals coming from SA node may occasionally stop.
- Heart Block: The signals from may form normally in the sinus node but fail to transmit from the upper to the lower chambers.

All the above conditions cause the heart to pump too slowly. This can cause symptoms such as dizziness or fainting. Pacemakers are usually recommended in these situations. Artificial pacing helps to restore the heart rhythm towards normal improving the heart's ability to circulate blood through the body.

Chapter 3 - Pacemaker and its components

A pacemaker is a small device that's placed in the chest or abdomen to help control abnormal heart rhythms. A pacemaker system consists of two main parts: the pulse generator and pacing leads.

Pulse Generator: The pulse generator houses the battery and electronic circuits (like a small computer). These circuits contain timers that regulate how often the pacemaker must send impulses to stimulate the heart. The pulse generator is small, measuring approximately 2" x 2" x 1/4" (45mm x 45mm x 6mm) and weighing less than 2 ounces (20-30g). The generator consists of two parts: the power supply or batteries send the electronic circuitry. The majority of pulse generators are powered by lithium type. These last longer than the mercury type batteries which were used previously.

Leads: The pacing leads are flexible, insulated wires that connect to the pulse generator and carry the electronic impulse to the heart. In addition, the leads also carry signals back from the heart to the pulse generator allowing the pulse generator to sense the heart's natural electrical activity.

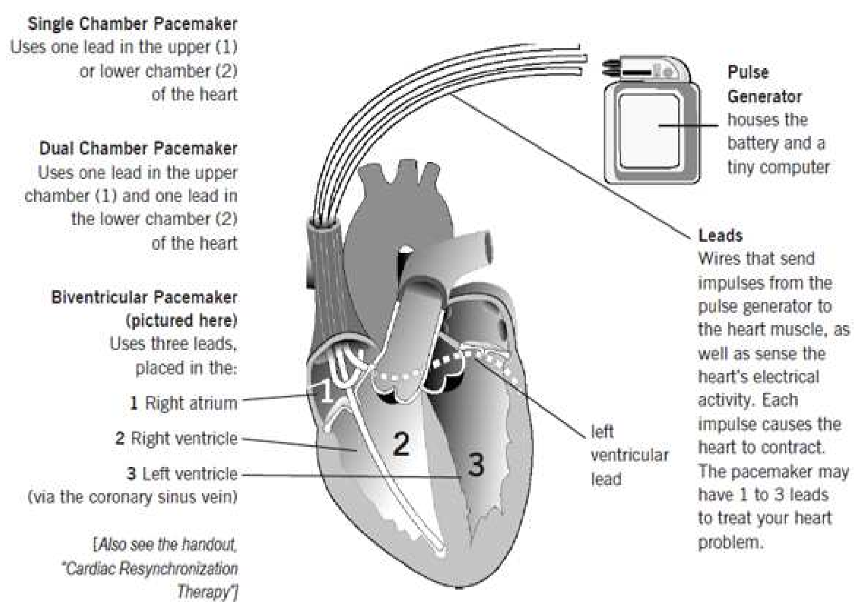

Figure3.1 Pacemaker and its components

(http://my.clevelandclinic.org/heart/services/tests/procedures/pacemaker.aspx)

3.1 Types of pacemaker:

There are three types of Pacemakers based on the number of leads inserted:

3.1.1 Single Chamber Pacemaker

This pacemaker uses one lead in the upper chamber (Right Atrium) or lower chamber (Right Ventricle) of the heart. A single lead in the right atrium is commonly used in conditions where the normal pacemaker of the heart is not working adequately, such as in the case of sick sinus syndrome. Atrial pacing is used when the sinus node is sending out signals that are too slow or irregular. However, to use this method of pacing, the rest of the heart's normal conduction system must be functioning normally.

More commonly, the single lead is placed in the right ventricle to help correct a slow or irregular heartbeat. This is most often the case when the electrical flow is slowed or blocked in the region of the atrio-ventricular (A-V) node and the normal impulses from the atria cannot reach the ventricle. This would result in too slow a heartbeat. The pacemaker system would keep the heart beating at a steady rate.

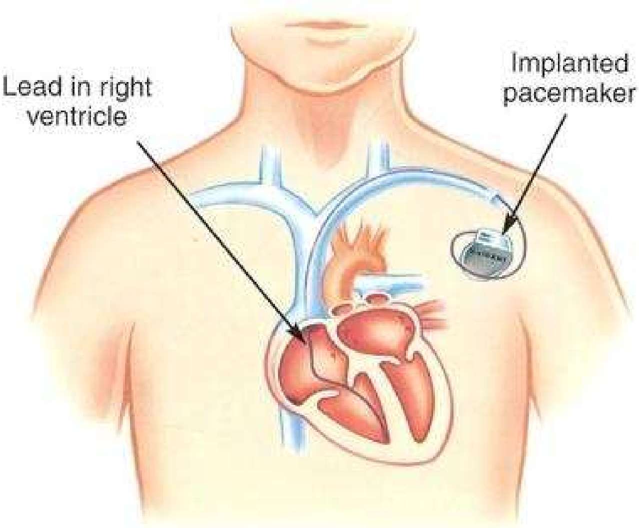

Figure3.2 Single Chamber Pacemakers

(http://www.mercyangiography.co.nz/PatientInfo/OurProcedures/Pacemakers.aspx)

3.1.2 Dual chamber Pacemaker:

This Pacemaker uses one lead into the upper chamber and one lead in the lower chamber of the heart. This type of pacing most closely mimics the heart's normal conduction pattern by pacing sequentially from atria to ventricle thus maximizing the heart's pumping ability. By having a lead in both the atria and ventricle the pulse generator is able to continuously regulate the heart's electrical activity in both chambers. These are the most commonly used pacemakers at the present time.

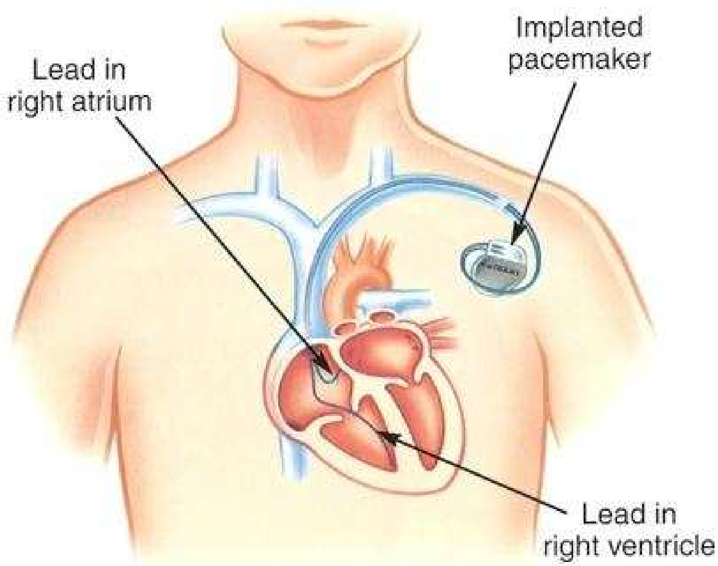

Figure3.3 Dual Chamber Pacemakers

(http://www.mercyangiography.co.nz/PatientInfo/OurProcedures/Pacemakers.aspx)

3.1.3 Bi Ventricular Pacemaker:

In the normal heart, the heart's lower chambers (ventricles) pump at the same time and in sync with the heart's upper chambers (atria). When a person has heart failure, often the right and left ventricles do not pump together. And when the heart's contractions become out of sync, the left ventricle is not able to pump enough blood to the body.

This eventually leads to an increase in heart failure symptoms, such as shortness of breath, dry cough, swelling in the ankles or legs, weight gain, increased urination, fatigue, or rapid or irregular heartbeat. Cardiac resynchronization therapy (CRT), also called biventricular pacing, uses a special kind of pacemaker, called a biventricular pacemaker, designed to help the ventricles contract more normally. It keeps the right and left ventricles pumping together by sending small electrical impulses through the leads. This therapy has been shown to improve the symptoms of heart failure and overall quality of life in certain patients with significant symptoms that aren't controlled with medication. This Pacemaker uses three leads 1 into upper chamber 2 into lower chamber and 3 in the left ventricle.

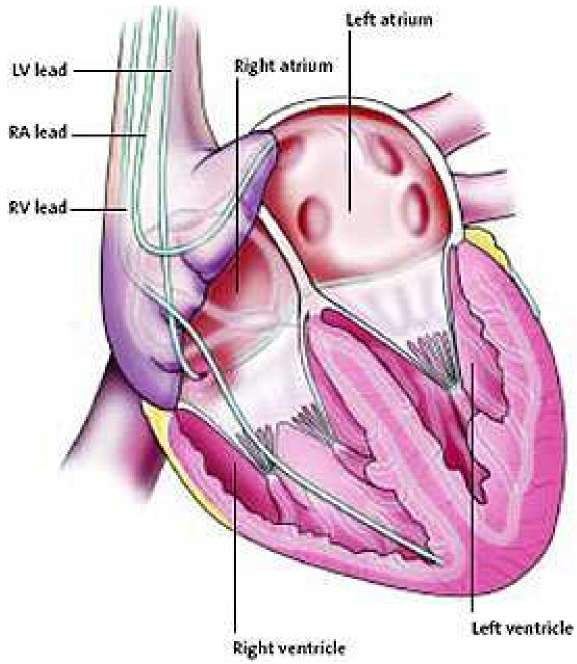

Figure3.4 Bi Ventricular Pacemakers

(http://www.columbiasurgery.org/news/research/2006_biventricular.html)

3.2 Pacing and Sensing of Pacemaker

Pacing and Sensing system of pacemaker work together to make the disturbed heartbeat at a more normal rate.

3.2.1 Pacing

Pacing is when a pacemaker sends tiny electrical signals to the heart through a pacing lead. Each tiny electrical signal is called a pacing pulse (pacing impulse, pace). This impulse travels through the insulated wires of a pacing lead until it reaches the metal electrode at the tip of the lead. The electrode, which is in direct contact with the heart, delivers the electrical impulse to the heart. The pacemaker paces (sends a pacing pulse to) the heart when the heart's own rhythm is interrupted, irregular, or too slow. A pacemaker may also sense (monitor) the hearts natural electrical activity. If a pacemaker senses a natural heartbeat, it will not deliver a pacing pulse to the heart. Here comes the concept of Sensing.

3.2.2 Sensing

Only by Sensing, a pacemaker will get to know when to send a pacing impulse. The pacing pulses are timed so that the heart beats in a manner very similar to a naturally occurring heart rhythm. For some pacemakers, this timing is exactly the same for each heartbeat. In other pacemakers, the timing is based on when the heart beats on its own. For these pacemakers, information about the heart's own electrical activity is sent back to the pacemaker through an electrode on the lead. This is called sensing. The heart’s intrinsic electrical activity (i.e. the P wave or QRS complex) transmits a small electrical current (a few mill volts), through the pacemaker leads, to the pulse generator. This current can be registered or sensed by the pacemaker circuitry. Pacemaker sensing describes the response of a pacemaker to intrinsic heartbeats. The P waves, or atrial activity, are transmitted through the atrial lead (if present) to the atrial channel of the pacemaker, and sensed as atrial activity. Ventricular activity (the QRS complex) is transmitted through the ventricular lead (if present) to the ventricular channel of the pacemaker, and this is sensed as ventricular activity. For electrical activity to be transmitted from the heart to the pacemaker, a closed electrical circuit must be present, just the same as for an electrical impulse to be transmitted from the pacemaker to the heart. If the pacemaker circuitry determines that the heart is beating too slowly, a pacing pulse is sent to start a heartbeat. If it determines that the heart is beating at a proper rate, the pacing pulse is withheld.

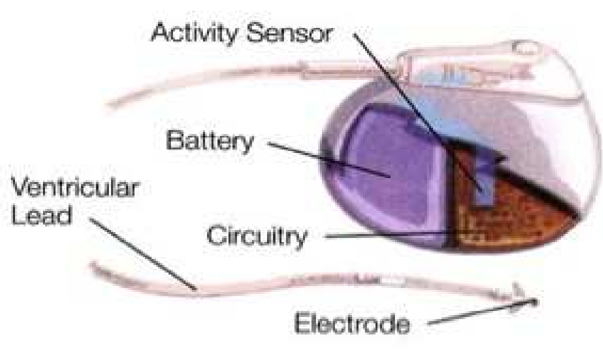

Figure3.5 Pacemaker showing a lead, Activity Sensor, circuitry and battery

(http://www.brighamandwomens.org/departments_and_services/medicine/services/)

3.3 Types of Pacemaker Programming

The three main types of programming for pacemakers are fixed-rate pacing, demand pacing and rate-responsive pacing.

- A Fixed-rate pacemaker discharge impulses at a single, steady rate, regardless of the heart's own electrical activity. A fixed-rate pacemaker cannot detect intrinsic heartbeats and will emit electrical impulses at the same time that the hearts own pacemaker fires, causing the competitive beats. Once thought to be harmless, competitive beats have been associated with higher mortality rates and health problems in pacemaker patients.
- A Demand pacemaker monitors your heart rhythm. It only sends electrical pulses to your heart if your heart is beating too slowly or if it misses a beat. The advantage of a demand pacemaker over Fixed-rate pacemakers is that they prevent the occurrence of what are known as competitive beats. Another advantage of the demand pacemaker is that firing less often allows it to reserve its battery power for a much longer period of time than fixed rate pacemakers.
- A Rate-responsive pacemaker will speed up or slow down your heart rate depending on how active you are. Rate-responsive pacemakers can use one of several technologies to determine the optimal heart rate, but two in particular have proven quite useful.

  ✓ One of these is the activity sensor, which detects body movement. The more active you are, the faster the pacemaker will pace your heart

  ✓ The other method commonly used to vary the rate of pacing is a breathing sensor, which measures your rate of breathing. The faster your breathing, the more active you are (presumably), and faster the pacing (again, within a pre-set range).

  Either of these technologies allows rate-responsive pacemakers to mimic the normal, moment-to-moment changes in heart rate provided by a normal heart rhythm.

Chapter 4 – Operating modes of pacemaker

4.1 Pacing Codes and Nomenclature

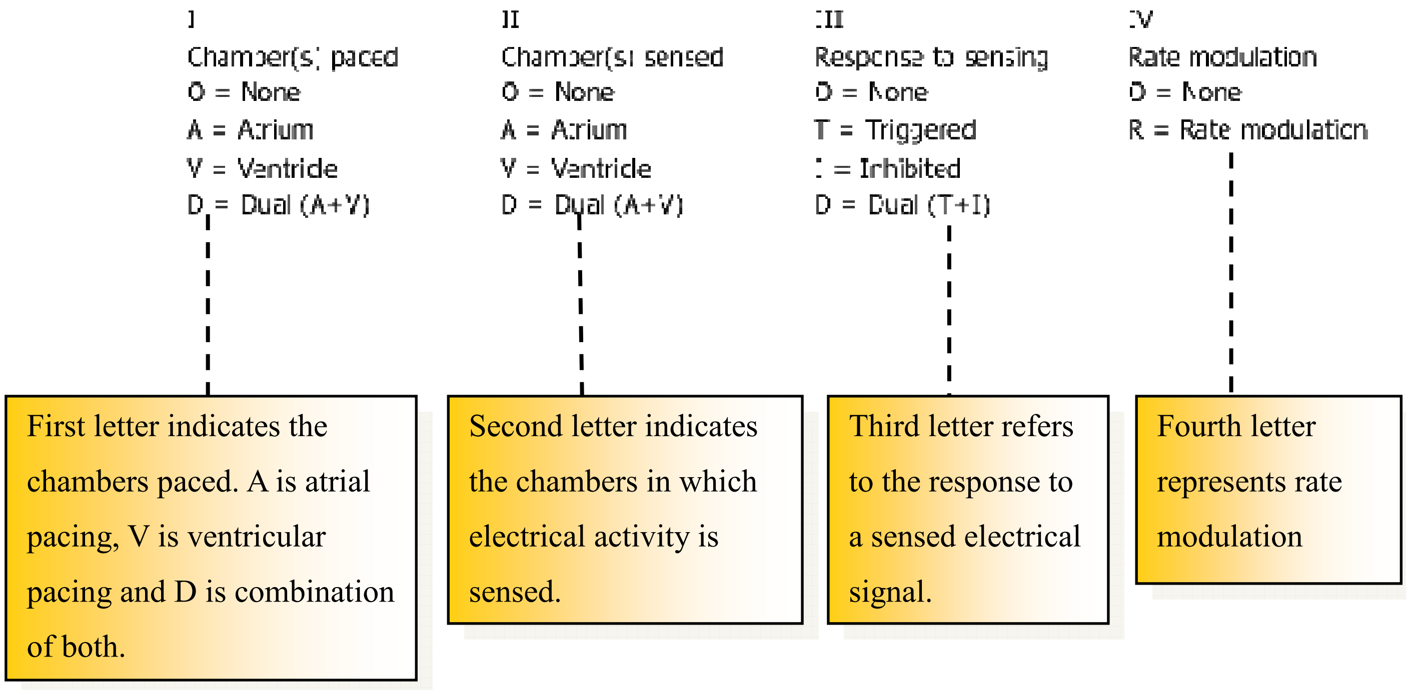

Figure4.1 Pacing Codes

- **First Letter:** The First Letter in any mode of pacemaker indicates the chamber that is being paced. This means, pacing can be done only in atrium or only in ventricle or both in atrium and ventricle or neither in both the chambers. So, it can take A, V, D or O where A stands for atrium, V stands for Ventricle, D stands for Dual(both in atrium and ventricle) and O stands for none.

- **Second Letter:** The Second Letter in any mode of pacemaker indicates the chamber that is being sensed. This means, sensing can be done, only in atrium or only in ventricle or both in atrium and ventricle or neither in both the chambers. So, it can take A, V, D or O where A stands for atrium, V stands for Ventricle, D stands for Dual(both in atrium and ventricle) and O stands for none.

- **Third Letter:** Third Letter refers to the response to a sensed electrical signal. The Third Letter in any mode of pacemaker indicates whether a pace is inhibited or triggered. Inhibition of pace is done when there is an intrinsic beat heard in the chamber and a new timing cycle starts. In Triggered mode, stimulus is emitted in one chamber in response to a sensed event in the other chamber. So, it can take I, T, D or O where I stands for inhibition of pace in the chambers sensed, T stands for triggering in the chambers sensed, D stands for Dual(Inhibition +Trigger) and O stands for none.

- **Fourth Letter:** The Fourth Letter in any mode of pacemaker represents the rate modulation. So, it can take R or O where R stands for rate modulation and O stands for no rate modulation. A Rate-responsive pacemaker implements these rate-responsive modes.

4.2 Basic Concepts of pacemaker programming:

1. **Timing Intervals versus Rate:** Timing Interval is expressed in milliseconds (ms) and Rate is expresses in beats per minute (bpm).
   Conversion Formula:
   - Interval (in ms) =60,000/Rate (in bpm)
   - Rate (in bpm) =60,000/Interval (in ms)

   A Pacemaker rate of 60bpm gives an interval of 1000ms.

2. **Lower Rate Limit:** Lower Rate Limit is the window of time in which there should be a heartbeat. In AOO or VOO (asynchronous) mode, this is the rate at which the pacemaker will pace. In AAI, or VVI mode, this is the rate at which the pacemaker will pace, unless it is inhibited by intrinsic beats occurring at a faster rate. Generally LRL rate is set for 60beats/min or LRL interval is 1000ms. Within this 1000msec, there should be a pace unless pacemaker senses some intrinsic activity. LRI may start after a ventricular event or atrial event depending on the mode of pacemaker.

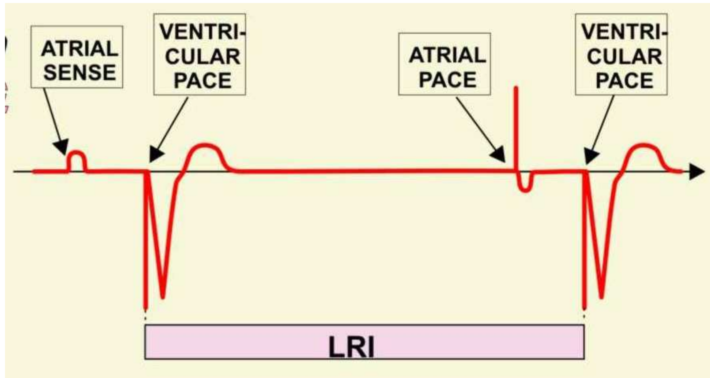

Figure4.2 Lower Rate Interval

(Cardiac Pacemakers and Resynchronization Step-by-Step)

3. **AVI:** The AVI is the time interval between an atrial paced or sensed event, and the delivery of a ventricular pacing stimulus. Because it involves events in two chambers, it is a programmable parameter in dual chamber pacemakers, but is not found in single chamber pacemakers. It is analogous to the intrinsic PR interval, in that it allows time for atrial contraction, and active ventricular filling, before ventricular contraction occurs. There are two types of AVI: sensed AVI and paced AVI. The terms "sensed" and "paced" refer to events in the atrium.

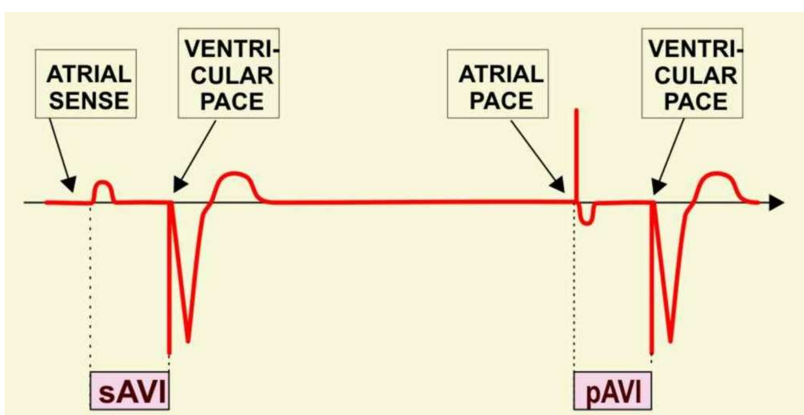

Figure4.3 sAVI after a sensed atrial event and pAVI after a paced atrial event

(Cardiac Pacemakers and Resynchronization Step-by-Step)

- **Paced AV-Delay (PAVI):** The AV-Delay is called Paced AV-Delay when the AV-Delay is started by an atrial pace.
- **Sensed AV-Delay (SAVI)**: The AV-Delay is called Sensed AV-Delay when the AV-Delay is started by an atrial sense.

4. **Atrial Escape Interval (AEI) or Ventricular-atrial interval (VAI):** The AEI is the time period from a ventricular event (Intrinsic or paced) to an atrial pace. Atrial pace takes place only when there is no intrinsic atrial event with in the programmed Ventricular-atrial interval.

AEI=LRL-AVI.

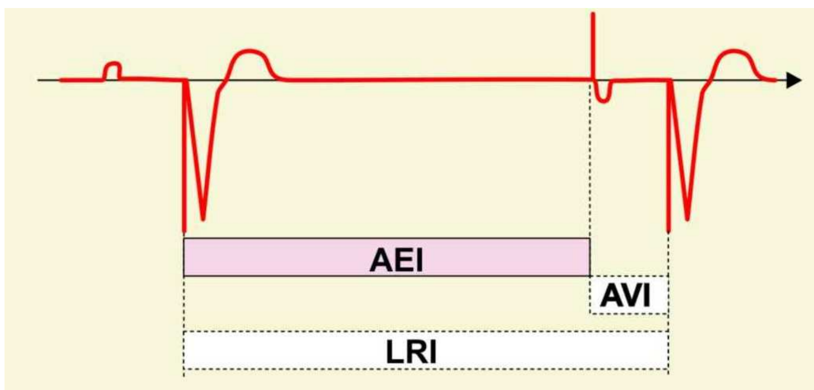

Figure4.4 Atrial Escape Interval

(Cardiac Pacemakers and Resynchronization Step-by-Step)

5. **Ventricular Refractory Period (VRP):** VRP is the time interval following a ventricular event (sensed or paced) during which signals in the ventricle are not sensed and lower rate interval is not reset even though a signal is detected. The pacemaker's sensing circuit does not respond to sensed events during this interval. The pacemaker is rendered insensitive to incoming signals. More advanced, modern pacemakers may sense during this period and use the information gathered to dictate some future activity. Typical values for the VRP are 200–350ms.

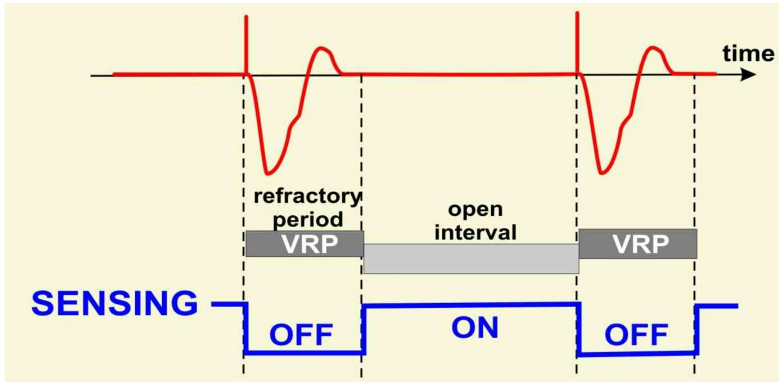

Figure4.5 Ventricular Refractory Period

(Cardiac Pacemakers and Resynchronization Step-by-Step)

6. **Atrial Refractory Period (ARP):** ARP is the time interval following an atrial event (sensed or paced) during which signals in the atrium are not sensed.

7. **Post Ventricular Atrial Refractory Period (PVARP):** PVARP is the time interval following a ventricular event (sensed or paced) during which signals in the atrium are not sensed.

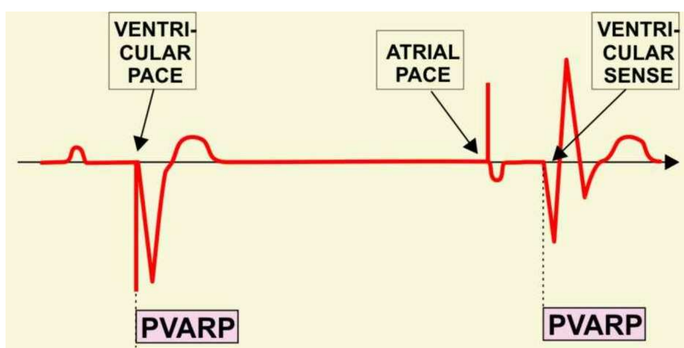

Figure4.6: Post Ventricular Refractory Period

(Cardiac Pacemakers and Resynchronization Step-by-Step)

8. **Total Atrial Refractory Period (TARP):** AVI and PVARP together form the Total Atrial Refractory Period.

TARP= AVI+PVARP

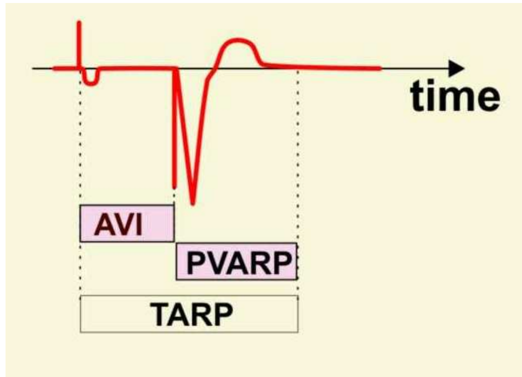

Figure4.7 : Total Atrial Refractory Period

(Cardiac Pacemakers and Resynchronization Step-by-Step)

9. **Upper Rate Interval (URI):** URI is used to limit the maximal rate at which the pacemaker can pace. The URI is the shortest period allowable between paced or sensed events, while still maintaining one-to-one (1:1) atrioventricular (AV) synchrony. 1:1 AV synchrony means that for every atrial beat there is a corresponding ventricular beat. The URI is the minimum time between a ventricular event and the next ventricular pace. URI interval turns out to be Total refractory atrial period. So with in this interval if a Ventricular pace occurs, it is ignored and a VP occurs only when URL interval expires. If this is not done, there can be many Ventricular paces continuously one after another which would rise the heart beat to more than 100 times. This situation is called Ventricular Tachycardia which may lead to Ventricular Defibrillation and finally to death.

URI= TARP= AVI+PVARP

Interval	Abbr.	Starts with:	Ends with:	Purpose
Lower rate interval	LRI	P or S ventricular event	Next P or S ventricular event	Sets the minimal number of beats per minute
Upper rate interval	URI	P or S ventricular event	Next P or S ventricular event	Sets the maximal number of beats per minute
Ventricular refractory period	VRP	P or S ventricular event	Timed out	Prevents crosstalk, oversensing, and undersensing
Atrioventricular interval	AVI	P or S atrial event	Either a S QRS complex or a P ventricular beat.	Mimics AV conduction, analogous to P–R interval. Provides time for ventricle to fill following an atrial contraction.
Ventriculoatrial interval	VAI	P or S ventricular event	P or S atrial event	Ensures an atrial pulse following a ventricular pulse.
Postventricular atrial refractory period	PVARP	P or S ventricular event	Timed out	Ensures atrium doesn't falsely sense ventricular activity
Total atrial refractory period	TARP	P or S atrial event	Completion of PVARP	Ensures atrium doesn't falsely sense ventricular activity

Figure4.8 : All Time intervals

Now, let us see the different modes of pacemaker.

4.3 Pacemaker Modes:

4.3.1 VOO MODE:

VOO mode: Pace Ventricle   Sense nothing   No response

Ventricular asynchronous (VOO) pacing is the simplest of all pacing modes because there is neither sensing nor mode of response. In VOO mode, Lower rate interval starts at a ventricular pace. Irrespective of any other events, the ventricular pacing occurs at the programmed Lower rate interval (LRI) and after this pace a new LRI starts. This cycle repeats and as there is no sensing, although if there is an intrinsic activity in the heart, it is ignored. The timing cycle cannot be reset by any intrinsic event. In the absence of sensing, there is no defined Ventricular refractory period (VRP).

In the Fig 4.9, we can clearly observe that an intrinsic QRS complex occurs after the second paced complex, but because there is no sensing in the VOO mode, the interval between the second and the third paced complex remains stable, which means LRI is not reset even though there was an intrinsic QRS complex.

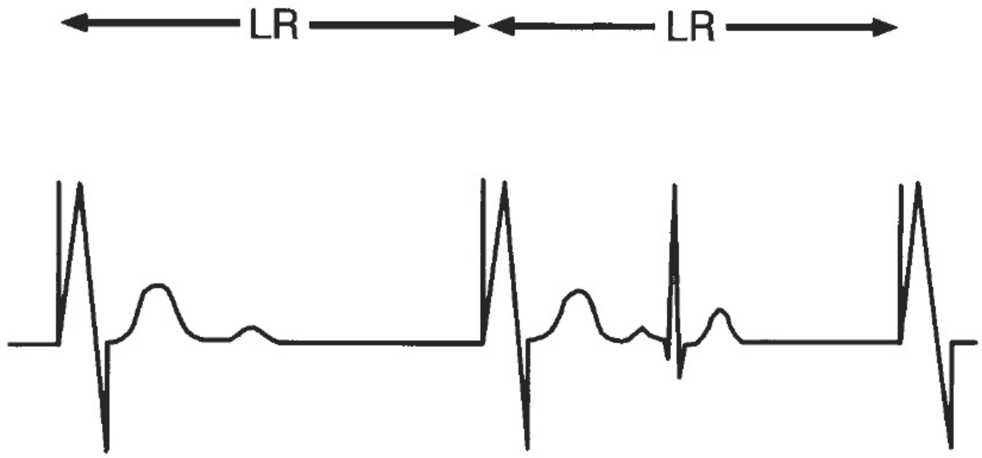

Figure4.9 : Timing Cycle of VOO mode

(http://www.blackwellpublishing.com/content/BPL_Images/)

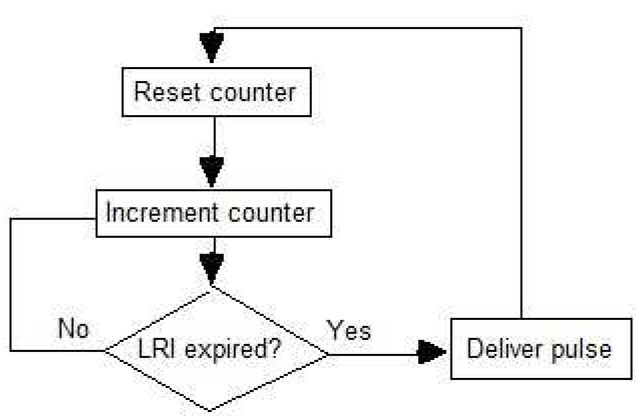

Figure4.10 : Flow chart of VOO mode

In this mode, because of continuous pacing on the ventricle, there will be extra beat which can be heard. Now pacemaker paced on the T wave of the extra beat causing an overlap of R wave on T wave which leads to Ventricular tachycardia (VT) as shown in Fig 4.11. Ventricular tachycardia (VT) is a rapid heartbeat that starts in the ventricles which can cause fainting or cardiac arrest and death. The entire point of a pacemaker sensing is to avoid R-on-T. When you select an asynchronous pacing mode such as VOO you are the sensor. The pacemaker is NOT sensing the electrical activity of the heart. You are responsible for sensing. If you detect extra beats, turn the pacing mode to one that senses such as DDD or VVI. So, never leave a person in VOO mode.

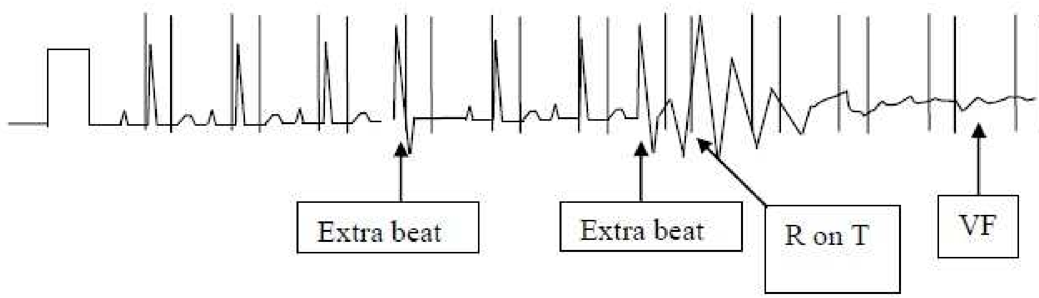

Figure4.11 : ECG showing an overlap of R on T waves causing Ventricular Tachycardia
(http://www.cardiacengineering.com/pacemakers-wallace.pdf)

4.3.2 AOO MODE:

AOO mode: Pace atrium   Sense nothing   No response

AOO mode is similar to VOO mode in all aspects except pacing is done in atrium. In this mode, the atrium is paced after every lower rate interval. The Lower rate interval starts as atrium is paced and as soon as this programmed interval ends, atrium is paced again. This cycle repeats and as there is no sensing, although if there is an intrinsic activity in the heart, it is ignored. The timing cycle cannot be reset by any intrinsic event. In the absence of sensing, there is no defined Atrial refractory period (ARP).

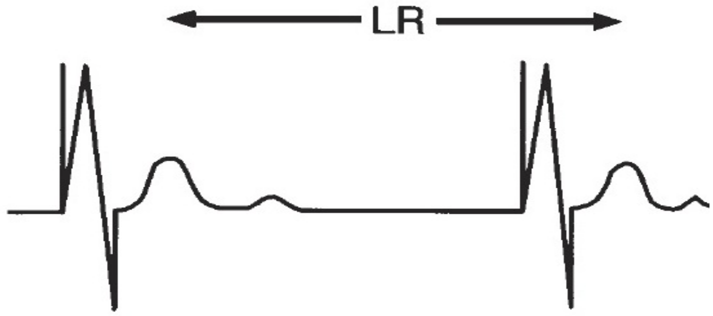

Figure4.12 : Timing Cycle of AOO mode

(http://www.blackwellpublishing.com/content/BPL_Images/)

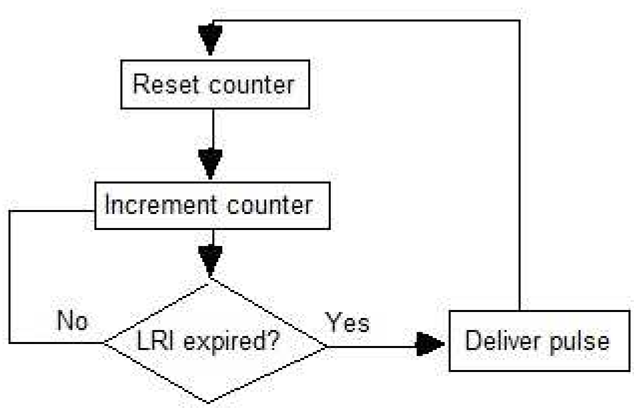

Figure4.13 : Flow chart of AOO mode

4.3.3 DOO MODE:

DOO mode: Pace atrium and ventricle   Sense nothing   No response

In DOO mode, both atria and ventricles are paced but there is neither sensing nor mode of response. The DOO timing cycle consists of only defined AV and VA intervals. The VAI is a function of the AV and VV intervals. An atrial pacing artifact is delivered, and the ventricular artifact follows at the programmed AVI. The next atrial pacing artifact is delivered at the completion of the VAI. The intervals do not vary because no activity is sensed, that is, nothing interrupts or resets the programmed cycles.

Here VV interval is nothing but LRI (1000msec). AV interval is generally considered to be 200msec. Thereby, the VAI interval can be calculated using LRI and VAI which comes out to be 800msec. So, if an AV interval starts with an atrial pace, after 200msec there will be a ventricular pace and VA interval starts. After 800msec, there will be an atrial pace which starts AV interval again. This repeats all the time and there will be no reset of AV or VA or LR intervals because in this mode any intrinsic activity is not sensed and thereby no mode of response. . In the absence of sensing, there is no defined Atrial refractory period (ARP) and Ventricular refractory period (VRP).

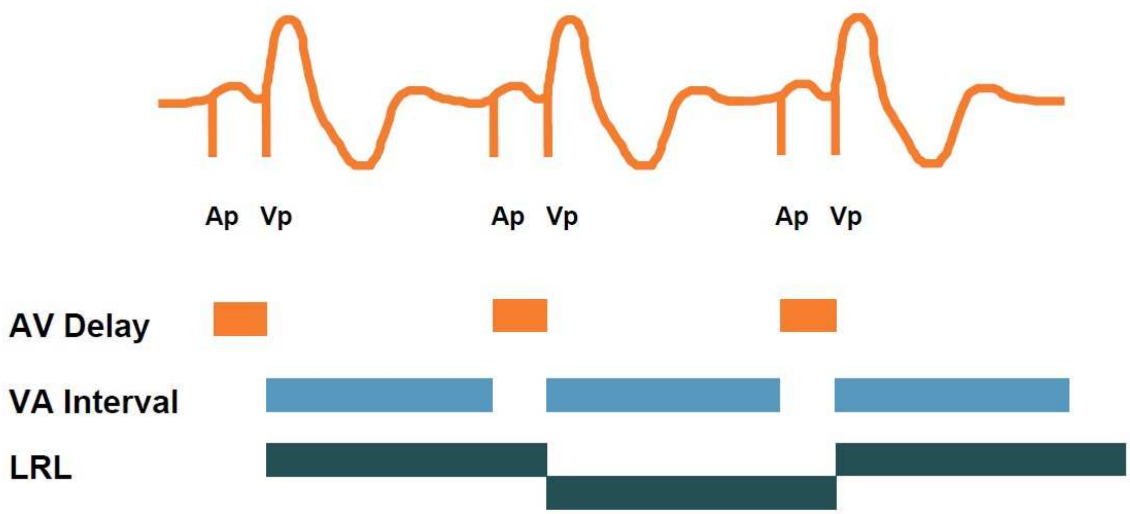

Figure4.14 : Timing Cycle of DOO

(http://sqrl.mcmaster.ca/_SQRLDocuments/Timing_Cycles.pdf)

In this mode, because of pacing on the ventricle, there will be extra beat which can be heard. Now pacemaker paced on the T wave of the extra beat causing an overlap of R wave on T wave which leads to Ventricular tachycardia (VT) as shown in Fig 4.10. Ventricular tachycardia (VT) is a rapid heartbeat that starts in the ventricles which can cause fainting or cardiac arrest and death. So never leave a patient in DOO mode.

Pacemakers running AOO, VOO, DOO modes were popular in the early days of pacemaker technology because they worked well and were electronically simple. In today's, market place, pacemakers without sensing abilities are obsolete.

4.3.4 VVI MODE:

VVI mode: Pace Ventricle   sense ventricle   Inhibit Pacing

In this mode, Pacemaker paces the ventricle and also senses the electrical activity in the ventricle. Initially LRI is set for a programmed interval and it starts with a sensed or paced ventricular event. During this LRI, by sensing, if pacemaker finds that there is an intrinsic ventricular beat, then it inhibits firing an electric signal (pace) and LRI is reset from this ventricular beat. In the other case, if it does not sense a ventricular beat till the end of LRI, then it instantly paces the ventricle and again LRI is reset.

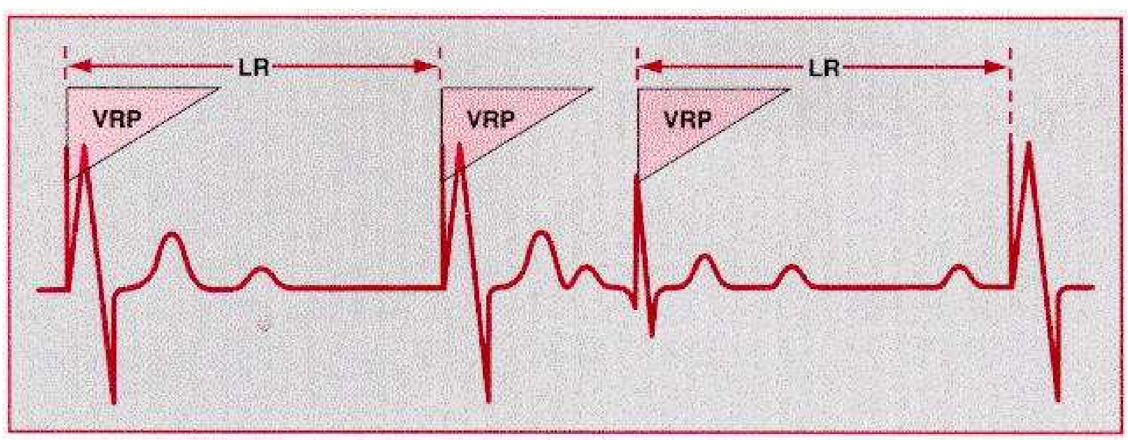

Figure4.15 : Timing Cycle of VVI

VVI pacemakers are refractory after a paced or sensed Ventricular event, a period known as the ventricular refractory period (VRP). Any ventricular event occurring within the VRP is not sensed and does not reset the LRI.

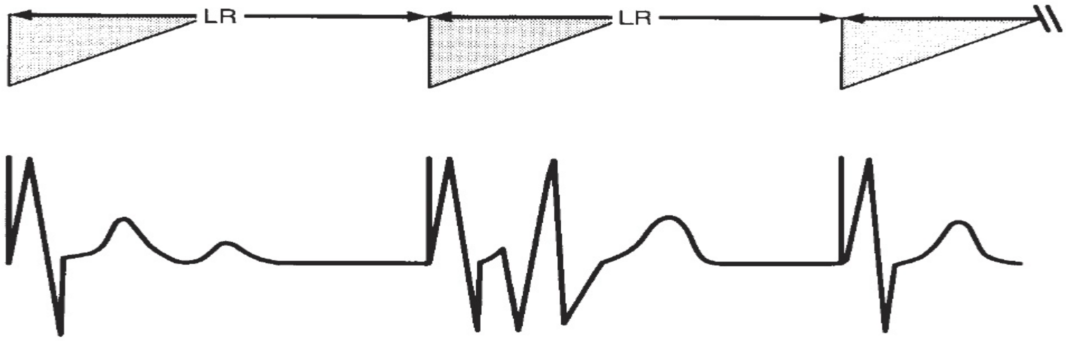

Figure4.16 : Unsensed ventricular event during the VRP (shaded triangles)

(http://www.blackwellpublishing.com/content/BPL_Images/)

Pacemaker implementing VVI mode employs two timing cycles, the lower rate interval (LRI) and the ventricular refractory period (VRP). Figure 4.16 shows that a VVI pacemaker's timing cycle always begins and ends with either a paced or sensed ventricular event. Suppose that the pacemaker has just delivered a pulse, its internal counters are reset and the pacemaker waits, continually incrementing its internal counters. The pacemaker monitors the ventricular channel for a QRS complex. If a QRS complex is sensed, and the ventricular refractory period expires, the counter is reset, and the cycle begins again. If the LRI expires before an event is sensed, a pulse is delivered by the pacemaker, and then the counter is reset.

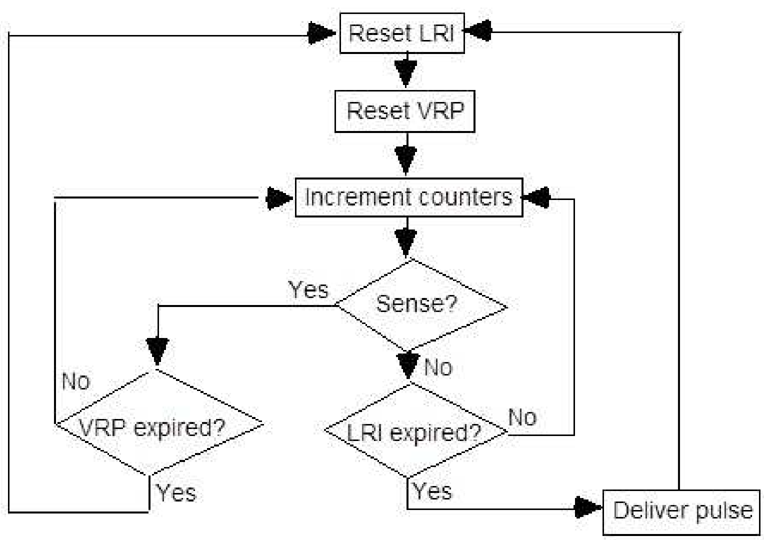

Figure4.17 : Flow chart of VVI mode

VVI remains the most commonly used pacing mode. Although VVI pacing will protect the patient from lethal bradycardias, it does not restore or maintain atrioventricular synchrony, nor does it provide rate responsiveness.

4.3.5 AAI MODE:

AAI mode: Pace Atrium   Sense Atrium   Inhibit Pacing

Atrial inhibited (AAI) pacing, the atrial counterpart of VVI pacing, incorporates the same timing cycles, with the obvious differences that pacing and sensing occur from the atrium and pacemaker output is inhibited by a sensed atrial event. In this mode, LR interval starts from an atrial event. An atrial paced or sensed event initiates an atrial refractory period (ARP) during which the pacemaker senses nothing. So, if there is some intrinsic atrial beat with in this ARP, it is not sensed and LR interval is not reset.

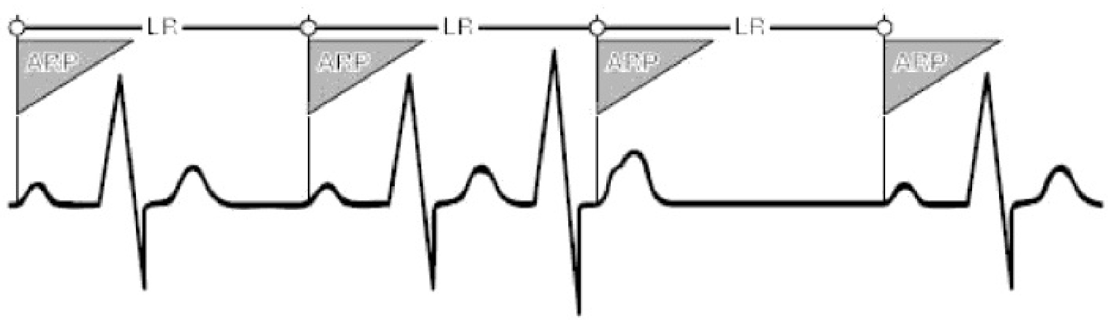

Figure4.18 : Timing Cycle of AAI with ARP

(http://www.blackwellpublishing.com/content/BPL_Images/)

Here in Fig 4.19, after first LR interval, there was an intrinsic atrial beat before the end of LR interval and after ARP, so the LR interval is reset

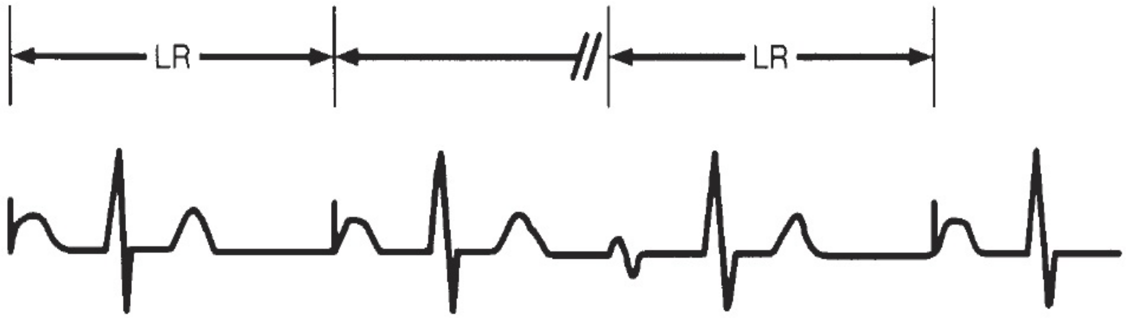

Figure4.19 : Timing Cycle of AAI

(http://www.blackwellpublishing.com/content/BPL_Images/)

Confusion can arise when multiple ventricular events occur during atrial pacing. For example, a premature ventricular beat following the intrinsic QRS that occurs in response to the paced atrial beat in the second LR interval, does not inhibit an atrial pacing artifact from being delivered (Fig.4.20). When the LR interval ends, the atrial pacing artifact is delivered regardless of ventricular events, because an AAI pacemaker should not sense anything in the ventricle.

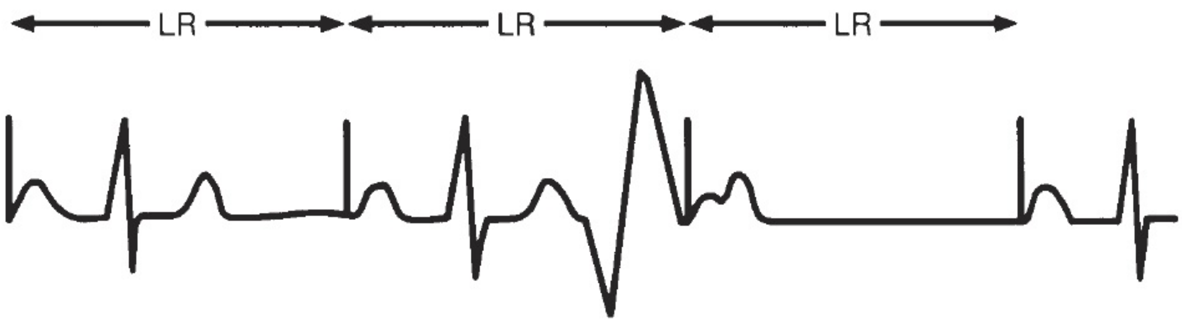

Figure4.20 : Example to show that AAI mode does not sense premature ventricular beats

(http://www.blackwellpublishing.com/content/BPL_Images/)

The single exception to this rule is far-field sensing; that is, the ventricular signal is large enough to be inappropriately sensed by the atrial lead. In this situation, the atrial timing cycle is reset. In Fig. 4.20, the LR interval is set for 1000msec (60ppm). The interval between the second and third paced atrial events is greater than 1000 milliseconds. The interval from the second QRS complex to the subsequent atrial pacing artifact is 1000 milliseconds. This occurs because the second QRS complex (asterisk) has been sensed on the atrial lead (far-field sensing) as an intrinsic atrial event and has inappropriately reset the LR interval. Sometimes this anomaly can be corrected either by making the atrial channel less sensitive or by lengthening the refractory period. Interpretation can be made easier in some devices when a programmable ADI mode is available which is almost same as AAI pacing mode, except the ventricular events are also recorded on the diagnostic channels.

Figure4.21 : Far-Filed Sensing in AAI mode

(http://www.blackwellpublishing.com/content/BPL_Images/)

4.3.6 DDD MODE:

DDD mode: Pace Atrium+Ventricle Sense Atrium+Ventricle Inhibit+Trigger

In this mode, Pacemaker paces both the atrium and ventricle and also senses the electrical activity both in atrium and ventricle. So, if it finds some intrinsic activity in atrium, it inhibits the pace but triggers a pace in the ventricle after the AV interval. If there is an intrinsic activity in ventricle, it inhibits the pace in the ventricle.

DDD pacemaker possesses six timing intervals: the LRI, the VRP, the URI, the AVI, the VAI, and the PVARP. LRI, AEI, VRP, PVARP, starts with a ventricular event (either sense or pace). AVI and ARP starts from an atrial event (either sense or pace). Now let us briefly review what all these intervals mean:

Lower Rate Limit (LRI): It is the number of generator pace pulses of atrium or ventricle (AP or VP) delivered per minute in the absence of sensed intrinsic activity. Fixed AV interval and Ventricular-atrial interval (VAI) together equals LRL interval.

Upper Rate Limit (URI):

- Upper rate interval is needed to control the ventricular beats, because if there are continuous atrial beats, there should be tracked QRS complexes (Ventricular paces) which leads to ventricular tachycardia. So, in order to control the number of ventricular beats, upper rate limit is set.
- The URL interval is the minimum time between a ventricular event and the next ventricular pace.
- URL is programmable parameter. If it's not programmed it takes the value equal to sum of AV interval and PVARP.

Non-Refractory Ventricular Sense: An intrinsic ventricular sense that occurs after the expiry of the Ventricular refractory period.

Non-Refractory Atrial Sense: An Atrial Sense that occurs after the expiry of the last atrial refractory period and post-ventricular atrial refractory period.

Refractory Ventricular Sense: A ventricular sense that occurs in the VRP.

Refractory Atrial Sense: An Atrial Sense that occurs either in the atrial refractory period or post-ventricular atrial refractory period.

Atrial-Ventricular interval (AVI): The AVI is the time period from an atrial event (Intrinsic or paced) to a ventricular pace. There are two types of AV interval: 1. **Paced AVI 2. Sensed AVI**

Ventricular-atrial interval (VAI) or AEI: The VAI is the time period from a ventricular event (Intrinsic or paced) to an atrial pace. Atrial pace takes place only when there is no intrinsic atrial event with in the programmed Ventricular-atrial interval.

VAI=LRI- AVI

Ventricular pace (VP): VP means Ventricular pace. In DDD mode, this occurs

- When a ventricular pace or non-refractory ventricular sense occurred LRL interval ago. (or)
- Atrial Pace occurred paced AV interval ago (or)
- Non_refractory Atrial sense occurred sensed AV interval ago (and)
- No Ventricular sense or pace occurred in the previous upper rate limit interval (URL)

Atrial Pace (AP): AP means Atrial Pace. In DDD mode, this occurs

- When an atrial pace or non-refractory atrial sense occurred LRL interval ago (and)
- Ventricular pace occurred VA interval ago.
- When a Non-refractory Ventricular sense occurred VA interval ago.

There are three refractory periods in DDD pacemaker which are to be considered, namely,

1. Atrial Refractory Period.
2. Ventricular Refractory Period
3. Post-ventricular atrial refractory period.

Atrial Refractory Period: ARP is the programmed time interval following an atrial event during which any atrial events are not sensed by the pacemaker.

Ventricular Refractory Period: VRP is the programmed time interval following a ventricular event during which any ventricular events are not sensed by the pacemaker.

Post-ventricular atrial refractory period: PVARP is the time interval following a ventricular event during which any atrial events are not sensed by the pacemaker.

Procedure:

- Initially, let us start pacing the ventricle, as if no pace or sense occurred in the previous LRL time interval.
- So, this should start the VRP, PVARP, LRI, URI and VA intervals.
- Any ventricular sense (VS) that occurs during the VRP is not sensed. This "VS" is considered as refractory Ventricular sense. Any "VS" that occurs out of VRP, it is considered as non-refractory ventricular sense (NR_VS).
- During PVARP, if any atrial sense (AS) occurs, it is ignored. This "AS" is considered as refractory atrial sense.
- After this PVARP, if any atrial sense occurs before VA interval expires, then it is considered to be intrinsic atrial event or non_refractory atrial sense (NR_AS).
- Sensed AV interval and ARP starts from here and this sense (NR_AS) in atrium should trigger a ventricular pace after this sensed AV interval and UR interval expires (P-wave Tracking).
- If any intrinsic atrial sense does not occur till VA Interval expires, then atrial pacing AP is done which starts the paced AV interval and ARP.

- So, during the ARP, if any intrinsic atrial beats occur, they are not sensed by the pacemaker.
- If any ventricular sense occurs within the sensed AV or paced AV interval, but if the URL interval is still on, then that "VS" is ignored.
- If any ventricular sense occurs within the sensed AV or paced AV interval and if the UR interval expires, then that "VS" is sensed which again starts VRP, PVARP, LRI, URI and VA intervals.
- Now if sensed AV or paced AV interval expires, we have to right away pace the ventricle VP, but if the URL interval is still on, ventricle is not be paced.
- Ventricular is paced when sensed or paced AV interval expires and URL interval has already ended.
- As soon as ventricular pacing is done, again VRP, PVARP, LRI, URI and VA intervals are started.
- This cycle continues giving a good heartbeat.

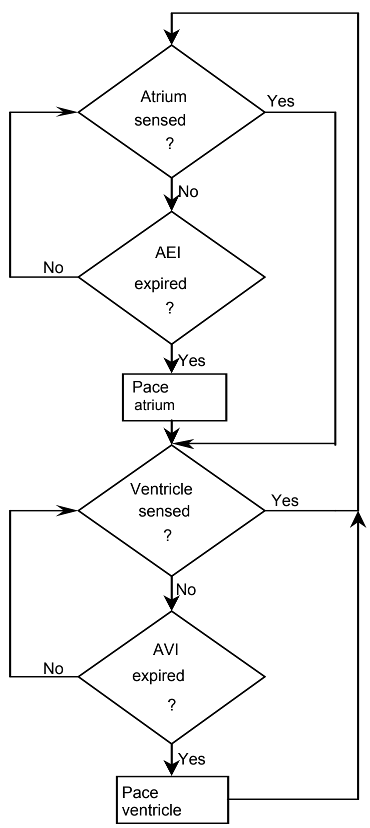

Figure4.22 : Flow Chart of DDD Mode

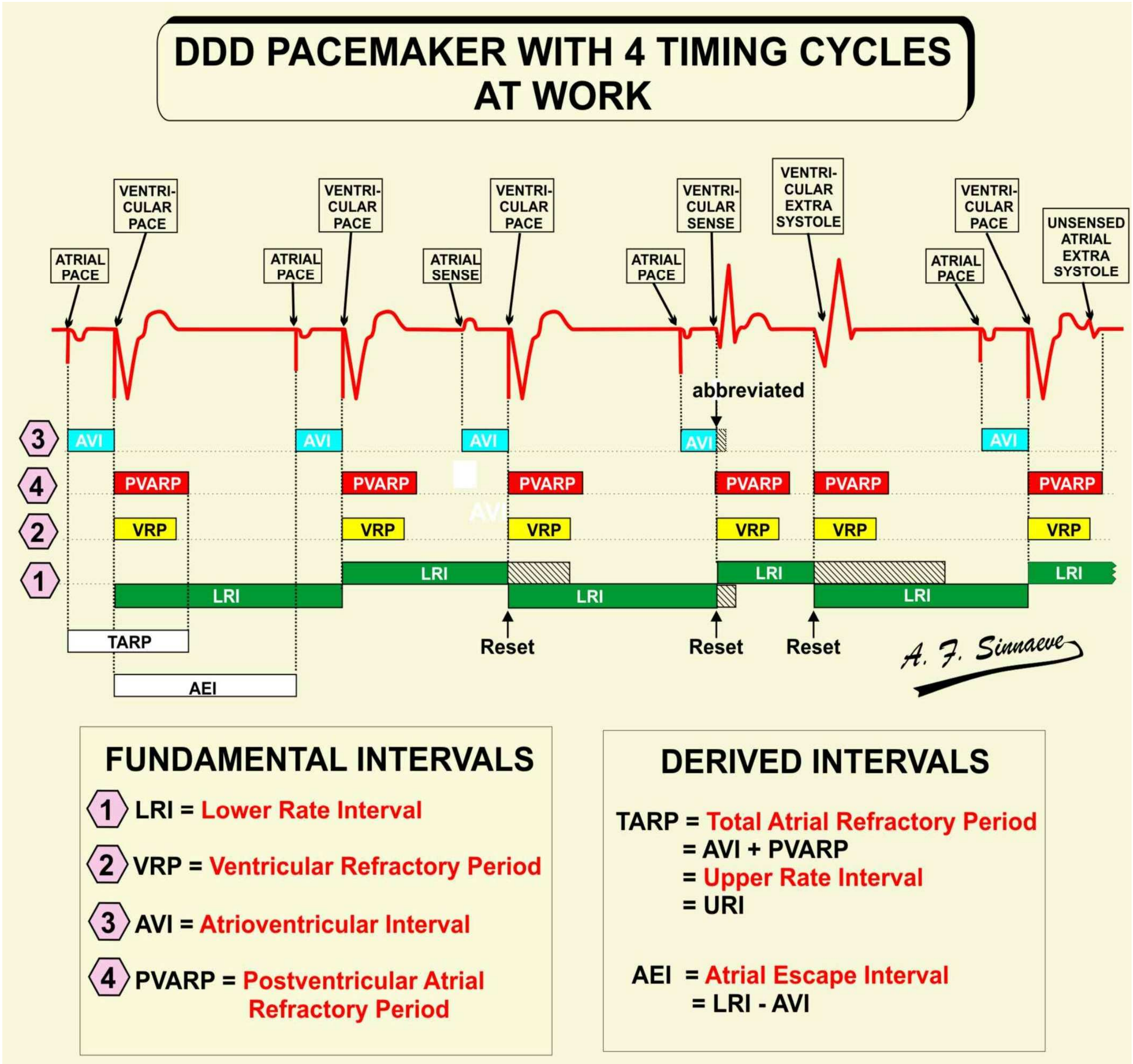

Figure4.23 : Basic Intervals of DDD Pacemaker without Upper rate limit

(Cardiac Pacemakers and Resynchronization Step-by-Step)

Four distinct patterns can be observed with DDD pacing

- Sensing in the atrium and sensing in the ventricle (AsVs)
- Sensing in the atrium and pacing in the ventricle (P wave tracking) (AsVp)
- Pacing in the atrium and sensing in the ventricle (ApVs)
- Pacing in the atrium and pacing in the ventricle (ApVp)

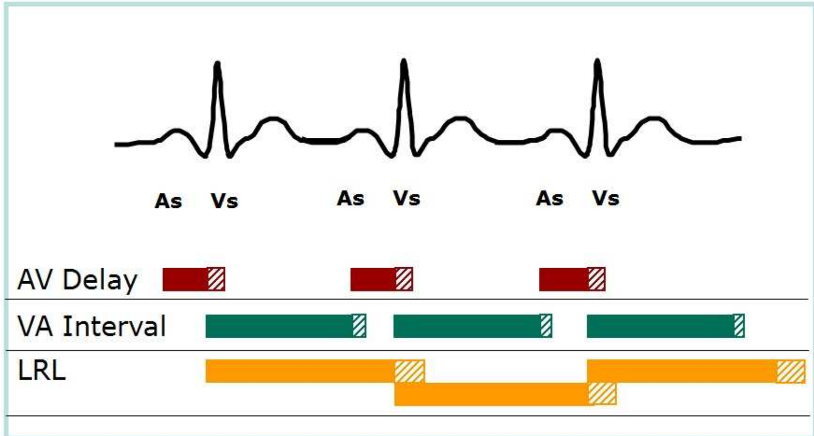

Figure4.24 : Complete Inhibition (A-Sense/V-Sense)
(Timing Cycles)

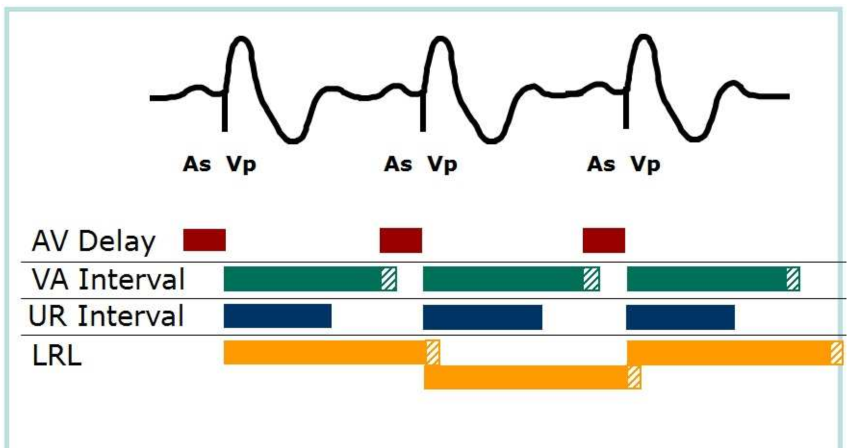

Figure4.25 : P-Synchronous Pacing (A-Sense / V-Pace):
(Timing Cycles)

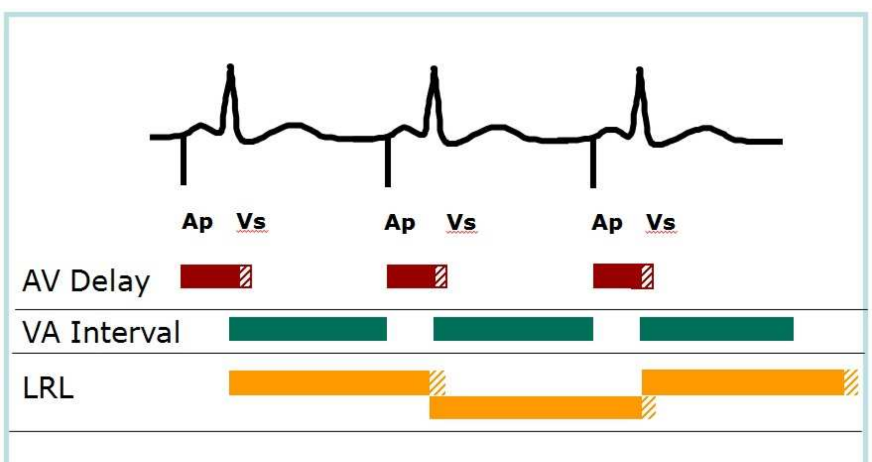

Figure4.26 : Atrial Pacing with Conduction (A-Pace / V-Sense):

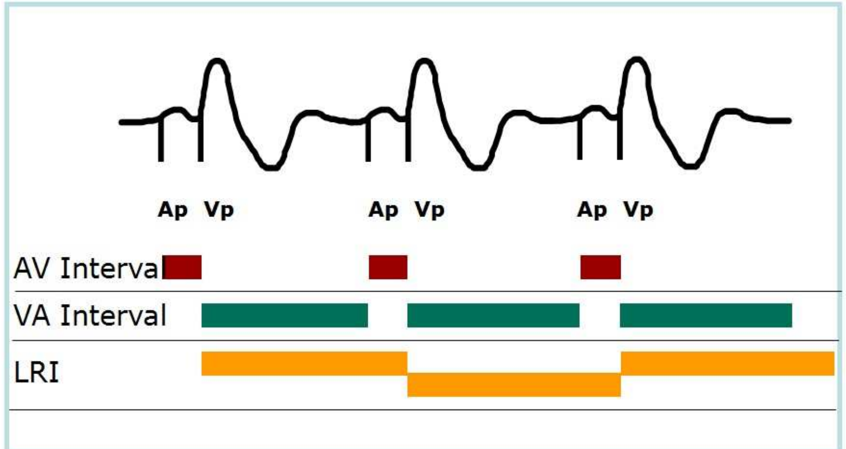

Figure4.27 : AV Sequential Pacing (A-Pace / V-Pace):

(Timing Cycles)

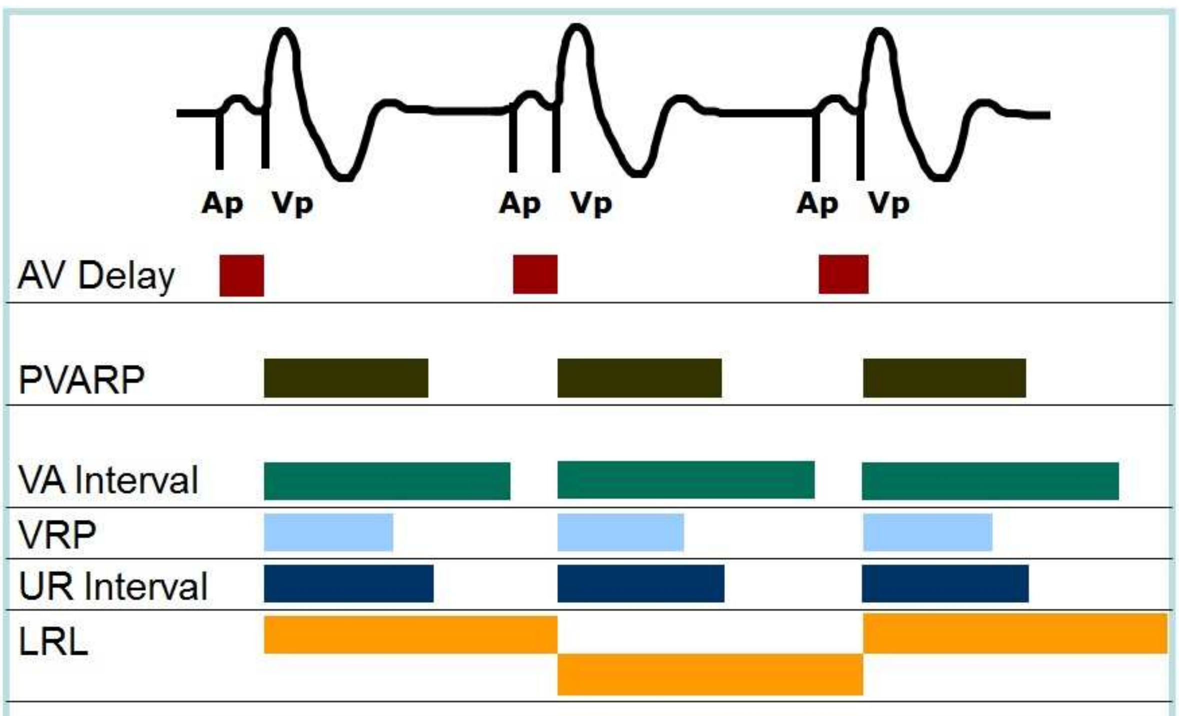

Figure4.28 : Timing Cycle of DDD

(Timing Cycles)

Dual-chambers pacemakers try to maintain 1:1 AV synchrony but this is not always possible. In the presence of high intrinsic atrial rates, pacemakers may revert to upper rate responses. The upper tracking rate is the maximum atrial rate at which a pacemaker will deliver a ventricular pacing stimulus following each sensed atrial beat (i.e. in a 1: 1 ratio). For example, if the upper tracking rate is set at 120 bpm, and the atrial rate is 130 bpm, the pacemaker will not deliver a ventricular pacing stimulus after each P wave. If it did, then it would be pacing the ventricle also at 130 bpm, and this would be said to "violate" the upper rate limit. If programmed correctly, the pacemaker rate will plateau at about 120 bpm. If the atrial rate is 130 bpm, and the ventricular rate is 120 bpm, this will have an appearance somewhat like Wenckebach conduction. This, therefore, is sometimes referred to as pseudo-Wenckebach or pacemaker-Wenckebach behavior.

Fixed-ratio block is a common upper rate behavior. It occurs when the patient's intrinsic atrial rate goes so fast that some atrial events fall into the refractory period and are not tracked. Note that for every two spontaneous atrial events a single ventricle beat is paced. As the atrial rate continues to increase, more and more P waves get blocked, eventually leading to *n*: 1 fixed ratio block. Figure 4.29 is a simplified diagram illustrating 2:1 fixed ratio block. In this diagram, the sinus node is pacing at a constant, rapid rate. The first P wave is sensed, this event initiates an AVI. At the completion of the AVI the ventricle is paced. The second P wave goes undetected, or is blocked, since it falls within the PVARP. The third P wave is then detected. Note that the ventricle beats once for every two atrial beats, this represents 2:1 fixed ratio block.

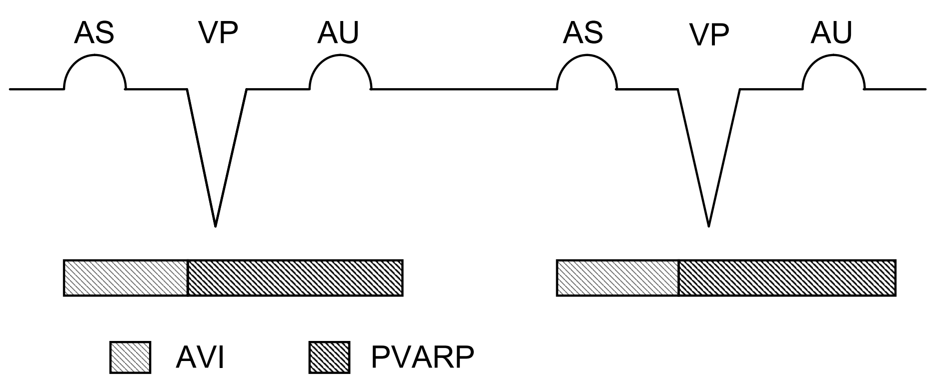

Figure4.29 : 2:1 Fixed Ratio Block

Wenckebach pacemaker response:

Figure 4.30 shows that in order for a pacemaker to implement the Wenckebach type of an upper rate response, a separately programmable URI is necessary. In addition, the URI must be programmed longer than the TARP. In these pacemakers, as the atrial rate increases, the AVI is lengthened so as not to yield a ventricular pacing pulse prior to the end of the upper rate limit. As atrial rate increases further, and P waves begin to fall within the PVARP, fixed-ratio block then occurs. The amount of time that the AVI is lengthened is equal to the URI minus the TARP.

The advantage with the Wenckebach response is that it avoids the sudden reduction of ventricular rate (which commonly occurs in fixed ratio block). In addition, this method also helps maintain some degree of AV synchrony at higher atrial rates. Note that as the atrium begins to speed up, the AVI is extended so that a ventricular pulse is not delivered before the expiration of the URI. So, we can see extended AV intervals in this scenario.

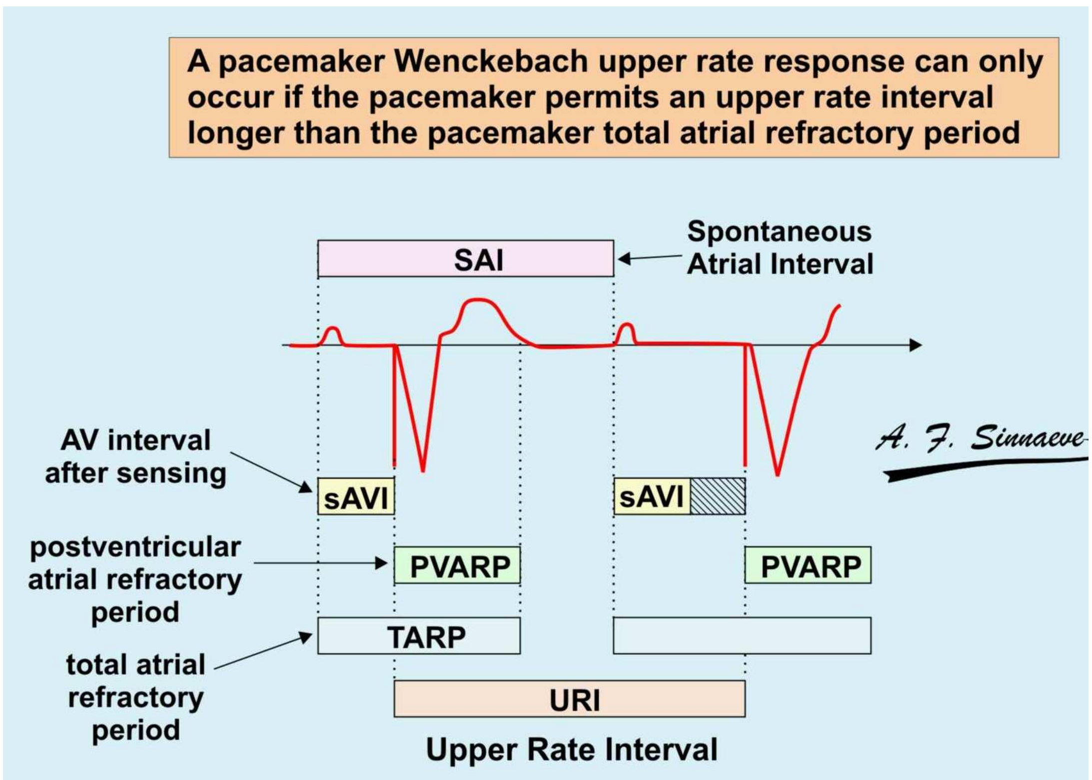

Figure4.30 : Wenckebach upper rate response- with extended AV intervals

(Cardiac Pacemakers and Resynchronization Step-by-Step)

Mode switching:

Mode switching is, as the term suggests, an automatic change from a triggered mode (e.g. DDD) to a non-triggered mode (e.g. DDI). This feature was developed to deal with the problem of the response of a pacemaker programmed in a triggered mode to atrial tachyarrhythmias, such as atrial fibrillation. Such rapid atrial arrhythmias would otherwise cause sustained high ventricular rates in triggered modes. Ventricular tracking of a rapid atrial rate is physiological during exercise, but if the rapid atrial rate is caused by an arrhythmia, ventricular tracking at the upper rate limit is not desirable. When a pacemaker with mode switch capability, programmed to the DDD mode, senses a very rapid atrial rate, it automatically switches to a non-tracking mode. (The patient may still have rapid intrinsic conduction, and a rapid ventricular response, but it will not be due to the pacemaker.) In practice, the pacemaker uses an atrial rate threshold to distinguish sinus tachycardia from atrial arrhythmias such as atrial flutter, which can have an atrial rate of 300 bpm, or atrial fibrillation, which is even faster. When the atrial rate falls below the rate programmed for mode switch, then the pacemaker changes back to a tracking mode.

4.3.7 DVI MODE:

DVI mode: Pace Atrium+Ventricle Sense Ventricle Inhibit Pacing

In atrio-ventricular sequential (also called sequential demand) mode, only the ventricle is sensed but both chambers are paced. The DVI timing cycle initially consists of defined AV and VV intervals. The VAI is a function of the AV and VV (LRI) intervals. Both chambers are paced at the same rate separated by a fixed AV sequential interval. The Ventricles are paced once the defined AV interval expires and then start a VA interval. As sensing is done in the ventricles, if there is some intrinsic ventricle beat with in this AV interval, the pace is inhibited by the pacemaker but VA interval is not reset. As there is no sensing in atria, even though there is some intrinsic atrial beat in the VA, the pace is not inhibited and the pacemaker surely paces atria once the VA interval expires. After this pace, AV interval starts again. This cycle repeats all the time.

1. Pacing is done both in atrium and ventricles as soon as AEI and LRI expire.
2. Pacing is done in atrium, but pacemaker sensed a ventricular beat in the VA interval, so ventricular pace is inhibited.
3. The intrinsic atrial beat is not sensed, but it was not paced after AEI, because ineffectual atrial stimulus falls in the atrial myocardial refractory period.

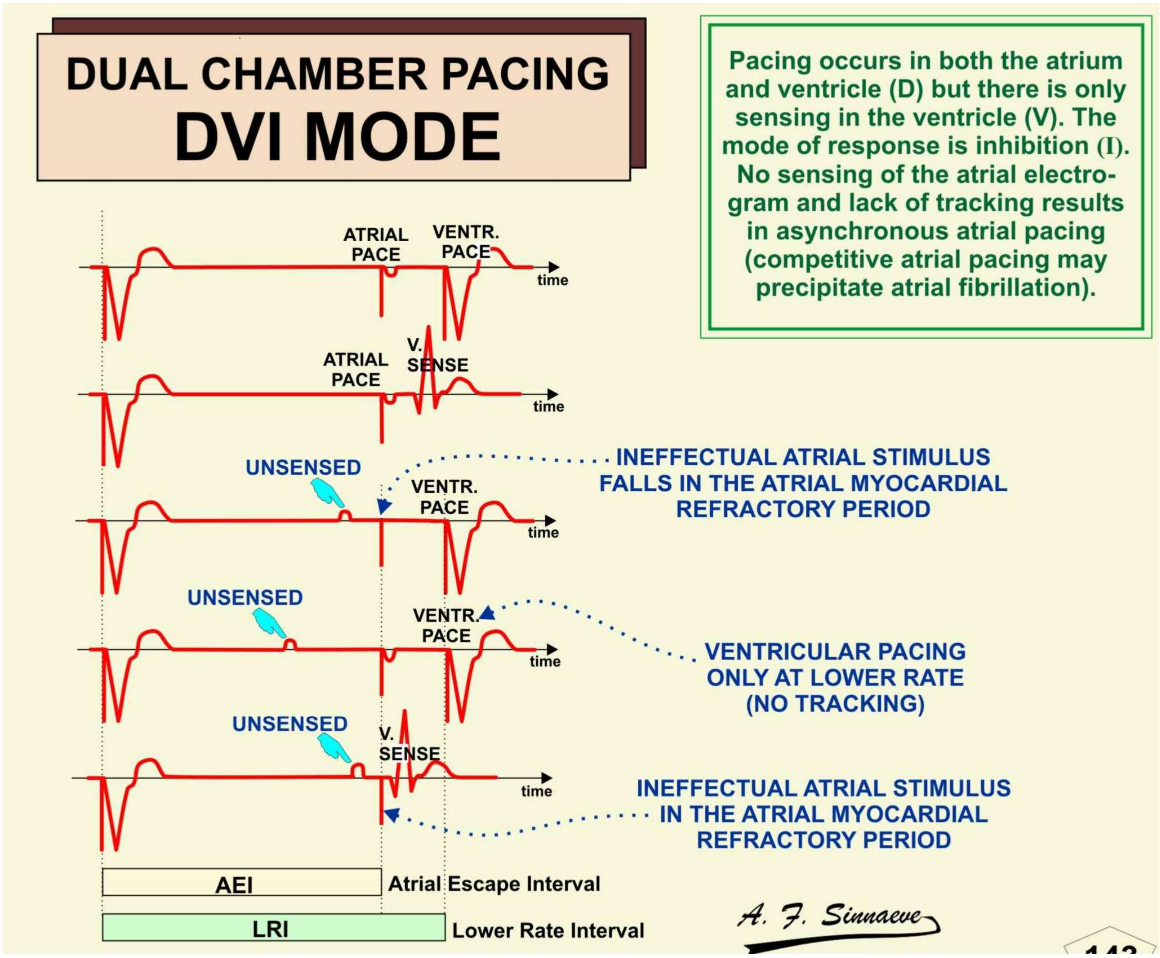

Figure4.31 : Different cases in DVI

(Cardiac Pacemakers and Resynchronization Step-by-Step)

4. The intrinsic atrial beat is not sensed, but atria are paced after AE interval expires. Ventricles are paced only when LRI expires because there is no tracking.
5. The intrinsic atrial beat is not sensed, but it was not paced after AEI, because ineffectual atrial stimulus falls in the atrial myocardial refractory period. After that there is an intrinsic ventricular beat, so the ventricular pace is inhibited.

Two types of DVI pacemakers may be used, a committed DVI and a non-committed DVI pacemaker. The committed DVI pacemaker does not sense intrinsic activity during the AV interval. It generates an impulse even if there is an intrinsic ventricular beat in the AV interval. The non-committed DVI pacemaker, on the other hand, is inhibited if an intrinsic ventricular beat occurs.

DVI mode is useful in situations where there are frequent supra ventricular tachycardia's or in situations where the patient should not track the atrial rhythm. But the lack of atrial sensing may lead to competitive atrial pacing and initiation of atrial rhythm disturbances. For these reasons DVI pacing is rarely the mode of choice at the time of implant but remains a programmable option in many dual-chamber pacemakers.

4.3.8 DDI MODE:

DDI mode: Pace Atrium+Ventricle Sense Atrium+Ventricle Inhibit Pacing

AV sequential pacing with dual-chamber sensing, non–P synchronous (DDI) pacing can be thought of as either an upgrade of DVI non-committed pacing or a downgrade of DDD pacing—that is, DDD pacing without atrial tracking. The difference between DVI and DDI is that DDI incorporates atrial sensing as well as ventricular sensing. This prevents competitive atrial pacing that can occur with DVI pacing. The DDI mode of response is inhibition only; that is, no tracking of P waves can occur. Therefore, the paced ventricular rate cannot be greater than the programmed LRL. The difference between DDI and DDD is that AV Interval is not reset with a sensed atrial event. The timing cycle consists of the LRL, AVI, VAI, VRP, post ventricular atrial refractory period (PVARP), and VRP.

1. Pacing is done in both atria and ventricles as soon as VA interval and AV interval expired respectively.
2. As the VA interval expires, atrial pacing is done but there is an intrinsic ventricular event which is sensed before the AV interval has expired. So, the ventricular pace is inhibited.
3. There is an atrial intrinsic beat before the VA interval expires, so the atrial pace is inhibited at the end of VA interval. Important thing to note here is that intrinsic atrial sense did not initiate a sensed AV interval. AV interval started only when VA interval expired. DDI is different from DDD in this aspect. In DDD, sensed AV interval starts as soon as there is an intrinsic atrial sense so as to achieve P-wave tracking and UR interval comes into the scenario.

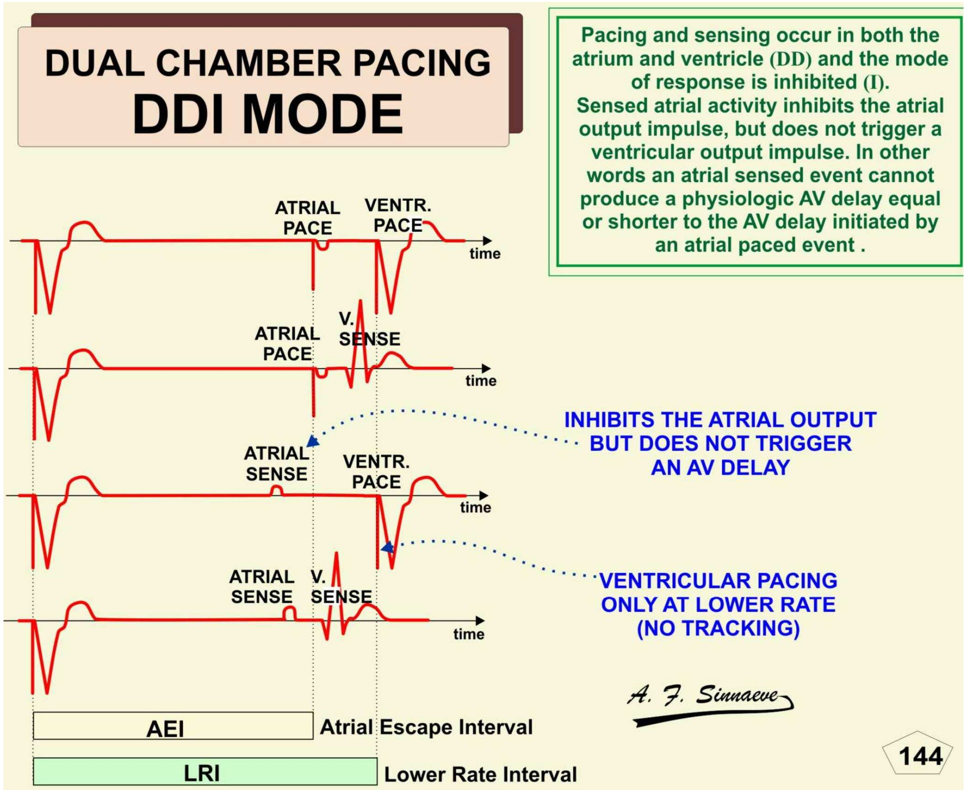

Figure4.32 : Different cases in DDI

(Cardiac Pacemakers and Resynchronization Step-by-Step)

4. There is an atrial intrinsic beat before the VA interval expires, so the atrial pace is inhibited at the end of VA interval. In the AV interval, there is an intrinsic ventricular sense, so the ventricular pace is inhibited.

This mode is similar to combining AAI and VVI modes. This mode is primarily used for atrial tachyarrhythmias and mode-switching algorithms.

4.3.9 VDD MODE:

VDD mode: Pace Ventricle   Sense Atrium+Ventricle   Inhibition+Trigerring

In this mode, pacemakers pace only in the ventricle (V), sense in both atrium and ventricle (D), and respond both by inhibition of ventricular output by intrinsic ventricular activity (I) and by ventricular tracking of P waves (T). The timing cycle of VDD consists of an LRL, a sensed AVI, a VRP and a URL. A sensed P wave initiates the sensed AVI. At the end of the

AVI, a ventricular pacing artifact is delivered if no intrinsic ventricular activity has been sensed, that is, P-wave tracking. Ventricular activity, paced or sensed, initiates the PVARP and the VAI (the LRL interval minus the AVI). If no P-wave activity occurs till the end of VA interval, there will not be any atrial pace but at the end of LRL, there will be a ventricular pace.

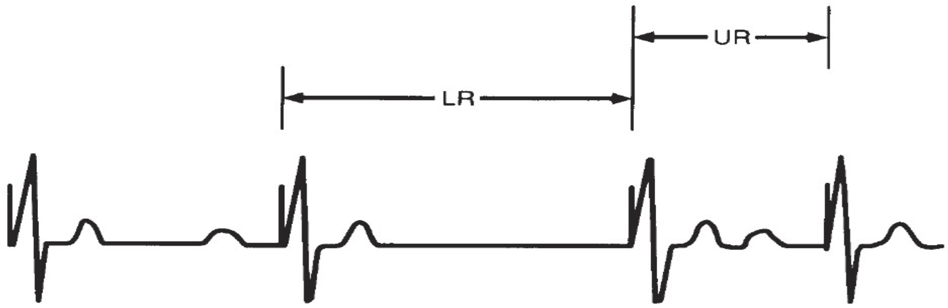

Figure4.33 : Timing Cycle of VDD

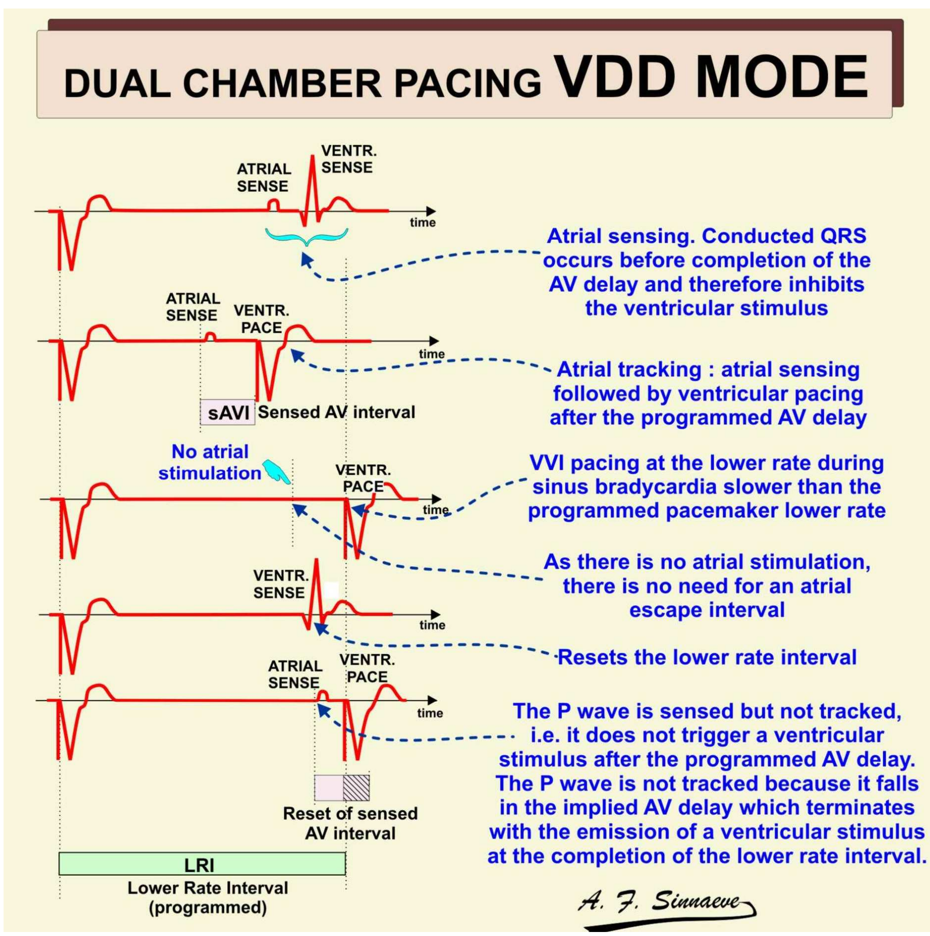

Figure4.34 : Different cases in VDD

(Cardiac Pacemakers and Resynchronization Step-by-Step)

1. An intrinsic atrial sense occurs in VA interval, which initiates a sensed AV interval, and the atrial pace is inhibited. Before the AV interval expires, there is an intrinsic ventricular sense and therefore ventricular pace is inhibited. LR interval is reset.
2. An intrinsic atrial sense occurs in VA interval, which initiates a sensed AV interval and the atrial pace is inhibited. As there is no intrinsic ventricular sense within the sensed AV interval, Ventricular pacing is done at the end of sensed AV interval called p-wave tracking.
3. There is no intrinsic atrial sense in the VA interval, but atrial pacing is not done at the end of the interval. At the end of LRL, there will be a ventricular pace.
4. There is no atrial sense but there is a ventricular sense before the end of LRL. So, the LR interval is reset.
5. There is an atrial sense after the end of VA interval, so this atrial sense falls in the AV interval, which initiates a sensed AV interval. So, at the end of this AV interval, ventricular pacing has to be done but this AV interval exceeds the LR interval which violates. So, the ventricular pacing is done as soon as LR interval expires and although the sensed AV interval does not expire.

VDD pacemaker has ability to “trigger” a ventricular pacing output in response to an intrinsic P-wave (P-wave tracking). As there is no atrial pacing, the patient must have normal sinus node function.

4.3.10 VAT MODE:

VAT mode: Pace Ventricle Sense Atrium Trigger pace in ventricle

In this mode, Ventricle is paced after every LR interval even if there is some ventricular sense in the LR interval (no inhibition), atrium is sensed and if it finds any intrinsic atrial activity, it triggers a pace in the ventricle after the sensed AV interval and a new LR interval starts. In VAT mode, LR interval, VRP, sensed AV interval are the programmable parameters. If there is no intrinsic activity in atrium, there will not be any pace in the atrium after the VA interval.

In both VAT and VDD modes, tracking of atrial activity triggers subsequent ventricular pacing after a programmable AV delay. The difference between these modes is that with VAT pacing, sensing is not performed in the ventricle potentially resulting in competition between spontaneous ventricular activity and uninhibited ventricular pacing at the same rate as the spontaneous activity in the atrium. In VDD mode, sensing occurs in both the ventricle and atrium; consequently, ventricular pacing is inhibited if spontaneous ventricular activity is sensed at a rate equal to, or greater than, the sensed atrial activity. As a result, the chance that an uninhibited pacing stimulus will trigger a ventricular tachyarrhythmia by exciting the ventricular myocardium during a vulnerable period is minimized. For these reasons, VAT pacing is considered obsolete.

VAT mode can be used in patients with complete heart block with normal sinus and atrial electrical function, but it should be avoided when an abnormality of sinus or atrial function is present.

4.3.11 VVT MODE:

VVT mode: Pace Ventricle Sense ventricle Trigger pace in ventricle

In this mode, ventricle is paced, sensed and if there is any intrinsic sense in the ventricle, a ventricular stimuli is delivered. In both the VVI and VVT modes, the ventricle is paced at the LRI cycle length as long as there is no spontaneous electric activity sensed in the ventricle outside the VRP. In VVI mode, ventricular pacing is inhibited by a spontaneous ventricular activation occurring outside VRP. But in Ventricular triggered mode, the pacemaker delivers a pulse not only when no ventricular event has been sensed within a preset Lower rate interval but also paces over any spontaneous ventricular event within the preset Lower rate interval. The mode was invented to overcome difficulties that the earlier VVI pacemaker encountered when exposed to magnetic interference in which case the pacemaker would falsely inhibit the delivery of pacing pulses. As the casing material and noise filters were improved, the VVI pacemaker became more resistant to magnetic interference. VVT is used only when a patient is routinely exposed to electromagnetic interference and where symptomatic tachycardia cannot be prevented by sensitivity programming adjustments. VVT is generally not used as it may cause tachyarrhythmia's up to the rate limit when over sensing occurs, in which case ventricular fibrillation may result.

In the Figure 4.38, V is ventricular paced event and R is intrinsic ventricular event. So, if there is no intrinsic event with in LR interval, then ventricles are paced at the end of LR interval. On the other hand, even though there is sensed ventricular event with in the LR interval, still the ventricular pace is triggered.

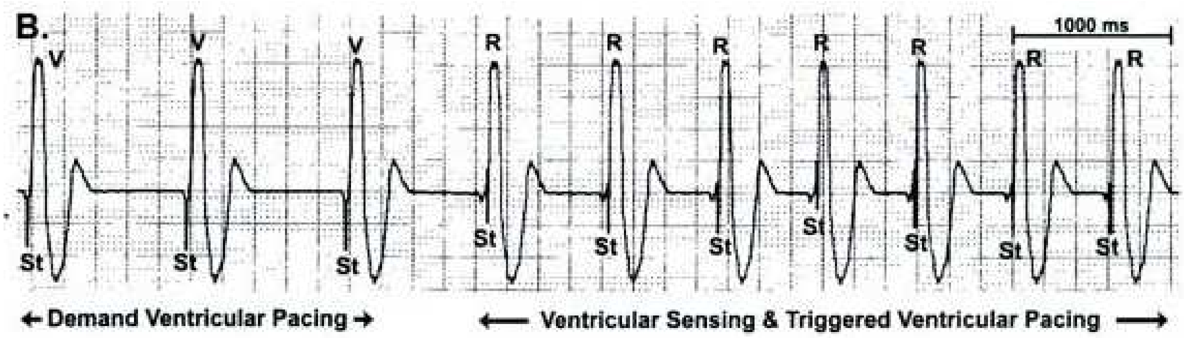

Figure4.35 : Timing Cycle of VVT

(Fundamental Approaches to the Management of Cardiac Arrhythmias)

4.3.12 AAT MODE:

AAT mode: Pace Atrium Sense Atrium Trigger pace in Atrium

In this mode, atrium is paced, sensed and if there is any intrinsic sense in the atrium, an atrium stimuli is delivered. In both the AAI and AAT modes, the atrium is paced at the LRI cycle length as long as there is no spontaneous electric activity sensed in the atrium outside the ARP. In AAI mode, atrial pacing is inhibited by a spontaneous atrial activation occurring outside ARP. But in atrial triggered mode, the pacemaker delivers a pulse not only when no atrial event has been sensed within a preset Lower rate interval but also paces over any spontaneous ventricular event within the preset Lower rate interval. In theory, this mode is used when due to symptomatic skeletal muscle sensing, the AAI mode cannot be used. AAT is preferred to AOO as it does not induce atrial fibrillation.

In the Figure 4.39, A is atrial paced event and P is intrinsic atrial event. So, if there is no intrinsic event with in LR interval, then ventricles are paced at the end of LR interval. On the other hand, even though there is sensed atrial event with in the LR interval, still the atrial pace is triggered.

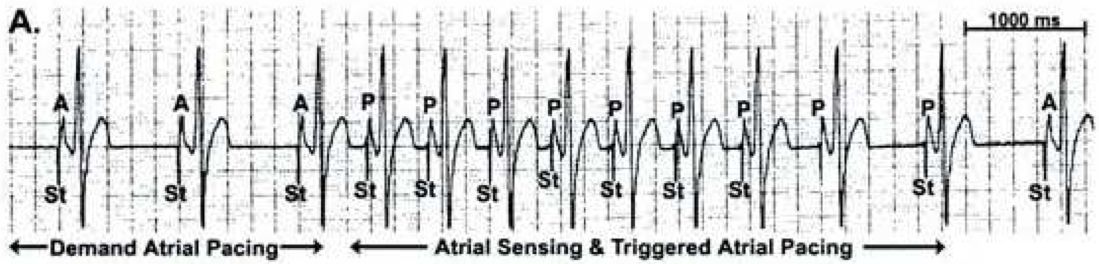

Figure4.36 : Timing Cycle of AAT

(Fundamental Approaches to the Management of Cardiac Arrhythmias)

Chapter 5 – Implementation of Modes

5.1 Hardware Requirements:

The following hardware requirements have been considered:

- NI USB-6008
- Pacemaker Board with PIC18F 4520 Microcontroller,
- PICkit 2 debugger/programmer

5.2 Software Requirements:

The following software requirements have been considered:

- Operating System: A Windows PC (2000/Me/XP/Vista/Windows 7), 256 MB of RAM, USB ports
- Language: C
- Tools: MPLAB IDE, NI-DAQmx 9.4, NI Lab VIEW SignalExpress, Microsoft Visual Studio
- Complier: MCC compiler

5.3 Setting up the hardware and Software

5.3.1 Software Installations:

- Download and Install MPLAB IDE
- Download and Install MCC Compiler for MPLAB IDE
- Download and Install NI-DAQmx
- Download and Install Lab VIEW SignalExpress

5.3.2 Hardware setup:

- Before connecting the pacemaker board to a power source, connect the serial port of the pacemaker board to the USB port of the computer by means of a USB-Serial Connector.
- Pacemaker Board and computer can also be connected by means of a serial cable if the computer has a serial port.
- Now connect the pacemaker to the power source by using the power adapter.

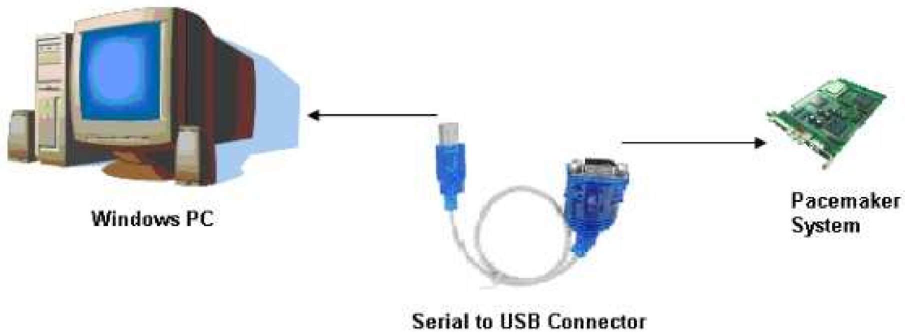

Figure5.1 : Connecting a Pacemaker board and PC using serial to USB connector

(http://www.cas.mcmaster.ca/~lawford/pacemaker/user_guide.pdf)

- Now connect a PICkit 2 Debugger/Programmer to the pacemaker board.
- Then connect the other end of the PICkit 2 to another USB port of the computer.
- Now connect the NI USB-6008 to the pacemaker board using pacemaker leads.
- Connect one end of the pacing leads to the atrial and ventricle ports as shown below.

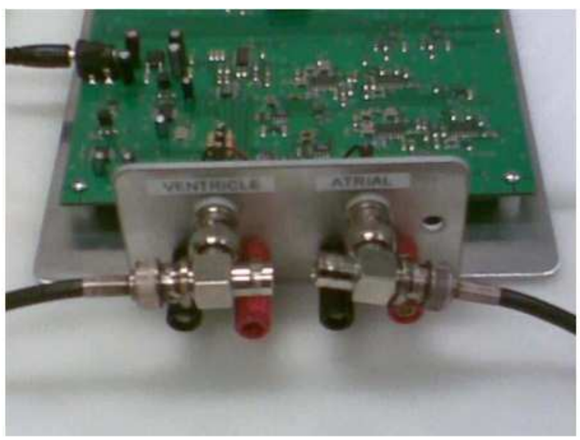

Figure5.2 : Connecting the pacing leads to Atrial and Ventricle Ports

(http://www.cas.mcmaster.ca/~lawford/pacemaker/user_guide.pdf)

- The other end of the leads is connected to NI USB-6008 as analog I/O.
- These Leads help the Pacemaker to sense the activity in USB-6008.
- Now the NI USB-6008 is connected to the USB port of the computer using a cable.

5.4 Pseudo code of different modes and their implementation

5.4.1 VOO pseudo code:

From the flow charts of VOO and AOO modes, the following pseudo code is written so as to develop the original code.

```
VOO
        -- Configuration Parameters:
          LRI_Config=1000msec                              //Lower Rate Interval
          Ventricle_ Pacing_Voltage_Config= 3.5 volts

        -- Initialization
          LRI = LRI_Config
          Pvoltage = Ventricle_ Pacing_Voltage_Config      //Pacing Voltage

Label L1:   Start Timer0 (LRI)                             //Timer0 runs from 0 to 1000
                Check if (Timer0 expired)                  //Expires when Timer0 reaches 1000
                 -- ** generate a pace @ Pvoltage *        //LRI expired, so generate a ventricular pace
                       Reset Timer0                        //Expires when Timer0 reaches 1000
                        Goto L1                            //Repeat
                End if
```

5.4.2 AOO pseudo code:

```
AOO
        -- Configuration Parameters:
        LRI_Config=1000msec                                //Lower Rate Interval
        Atrial_ Pacing_Voltage_Config = 2 volts

        -- Initialization
        LRI = LRI_Config
        Pvoltage = Atrial_ Pacing_Voltage_Config           //Pacing Voltage

Label L1:    Start Timer0 (LRI)                            //Timer0 runs from 0 to 1000
                 Check if (Timer0 expired)                 //Expires when Timer0 reaches 1000
                  -- ** generate a pace @ Pvoltage *       //LRI expired, so generate a Atrial pace
                        Reset Timer0                       //Timer 0 again set to 1000
                        Goto L1                            //Repeat
                  End if
```

Based on this pseudo code, both of these modes are implemented in “C” language using timers and Interrupt driven approach. Timer 0 of PIC18F MICROCHIP is set for LR interval of time. For VOO mode, Timer 0 starts with a ventricular event and for AOO mode Timer 0 starts with an atrial event. So as soon as this Timer 0 times out, there will be an interrupt which executes Timer0TimeoutISR () (Interrupt-service routine) which generates a pace in the ventricle for VOO mode and a pace in the atrium for AOO mode. This code is debugged, compiled by mcc18 complier and programmed on to the pacemaker board by means of PICkit2 debugger/programmer. Now run the code. Now open the Lab view signal Express, which shows up that for every 1000msec, there is a pace of 3.5volts. This pace can be seen as a spike pointing to 3.5volts on Y-axis.

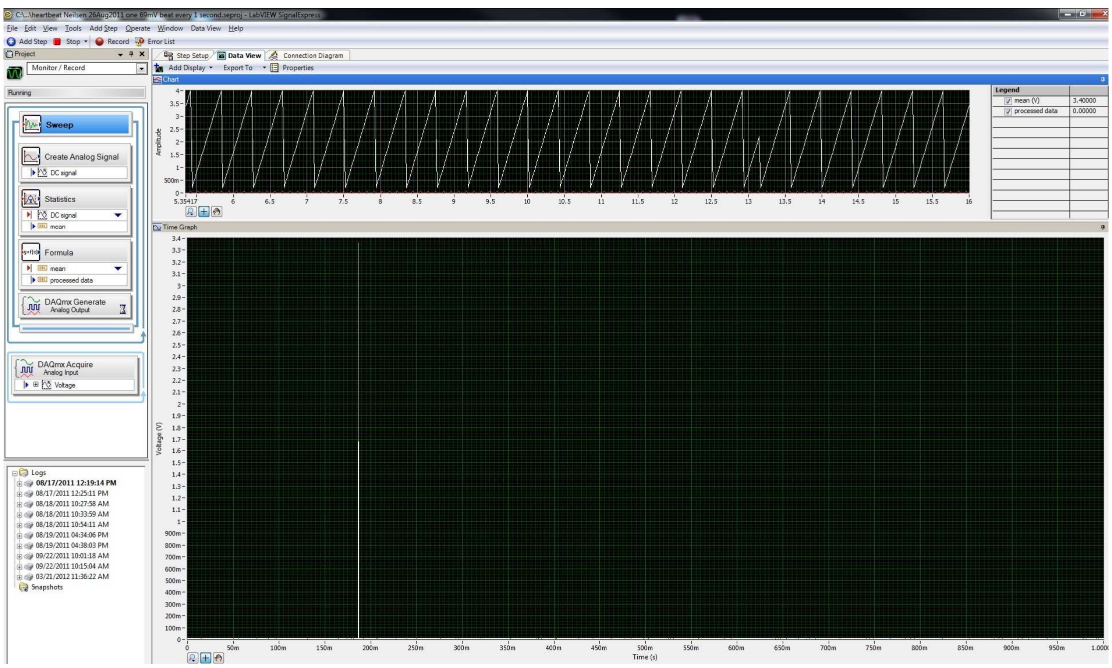

Figure5.3 : Lab view signal express VOO output

5.4.3 VVI pseudo code:

From the flow charts of VVI and AAI modes, the following pseudo code is written so as to develop the original code. Pseudo Code of AAI and VVI modes is similar with only difference that Sensing and Pacing is done in ventricle for VVI and in atrium for AAI. The refractory period for VVI mode is VRP and for AAI mode is ARP. Hence, only the pseudo code of VVI mode is written in this report.

```
VVI
        --- Configuration Parameters:
            LRI_Config=1000msec
            Ventricle_voltage_sensitivity_Config=2.5milli Volts
            Ventricle_ Pacing_Voltage_Config = 3.5 volts
            VRP_Config= 350msec

        --- Initialization
            LRI = LRI_Config
            VSensitivity= Ventricle_voltage_sensitivity_Config
             Pvoltage = Ventricle_ Pacing_Voltage_Config
             VRP=VRP_Config

 Label L1:    Start Timer0 (LRI)
                  Check if (Timer0 expired)
                        -- ** generate a pace @ Pvoltage *      //LRI expired, so generate a Ventricular pace
                         Reset Timer0                          //Timer 0 again set to 1000
                          Goto L1
                  Else If (Intrinsic Ventricular Sense< VSenstitivity)
                         Return                                //Ignore Sense
                   Else If Intrinsic Ventricular Sense>VSensitivity) and (get Timer0 () <VRP_Config)
                         Return                                //Ignore Sense
                   Else If (Intrinsic Ventricular Sense>VSensitivity) and (get Timer0 ()>VRP_Config)
                         Reset Timer0                          //Timer 0 again set to 1000
                         Goto L1
                  End if
```

Based on this pseudo code, VVI and AAI modes are implemented in “C” language using timers and Interrupt driven approach. Timer 0 is set for LR interval of time. For VVI mode, Timer 0 starts with a ventricular event and for AAI mode Timer 0 starts with an atrial event. In these modes, pacemaker senses the activity of NI USB-6008 DAQ. So, if there is an intrinsic sense in the ventricle after the ventricular refractory period, the VentricleDetectISR (Interrupt service routine) is executed in which the pacemaker inhibits the pace and resets the Timer0. If there is no intrinsic activity till the Timer0 times out, then there will be an interrupt which executes Timer0TimeoutISR () (Interrupt-service routine) which generates a pace in the ventricle and Timer0 is reset again. This code is debugged, compiled by mcc18 complier and programmed on to the pacemaker board by means of PICkit2 debugger/programmer. Now run the code. Now open the Lab view signal Express, which shows up that for every 1000msec, there is a pace of 3.5volts and if there is some intrinsic sense within 1000msec, pace is inhibited.

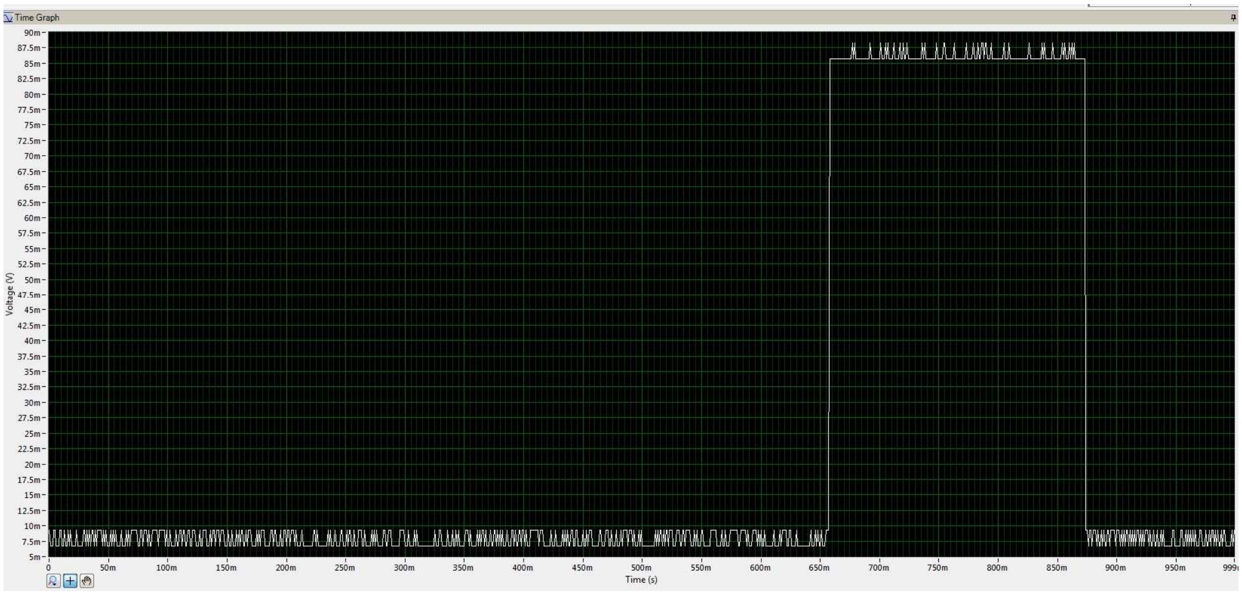

Figure5.4: Lab view signal express VVI output showing a sense in the ventricle

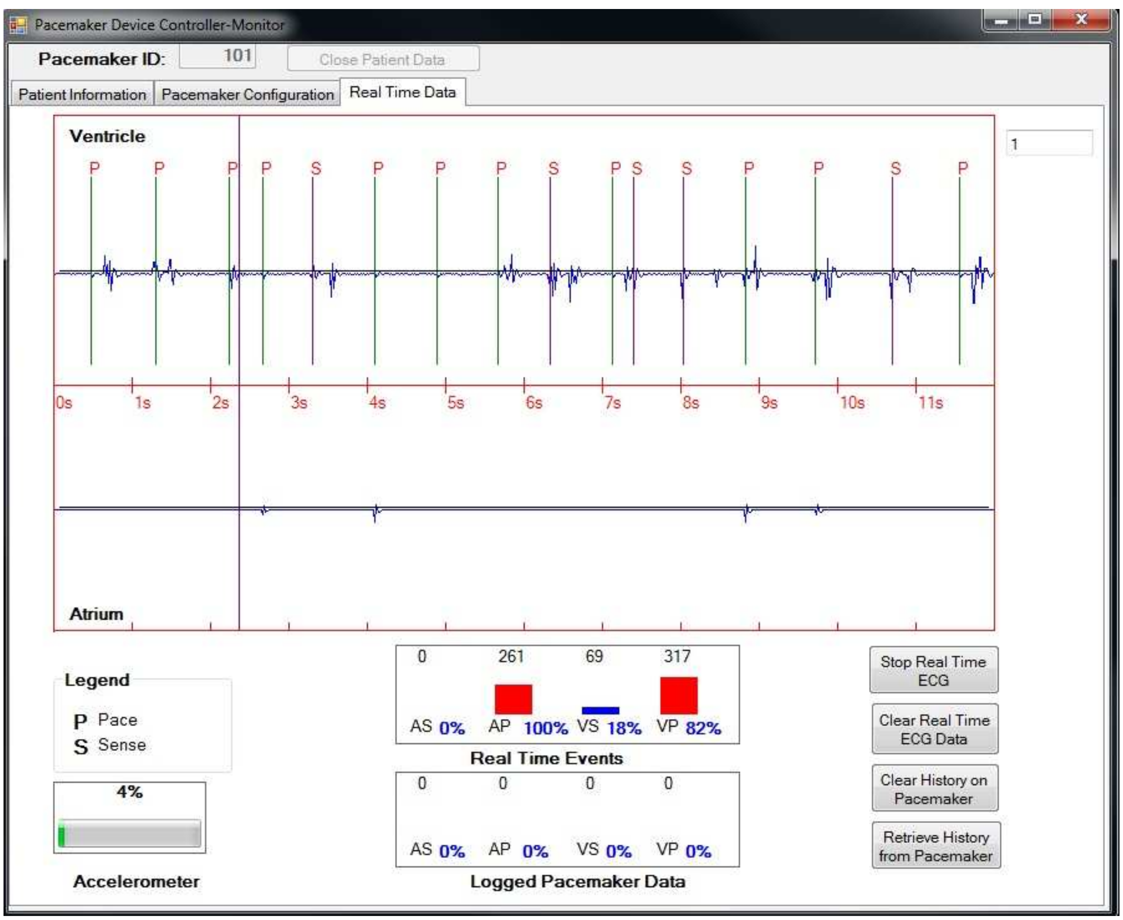

Figure5.5: ECG showing senses and Pulses in ventricle in VVI mode

5.4.4 VVT pseudo code:

In VVT mode, in addition to the concepts of VVI, if the pacemaker senses some ventricular activity, it right away triggers a pace in the ventricle. So, if there is an intrinsic sense in the ventricle after the ventricular refractory period, the VentricleDetectISR (Interrupt service routine) in which ventricle is paced and Timer0 is reset. Rest of the thing remains the same. It's the same with AAT mode, if there is a sense in atrium; it triggers a pace in the atrium.

```
VVT

        --- Configuration Parameters:
            LRI_Config=1000msec
            Ventricle_voltage_sensitivity_Config=2.5milli Volts
            Ventricle_ Pacing_Voltage_Config = 3.5 volts
            VRP_Config= 350msec
        --- Initialization
            LRI = LRI_Config
            VSensitivity= Ventricle_voltage_sensitivity_Config
             Pvoltage = Ventricle_ Pacing_Voltage_Config
             VRP=VRP_Config

Label L1:     Start Timer0 (LRI)
                     Check if (Timer0 expired)
                          -- ** generate a pace @ Pvoltage *        //LRI expired, so generate a Ventricular pace
                          Reset Timer0                              //Timer 0 again set to 1000
                            Go to L1
                     Else If (Intrinsic Ventricular Sense< VSenstitivity)
                            Return                                  //Ignore sense
                     Else If Intrinsic Ventricular Sense>VSensitivity) and (get Timer0 () <VRP_Config)
                            Return                                  //Ignore Sense
                     Else If (Intrinsic Ventricular Sense>VSensitivity) and (get Timer0 ()>VRP_Config)
                          -- ** generate a pace @ Pvoltage *        //Trigger a Pace after sensing a Ventricular Sense
                          Reset Timer0                              //Timer 0 again set to 1000
                          Go to L1
              End if
```

In Figure 5.6, we can clearly observe that if there is a sense in the ventricle, it is immediately followed by a pace that can be seen by an overlap of S and P in the figure. After this pace, timer0 is reset for LRL period. On the other hand, if there is no sense till the end of Timer0 then ventricle is paced and again the timer0 is reset for LRL period.

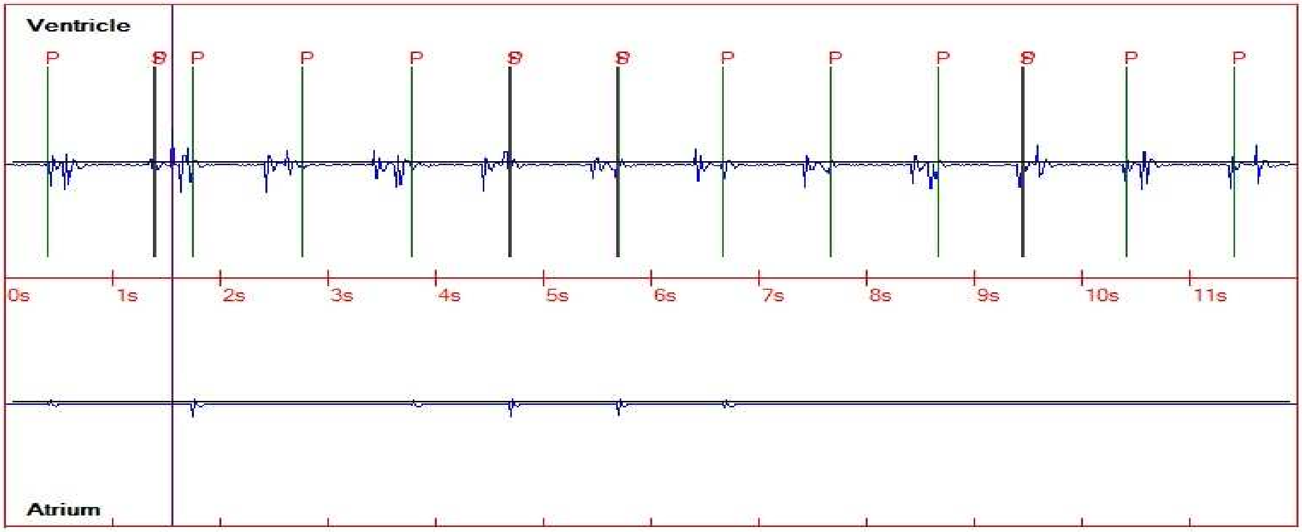

Figure5.6: ECG showing senses and Pulses in ventricle in VVT mode

5.4.5 DDD pseudo code:

From the flow chart of DDD mode, the following pseudo code is written so as to develop the original code. LRI, Sensed AVI, Paced AVI, URI, VRP, ARP, PVARP, PAVB are the parameters for this mode. Some of these values are initialized and some of them are dynamically taken from the user interface.

```
DDD
        --- Configuration Parameters:
            LRI_Config=1000msec
            Sensed AVI_Config=200msec
            Paced VAI_Config=250msec
            URI_Config=400msec
            Ventricle_voltage_sensitivity_Config=7milli Volts
            Atrium_voltage_sensitivity_Config=7milli Volts
            Ventricle_ Pacing_Voltage_Config = 3.5 volts
            Atrium_ Pacing_Voltage_Config= 3.5 volts
            VRP_Config= 350msec
            ARP_Config= 350msec
            PVARP_Config= 250msec
            PAVB_Config=40msec

                                                            (Contd. . .)
```

```
--- Initialization
    LRI= LRI_Config
     Sensed AVI =Sensed VAI_Config
     Paced AVI=Paced AVI_Config
     VAI=LRI-Fixed AVI
     URI = URI_Config
     PVARP=PVARP_Config
     PAVB=PAVB_Config
     VRP=VRP_Config
     ARP=ARP_Config
     VSensitivity= Ventricle_voltage_sensitivity_Config
     ASensitivity= Atrium_voltage_sensitivity_Config
      Pvoltage_V = Ventricle_Pacing_Voltage_Config
      Pvoltage_A = Atrium_Pacing_Voltage_Config
      Last Event=Atrium
  Start Timer0 (Fixed AVI+VAI)
//There may be interrupts which should execute their corresponding interrupt service routine
```

Ventricle Interrupt:

```
Interrupt_time= get Timer0 ();          //Gets the current time at which interrupt occurs
URI_time=get Timer1 ();
Check if (Interrupt_time <PAVB)
      Return
Else if (Interrupt_time>=PAVB) and (Intrinsic Ventricular signal>VSensitivity) and (URI_time>URI)
      Reset Timer0 (VAI)                //Timer 0 set to 800msec
      Start Timer0 (VAI)
      Reset Timer1 (URI)                //Timer 1 set to 400msec
      Start Timer1 (URI)
Else if (Timer0 expired) and (URI_time>URI)
      -- ** generate a pace @ Pvoltage_V *     //AV expired, so generate a Ventricular pace
      Reset Timer0 (VAI)                //Timer 0 set to 800msec
      Start Timer0 (VAI)
      Reset Timer1 (URI)                //Timer 1 set to 400msec
      Start Timer1 (URI)
End if
```

Atrial Interrupt:

```
Interrupt_time= get Timer0 ();          //Gets the current time at which interrupt occurs
Check if (Interrupt_time <PVARP)        //Gets the current time at which interrupt occurs
      Return                            //Ignore Sense
Else if (Interrupt_time>=PVARP) and (Intrinsic atrial signal< ASensitivity)
      Return                            //Ignore Sense
Else if (Interrupt_time>=PVARP) and (Intrinsic atrial signal>ASensitivity)     //accept Sense
      Reset Timer0 (Sensed AVI)         //Timer 0 set to 200msec
      Start Timer0 (Sensed AVI)
Else if (Timer0 expired)
      -- ** generate a pace @ Pvoltage_A *     //VAI  expired, so generate an Atrial pace
      Reset Timer0 (Paced AVI)          //Timer 0 set to 250msec
      Start Timer0 (Paced AVI)
End if
```

Initially start the Timer0 set to LRI. Let's say that there is a sense in the ventricle, which invokes an interrupt that should execute the VentricleDetectISR (Interrupt service routine). This ISR verifies whether the intrinsic sense falls in PAVB period. If yes, it neglects this sense and wait for next intrinsic activity. If no, it checks whether the intrinsic sense falls in UR interval (URI). If yes, it ignores this sense. If no, it accepts this ventricular sense and reset the Timer0 to VA Interval and set the Timer1 to URI. Otherwise, if there is no intrinsic activity in ventricle till Timer0 expires, then ventricle is paced and Timer0 is reset to VAI and Timer1 is reset to URI.

If there is a sense in the atrium, it invokes an interrupt that should execute the AtrialDetectISR (Interrupt service routine). This ISR verifies whether the intrinsic sense falls in PVARP period. If yes, it neglects this sense and wait for next intrinsic activity. If no, it accepts this atrial sense and reset the Timer0 to Sensed AV Interval. Otherwise, if there is no intrinsic activity in atrium till Timer0 (Set to VAI in VentricleDetectISR) expires, then atrium is paced and Timer0 is reset to Paced AV interval.

Again if this Timer0 expires, ventricle is paced and Timer0 and Timer1 are reset to VAI and URI respectively. Thus Timer0 is set to VAI as soon as any valid ventricular event takes placed and AVI as soon as any valid atrial event takes place. Timer1 is set to URI as soon as any valid Ventricular event takes place.

Chapter 6

6.1 My Contribution

As hardware, NI USB-6008, Pacemaker Board with PIC18F 4520 Microcontroller, PICkit 2 debugger/programmer is provided. I got the VVI, DDD and DDDR modes from Mark Lawford Pacemaker page http://www.cas.mcmaster.ca/~lawford/pacemaker/ . With the support of this code, I have developed the pseudo code and corresponding C code for VOO, AOO, DOO, VVI, AAI, VVT and AAT modes. I added these modes to the existing modes and got them working on the pacemaker board. I have made a power point presentation which explains basics of a pacemaker and the different modes of it in detail.

6.2 Conclusions

In this way, the different modes of pacemaker can be simulated using Pacemaker Board and NI USB Data acquisition device. The senses and paces can be observed in the Lab view Signal Express. The number of ventricular senses, ventricular paces, atrial senses and atrial paces are noted for a reference in the future. This helps us to understand the previous activity of patient's heart which helps us select the right pacing mode for the patient. A sample database of patients is taken and a GUI is developed which displays the programmed parameters and the electrical activity of the patient in an ECG.

6.2 Future Enhancements

The remaining modes such as VAT, AAT, AAI, VDD, DVI, DDI, DDIR, and VVIR can also be programmed in the same way. Then the time graph of Lab view signal express for all these modes is to be clearly analyzed. The pros and cons of these modes are to be noted for any future use.

All these programmed modes are done in simulation. This simulation can be extended to real time after clearly analyzing the results and performing various tests. There should be an application showing a GUI which should act as ECG. It should also allow the clinician to select the required programmable parameters for all the modes. So, based on these parameters the pacemaker should work. In the mean time if there is some problem with a mode or with the patient's heart activity, the pacemaker should directly switch over to default safe mode.

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