Spring 2020

CSEN 1099 – Introduction to Biomedical Engineering

ECG and Heart Signals

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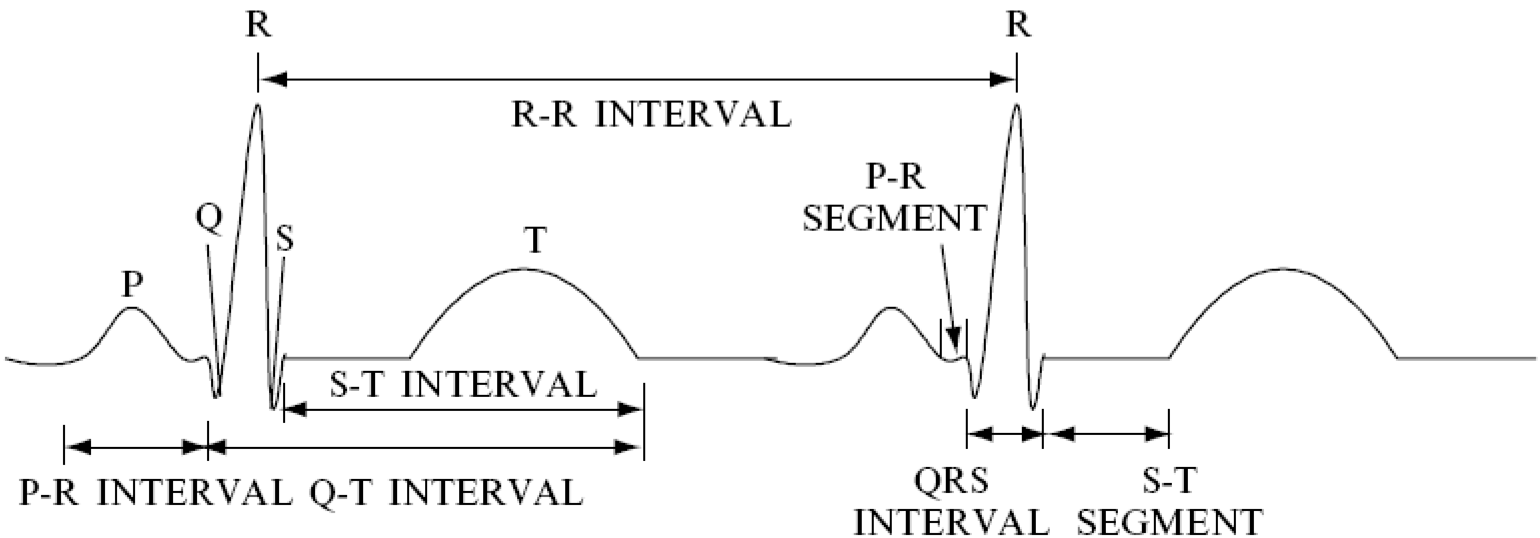
ECG and Heart Signals

- References for this lecture are:
  - U.R. Acharya, J.S. Suri, J.A.E. Spaan, S.M. Krishnan, "Advances in Cardiac Signal Processing", Springer (Chapter 1)
  - K.Blinowska and J. Zygierewicz, “Practical Biomedical Signal Analysis Using Matlab,” CRC Press, Boca Raton, FL, USA, 2011 (Chapter 4: Section 4.2)

ECG Waveform

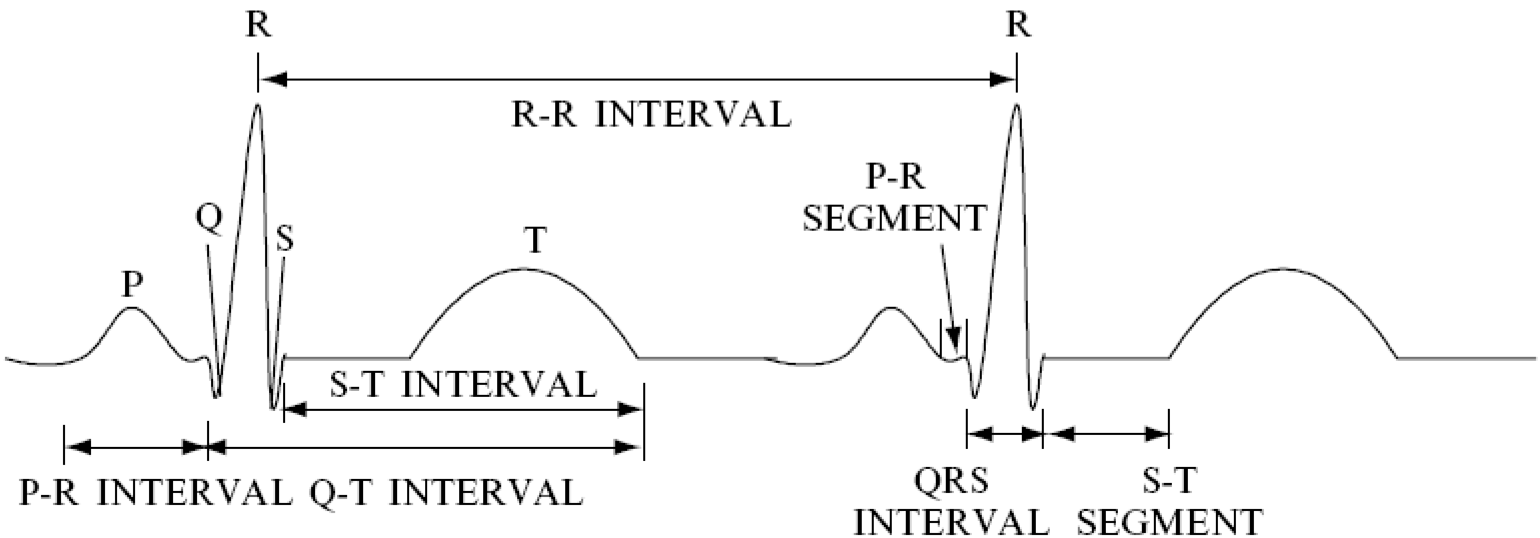
- A typical Electrocardiogram (ECG) signal of a normal person is as follows:



- P-wave corresponds to the depolarization of the atria and indicates the start of atrial contraction that pumps blood to the ventricles
- The Q, R, and S waves are usually treated as a single composite wave known as the QRS-complex. The QRS-complex reflects the depolarization of ventricles, and indicates the start of ventricular contraction that pumps blood to the lungs and the rest of the body

ECG Waveform

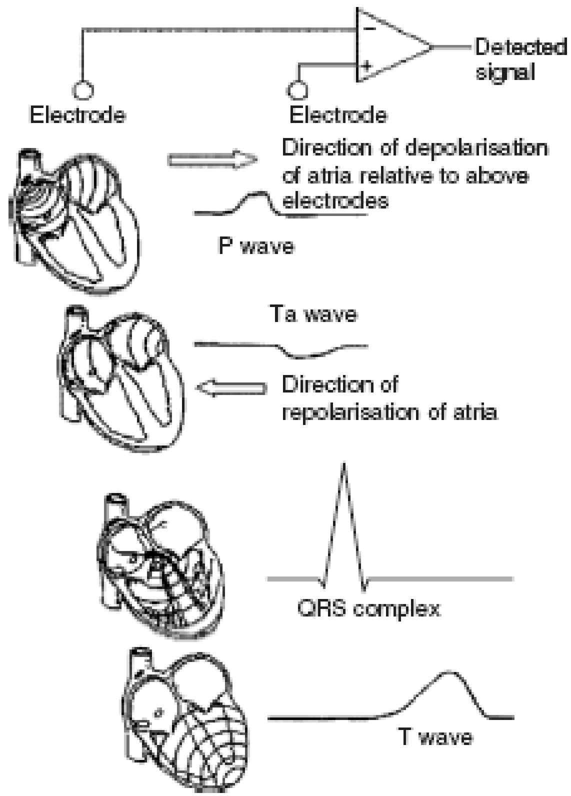
- A typical Electrocardiogram (ECG) signal of a normal person is as follows:



- The T-wave corresponds to the repolarization of the ventricles, which is a necessary recovery process for the heart to depolarize and contract again. The end of the T-wave coincides with the end of ventricular contraction. Atrial repolarization (Ta-wave) is usually not visible as it normally coincides with the QRS-complex (and is buried in the larger waveform)

ECG Waveform

- Different components of ECG as recorded by an electrode



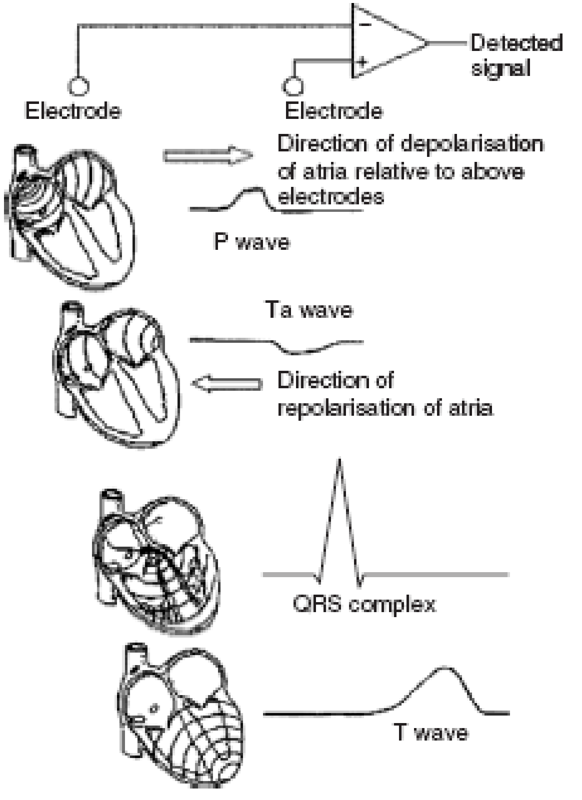
- When depolarization propagates towards the positive electrode of the amplifier, the voltage detected is seen as positive and is represented by an upward deflection in the ECG

ECG Waveform

- Consider having the +ve electrode of the amplifier on the left arm and the –ve electrode on the right arm:

  - Atrial depolarization is seen as a positive (upright) P-wave because the impulse propagates from the right atrium towards the left

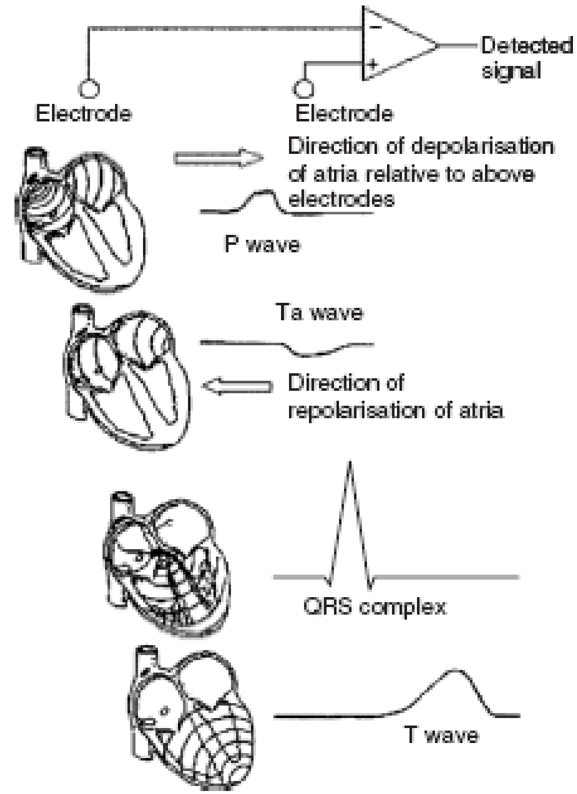
  - Repolarisation (Ta-wave) is seen as a negative (inverted) P-wave but will be masked by the QRS-complex



ECG Waveform

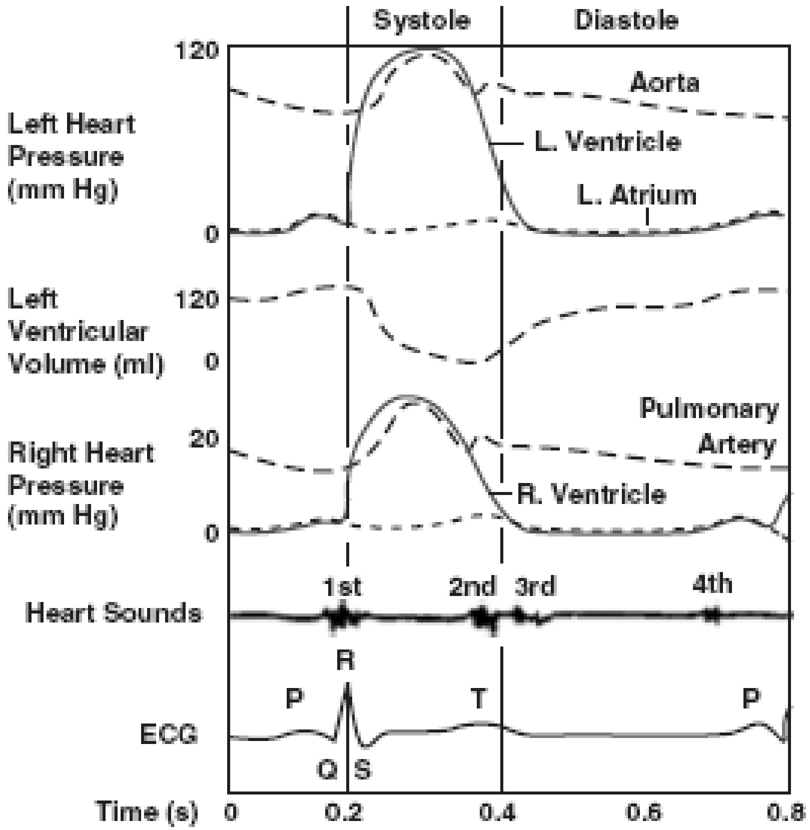
- Consider having the +ve electrode of the amplifier on the left arm and the –ve electrode on the right arm:

  - The depolarization of ventricles starts from left to right, generating the Q wave of the ECG in the left-sided leads. This is followed by the near-simultaneous depolarization of the right and left ventricles. Although the right and left ventricles are depolarizing in opposite directions, the net (sum) direction along the horizontal axis is to the left of the heart, because of the much thicker left ventricular wall generates a larger electrical potential (R wave)



ECG Waveform

- Heart Pressure with ECG



ECG Lead Placements

- The graphical recording of electrical heart signals or the ECG is obtained by using electrodes attached to the skin across different areas of the heart

- The placement of the electrodes determines the directional viewpoint of the heart. Each viewpoint is called a **lead**

- The standard ECG as recorded by clinicians is the 12-lead ECG, which uses 10 electrodes

- A single-lead ECG recorder would typically have three electrodes: the positive electrode, the negative electrode and an indifferent electrode (ground or “right-leg” drive electrode)

ECG Lead Placements

- Surface electrodes are attached to the skin of the patient and are labeled according to their location on the patient's anatomy

  LA = Left Arm Electrode

  RA = Right Arm Electrode

  LL = Left Leg Electrode

  RL = Right Leg Electrode (indifferent electrode)

  Vx = Chest Electrodes: V1 to V6

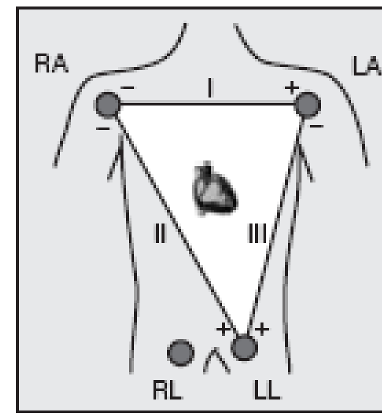
- Three sets of leads are used
  - The limb leads (Bipolar)
  - The augmented limb leads (Unipolar)
  - The precordial leads (Unipolar)

The Limb Leads

- The limb leads are called as such because the electrodes are attached to the limbs

- Each lead has two electrodes (hence bipolar): One electrode acts as the positive electrode while the other as the negative electrode

Lead	Electrode+ (real)	Electrode− (real)	Signal combination	Medical angle	Mathematical angle
I	LA	RA	LA–RA	0°	0°
II	LL	RA	LL–RA	+60°	−60°
III	LL	LA	LL–LA	+120°	−120°



- Electrically, the placement of a limb electrode at any position along the arm is the same. The minor difference is the extra impedance of tissue resistance if the electrode is placed further from the heart

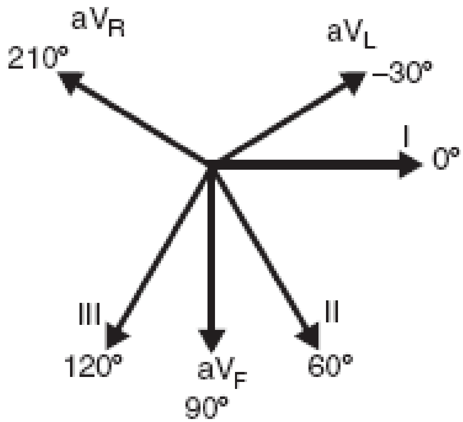
The Augmented Limb Leads

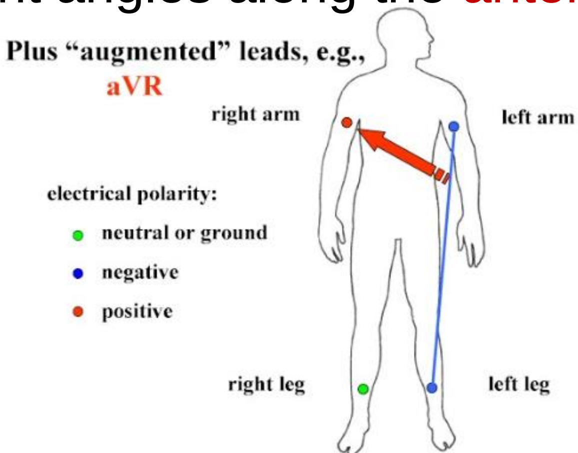
- The signals from the limb electrodes can be combined to give further views called the augmented leads

- One of the limb electrodes serves as the positive electrode. The negative electrode is virtual, being the average of the signals from the remaining two limb electrodes

Lead	Electrode+ (real)	Electrode− (virtual)	Signal combination	Medical angle	Mathematical angle
aVL	LA	RA, LL	LA−1/2(RA + LL)	−30°	+30°
aVF	LL	RA, LA	LL−1/2(RA + LA)	+90°	−90°
aVR	RA	LA, LL	RA−1/2(LA + LL)	−150°	+150°

- In total there are six views obtained from the limb leads and they all view the heart signals from different angles along the anterior plane



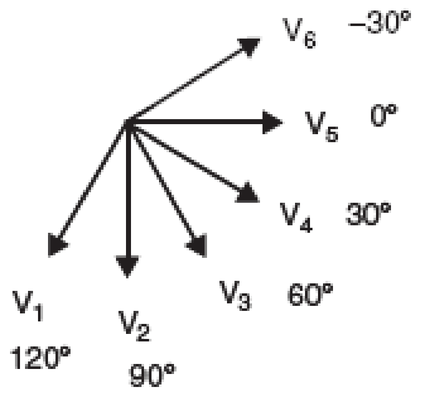


The Precordial Leads

- There are six chest electrodes V1, V2. . .V6 giving rise to six views of the heart signals across the front of the chest

- The positive electrode is the chest electrode. The negative electrode is a virtual electrode commonly called the Wilson Central Terminal (WCT) which is the average of the signals from the three electrodes LA, RA and LL

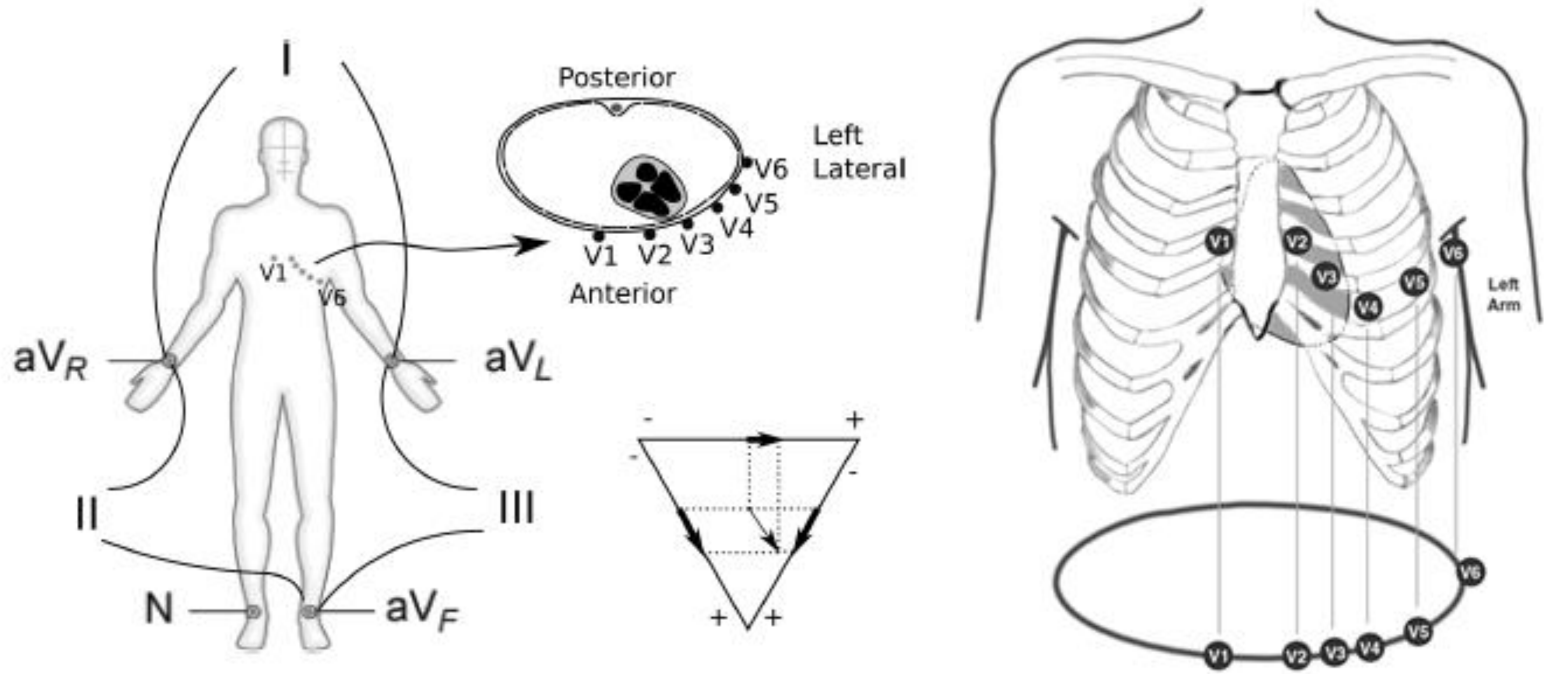
View	Electrode+ (real)	Electrode− (virtual)	Signal combination	Approx medical angle	Mathematical angle
V1	V1	LA, RA, LL	V1−1/3(LA + RA + LL)	+120°	−120°
V2	V2	LA, RA, LL	V2−1/3(LA + RA + LL)	+90°	−90°
V3	V3	LA, RA, LL	V3−1/3(LA + RA + LL)	+60°	−60°
V4	V4	LA, RA, LL	V4−1/3(LA + RA + LL)	+30°	−30°
V5	V5	LA, RA, LL	V5−1/3(LA + RA + LL)	+0°	+0°
V6	V6	LA, RA, LL	V6−1/3(LA + RA + LL)	−30°	+30°



- All the six unipolar chest leads view the heart signals from different angles along the transverse plane

The Precordial Leads

- Together with the limb leads, a total of 12 views are used for diagnosis – resulting in the standard 12-lead ECG. These leads are designed to primarily look at the left side of the heart



- If investigations are needed to look at the right side of the heart, then the chest leads may be mirrored and applied in a similar manner on the right side of the chest

ECG Signal Processing

- The first step in ECG signal processing is artifact removal

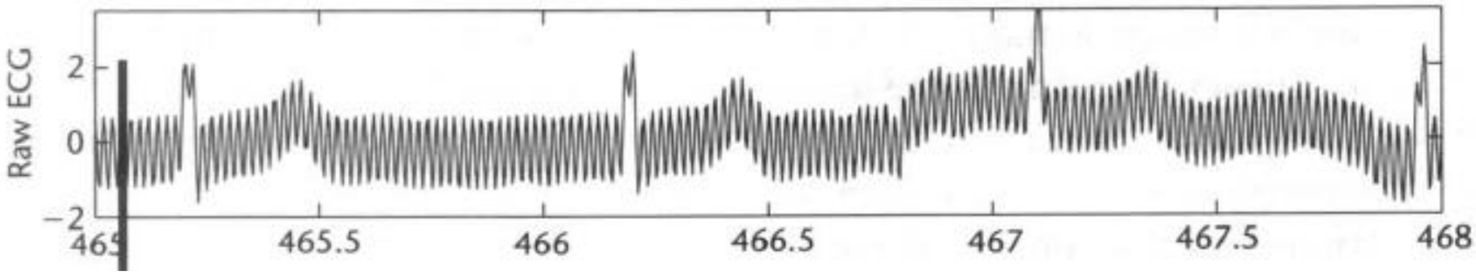
- ECG maybe corrupted with two types of artifacts:
  - Technical artifacts: such as power line interferences, artifacts due to bad electrode contacts, quantization or aliasing errors, noise generated by other medical equipment present in the patient care environment

  - Biological artifacts: such as patient-electrode motion artifacts, muscular activity, baseline drift—usually due to respiration

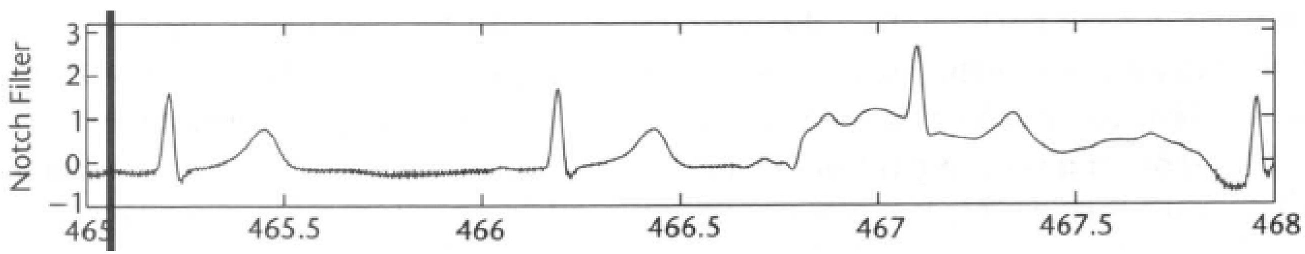
- Technical artifacts may be avoided by designing proper measurement procedures. Elimination of biological artifacts is much more difficult and requires special signal analysis techniques

ECG Signal Processing: Noise Filtering

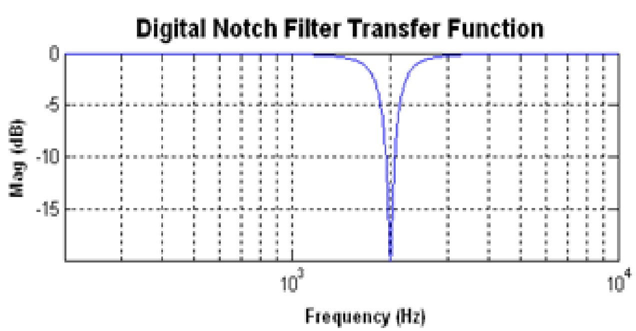
- A typical noisy ECG signal will appear along with a 50Hz (or 60 Hz) mains noise



- A notch filter with a filtered frequency of 50Hz can be used to remove the baseline 50Hz

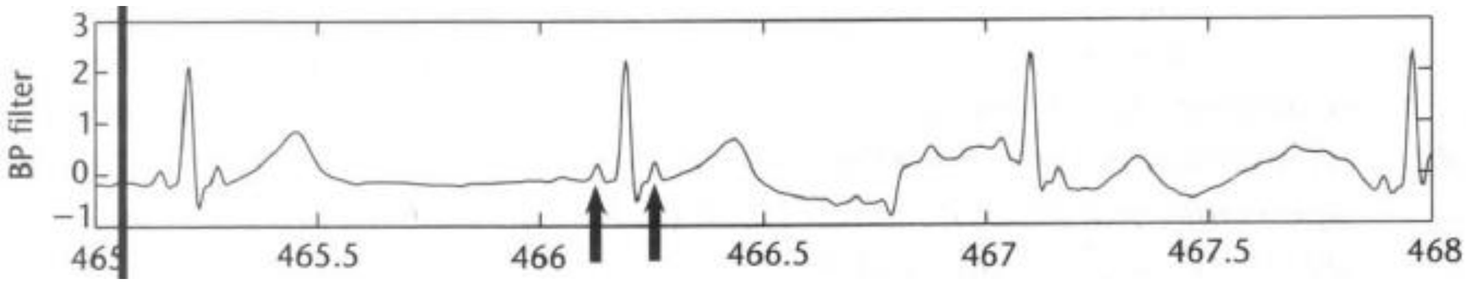


- Example of a notch Filter with a stop frequency of 2000 Hz



ECG Signal Processing: Noise Filtering

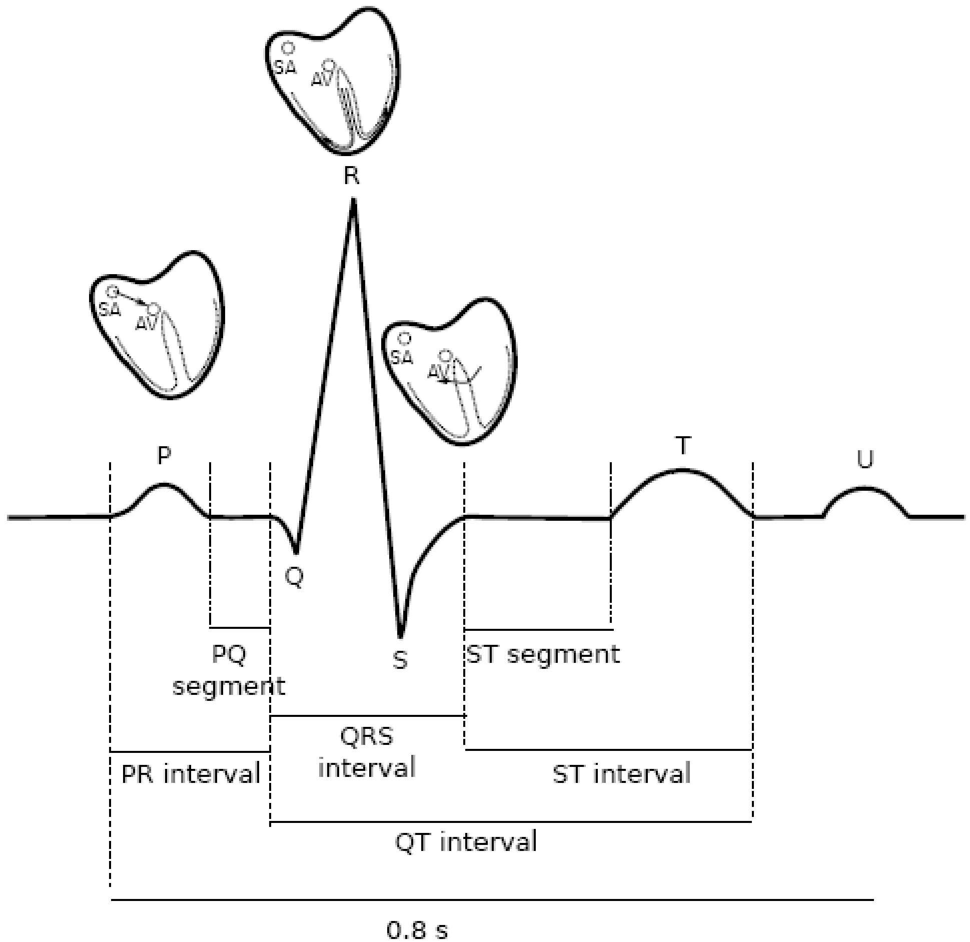
- The ECG signal is further filtered using a Band-pass filter with a bandwidth of 0.1-45 Hz



- Cut-off frequency above 0.8Hz would distort the ECG waveform

ECG Signal Processing: Morphological Features

- Clinical assessment of ECG mostly relies on evaluation of its time domain morphological features such as positions, durations, amplitudes, and slopes of its complexes and segments

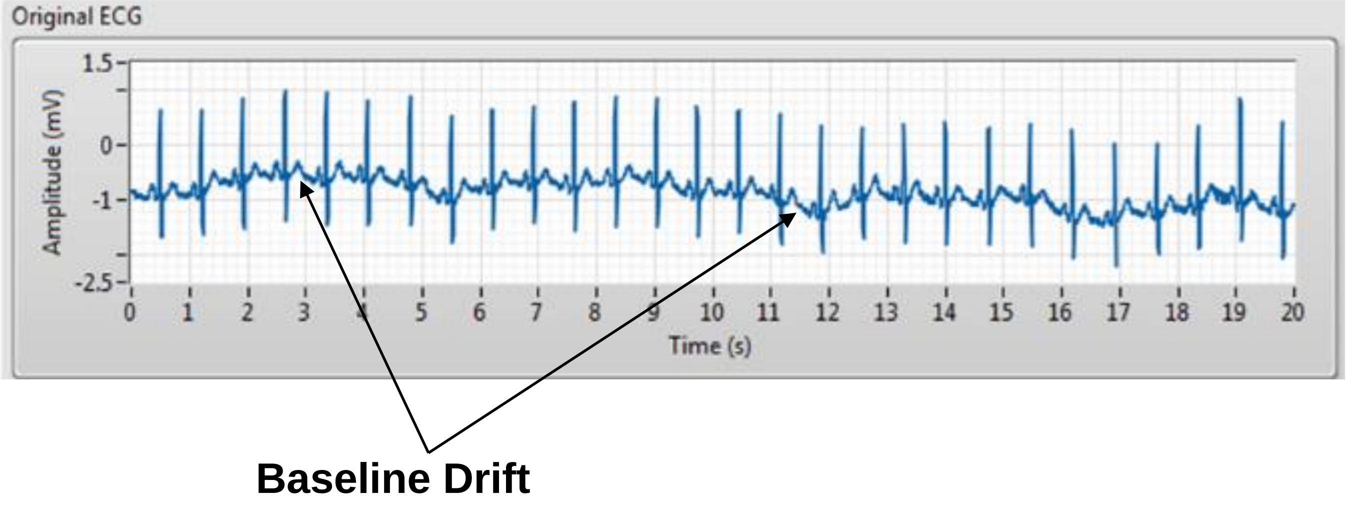


ECG Signal Processing: Morphological Features

- The first step in the analysis is usually detection of the QRS complex; it serves as a marker for averaging of heart cycles, for evaluation of heart rate, for finding the heart axis

- One way to detect ECG is to use a single threshold above which any signal would be considered as part of the QRS complex

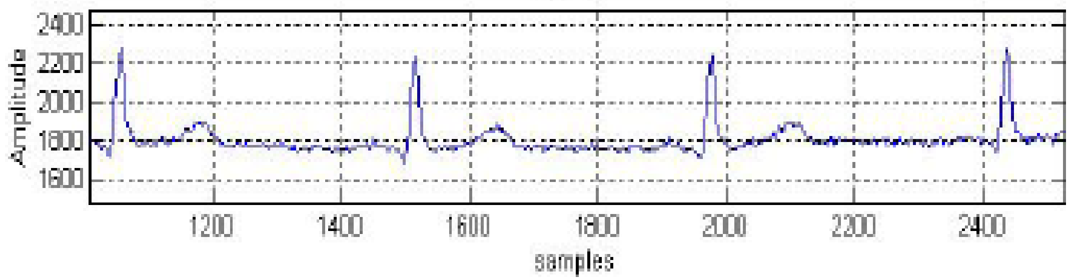
- One problem with this method is baseline drift with which a single threshold might detect false signals



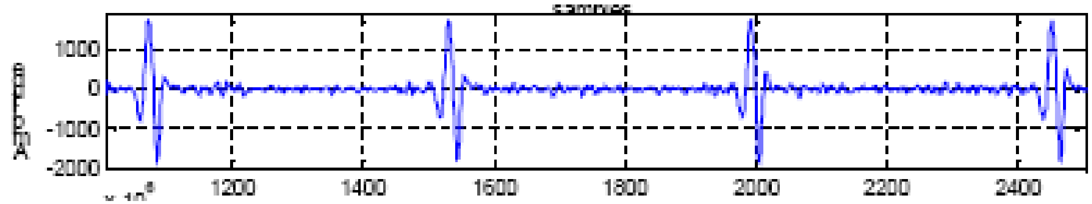
ECG Signal Processing: Morphological Features

- One way to overcome baseline drifts is to differentiate the ECG signal since we are looking for large slopes in the signal

ECG Signal



After Differentiation



- To do the derivative, the following 5-point difference equation can be used

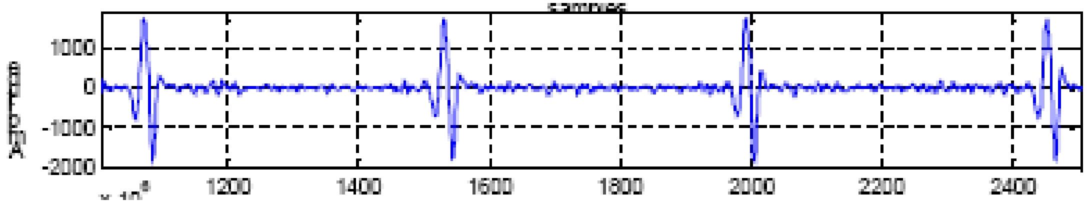
$$y(nT) = (1/8T)\,[-x(nT - 2T) - 2x(nT - T) + 2x(nT + T) + x(nT + 2T)]\,.$$

ECG Signal Processing: Morphological Features

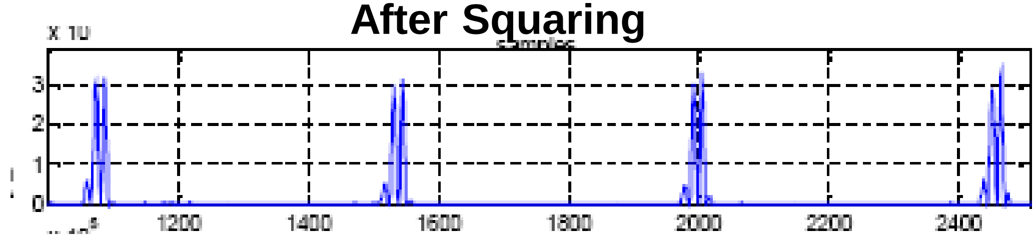
- The next step is to square the derivative. This makes all data points positive and does nonlinear amplification of the output of the derivative emphasizing the higher frequencies (i.e., predominantly the ECG frequencies)

$$y(nT) = [x(nT)]^2$$

After Differentiation



After Squaring



ECG Signal Processing: Morphological Features

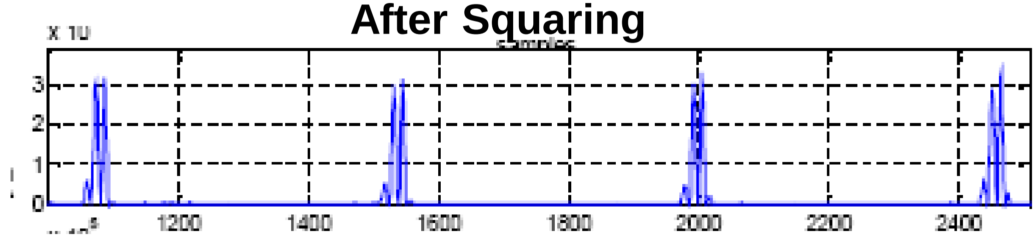
- The next step is to smooth the squared signal using a moving average window

$$y(nT) = (1/N)\,[x(nT - (N-1)\,T) + x(nT - (N-2)\,T) + \cdots + x(nT)]$$

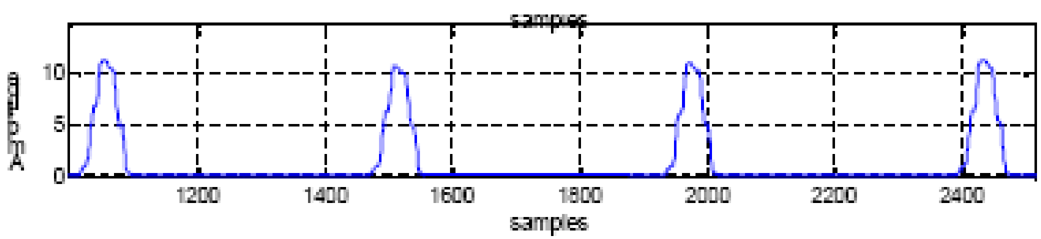
where N is the number of samples in the width of the moving average window

- N should be set approximately the same as the widest possible QRS complex

After Squaring

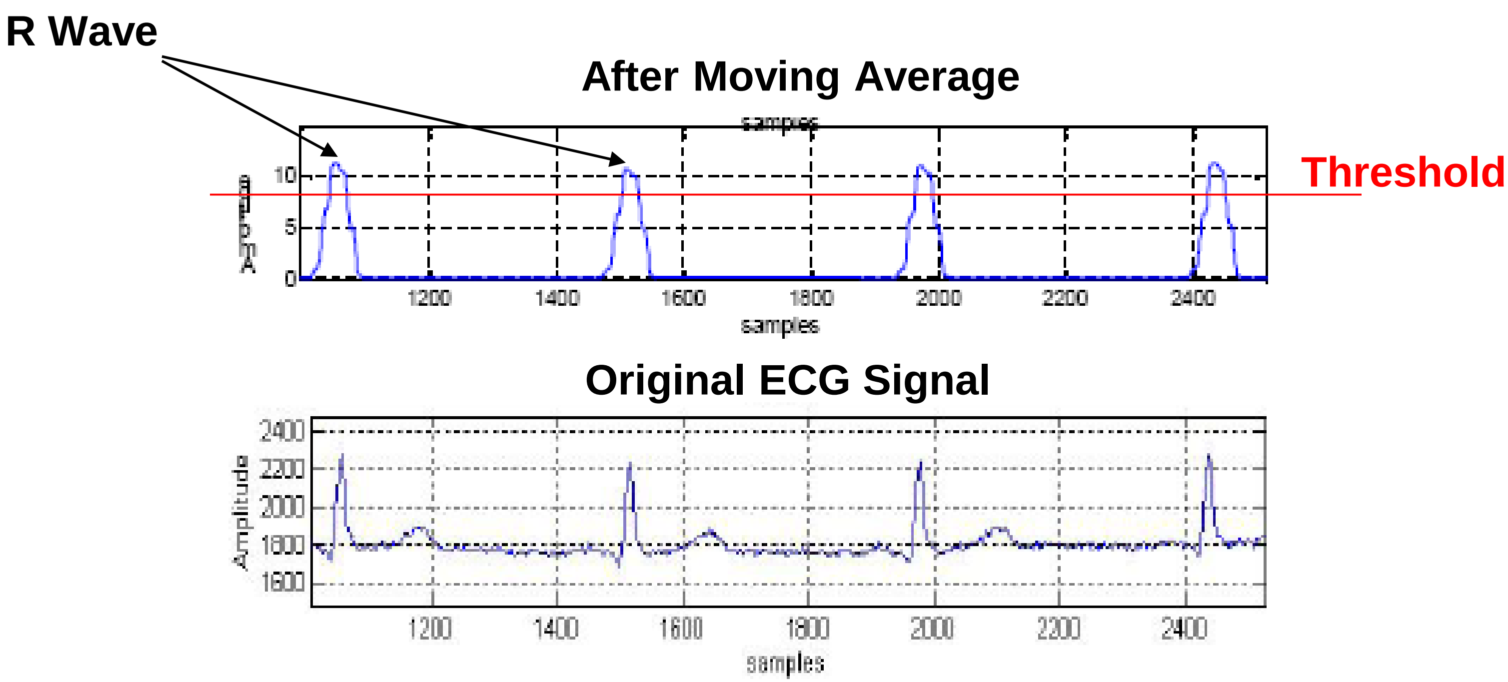


After Moving Average



ECG Signal Processing: Morphological Features

- The final step is to set a threshold on the moving average output. The peak value above the threshold within the moving average window is approximately the R wave



Heart Rate Variability Analysis

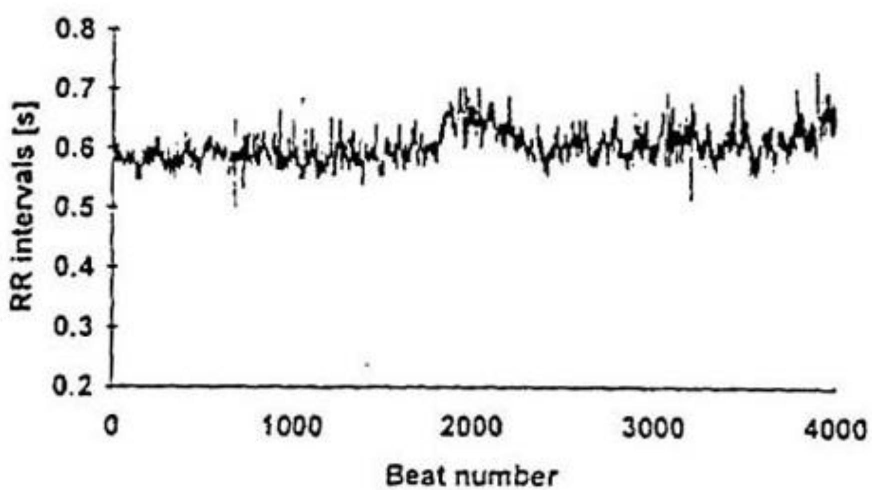
- The sequence of RR intervals—that is, all intervals between adjacent QRS complexes resulting from sinus node depolarizations—forms the RR interval time series or RR tachogram

$$\mathrm{RR}_i = t_i - t_{i-1}$$

- A corresponding sequence of instantaneous heart rate is defined as

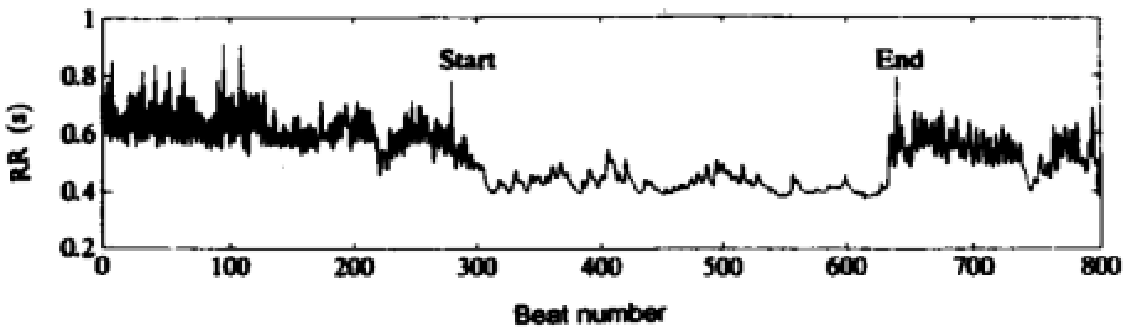
$$\mathrm{ff}_i = \frac{1}{\mathrm{RR}_i}$$

- Heart rate variability (HRV) is a physiological phenomenon of the variation of the time interval between heartbeats



Heart Rate Variability Analysis

- Symptoms and diseases affect the HRV signal. For example, the HRV of a heart with a period of artery occlusion will be as shown below



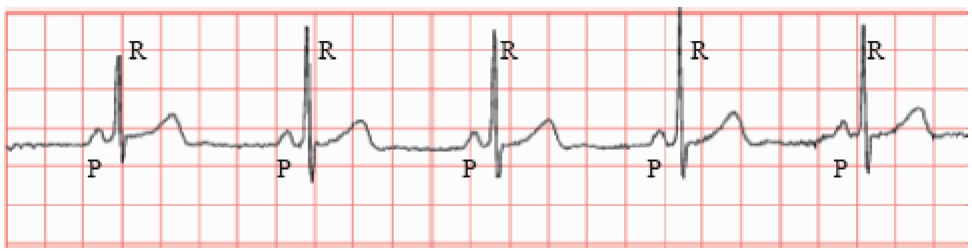
Heart Disorders and ECG

- Looking at an ECG, one can determine the type of heart disorder of a patient
- The manner in which the heart contracts over time determines the rhythm of the heart
- **Normal sinus rhythm** (NSR) is the normal rhythm of the heart when there is no disease or disorder affecting it. NSR is characterized by a heart rate of 60 to 100 beats per minute
- The regularity of the R-R interval varies slightly with the breathing cycle, typically shortening slightly during respiration

Heart Disorders and ECG

- When the heart rate increases beyond 100 beats per minute, the rhythm is known as **sinus tachycardia**. This is a normal response of the heart to higher demand for blood circulation

Normal ECG



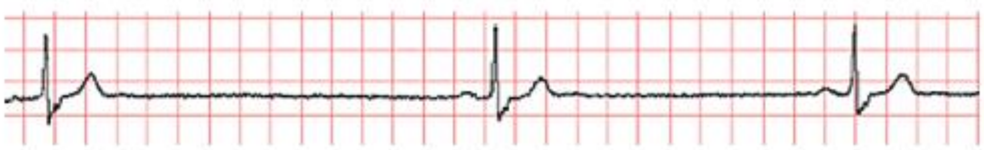
Sinus Tachycardia

Sinus Node Arrhythmias

- The arrhythmia arises from the S-A node for this group of disorders. Since the electrical impulse is generated from the normal pacemaker, the consistent characteristic feature of these arrhythmias is that P-wave wave shape of the ECG is normal

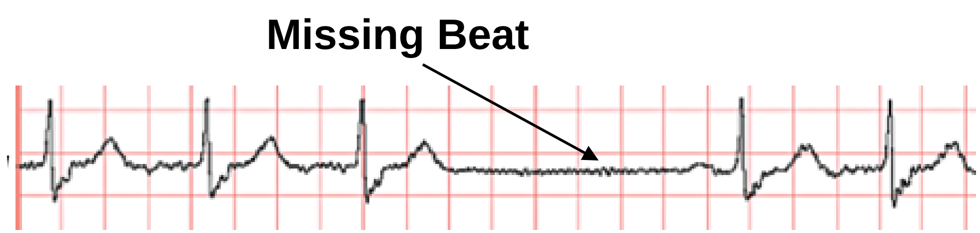
- Sinus Bradycardia:

  The rhythm originates from the S-A node but at a rate of less than 60 beats per minute



- Sinus Arrest:

  The S-A node intermittently fails to fire. There is no P-wave and therefore no accompanying QRS-complex and no T-wave



Atrial Arrhythmias

- Atrial arrhythmias result from electrical impulses that originate outside the S-A node but within the atria

- Since the origin is not from the S-A node, the P-wave inscribed is different in morphology from the sinus P-wave

- Wandering Atrial Pacemaker:

  Instead of the S-A node being the dominant pacemaker, other parts of the atria fire at a rate faster than the S-A node and take control of the heart rate from the S-A node. As the pacemaker site changes, the P-wave size and shape also vary

Atrial Arrhythmias

- Atrial Fibrillation:

  The atrial rate exceeds 350 per minute. This arrhythmia occurs because of uncoordinated activation and contraction of different parts of the atria

  Multiple sites of re-entry in the atria fire rapidly in a haphazard fashion resulting in chaotic atrial contraction

Ventricular Arrhythmias

- In ventricular arrhythmias, the impulses originate from the ventricles and spread outwards to the rest of the heart

- For ventricular arrhythmias, the QRS-complex is wide and bizarre in shape because the impulse is not propagated through the normal pathway but through non-specialized locations that conducts more slowly (hence a wide QRS-complex) and in a different direction

- Premature Ventricular Contractions:

  An extra (abnormal) ventricular contraction originating from the ventricles not preceded by a P-wave