ELECTROCARDIOGRAM (ECG)

Some times it is called EKG from the German electrocardiogram. It is the study of the electrical activity of the heart muscles. ECG is the graphic recording or display of the time-variant biopotentials produced by myocardium (heart muscles) during cardiac cycle i.e. it reflects the rhythmic electrical depolarization and repolarization of myocardium associated with contractions of atria and ventricle.

An instrument used to obtain and record the electrocardiogram is called an electrocardiograph.

The figure shows a typical normal ECG waveform. The different waves in the ECG and the reasons for their formation are specified below.

The horizontal segment of this waveform before P wave is called the base line or isopotential line.
P wave – Depolarization or contraction of atria
QRS complex – Repolarization of atria and depolarization of ventricles occurring simultaneously.
T wave – Repolarization of both ventricles (relaxation of myocardium)
U wave – after potentials in the ventricular muscle or slow repolarization of purkinje fibers.

The normal values of amplitudes and durations of important ECG parameters are

**Amplitude:**
- \( P = 0.25 \text{mV} \)
- \( R = 1.60 \text{mV} \)
- \( Q = 25\% \text{ of R wave} \)
- \( T = 0.1 - 0.5 \text{ mV} \)

**Duration:**
- PR interval (Indicates time taken by an impulse leaving the SA node, to reach the ventricles) = 0.12 – 0.20 sec
QT interval (Period for one complete ventricle contraction (Systole))
\[= 0.35 - 0.44\text{sec}\]

ST segment \[= 0.05 - 0.15\text{sec}\]

P wave interval \[= 0.11\text{sec}\]

PQ interval (Indicates the time during which the excitation wave (action potential) is delayed in the fibers near the AV node)

QRS interval (Indicates the time the heart impulse travels first through the inter-ventricle system and then through the free walls of the ventricles)
\[= 0.05 - 0.10\text{sec}\]

If the heart rate is lower than the normal heart rate - Bradycardia (slow heart)
If the heart rate is higher than the normal heart rate - Tachycardia (fast heart)

Under pathological conditions, several changes may occur in the ECG. These include altered paths of excitation in the heart, changed origin of waves (ectopic beats), altered sequences of features, changed magnitudes of one or more features and differing durations of waves or intervals.

Cycles are not evenly spaced – Arrythmia

PR interval greater than 0.2sec – blockage of AV node

Missing of one or more basic features of ECG – any heart block

**Electrical axis** – The electrical axis (parallel to anatomical axis) is defined as the line along which the greatest electromotive force is developed at a given instant during the cardiac cycle. The electrical axis shifts continually through a repeatable pattern during every cardiac cycle.

The position of the heart within the thoracic region of the body and the position of the body (whether erect or recumbent) influences the “electrical axis” of the heart.

The figure shows the electrical axis of the heart that is examined by six of the standard leads.
Electrodes and Leads:
The electrodes affixed to the body, are connected to the ECG machine by separate electrical wires. These wires and the electrodes to which they are connected are usually called leads. For e.g. the electrode applied to the right leg of the patient is called RL lead.

To record an ECG, five electrodes are affixed to the right arm (RA), left arm (LA), left leg (LL), right leg (RL) and chest (C) of the patient. Two of these electrodes or one electrode and an interconnected group of electrodes are selected and connected to the two input terminals of the ECG recorder amplifier. The particular electrodes selected and the way in which they are connected to the amplifier, is also called as a lead.

The voltage generated by the pumping action of the heart is actually a vector whose magnitude and spatial orientation changes with time. Because the ECG signal is measured from electrodes applied to the surface of the body, the waveform of this signal is very dependent on the placement of the electrodes. Some of the segments of the ECG waveform disappear for certain electrode placements. Hence in a normal electrocardiographic examination, the ECG is recorded from a number of different leads usually 12 to ensure that all important details of the waveform are obtained.

The placement of the electrodes and the color code used to identify each electrode is shown in the figure below.

ECG lead configuration:
ECG has three types of lead configurations. They are
1. Three bipolar limb leads
2. Three augmented unipolar limb leads
3. Unipolar chest leads

In the normal electrode placement shown in the figure, four electrodes are used to record the ECG and the electrode in the right leg is used for ground reference because it is away from heart. The plate electrodes are used at the extremities whereas the chest or precordial electrode is often the suction type.
1. **Bipolar limb leads:**

   It was introduced by Einthoven. The three bipolar limb leads are shown in figure 1.12. The three leads are

   1. Lead I – is measured between left arm (LA) and right arm (RA). LA is connected to amplifier’s non-inverting input while RA is connected to inverting input.
   2. Lead II – is measured between left leg (LL) and right arm (RA). LL is connected to amplifier’s non-inverting input while RA is connected to inverting input.
   3. Lead III – is measured between left leg (LL) and left arm (LA). LL is connected to non-inverting input while LA is connected to the inverting input.

Blue – Cardiac axis
Right leg is used for connecting reference electrode. These leads are called bipolar because for each lead the ECG is recorded from two electrodes and the third electrode is not connected. In each of these lead positions, the QRS of a normal heart is such that the R wave is positive.

**Einthoven triangle** – Closed path from right arm (RA) to left arm (LA) to left leg (LL) back to right arm (RA) is an equilateral triangle with heart near the center of the triangle. This is called Einthoven triangle. The below figure shows the Einthoven triangle.

The sides of the triangle represent the lines along which the three projections of the ECG vector are measured. Based on this, Einthoven showed that the instantaneous voltage measured from any one of the three limb lead positions is approximately equal to the algebraic sum of other two or that the vector sum of the projections on all three lines is equal to zero. For these
statements to actually hold true, the polarity of the lead II measurement must be reversed. Out of the three limb leads, lead II produces the greatest R wave potential. Thus when the amplitudes of the three limb leads are measured, the R-wave amplitude of lead II is equal to the sum of the R-wave amplitudes of leads I and III.

**Einthoven law** – States that human body is a homogenous volume conductor. All the limbs can pickup signal only in the frontal plane. The law states that the algebraic sum of complex in lead I and lead III is equal to lead II recorded at that instant.

2. **Augmented unipolar limb leads:**

   It was introduced by Wilson in 1944. The ECG is measured between a limb electrode and a central terminal obtained by connecting the other two limb electrodes through resistors of equal size. The amplitude of the ECG signal is increased without changing its waveform appreciably. The three augmented unipolar limb leads are shown in figure. The three leads are

   1. **Augmented voltage right arm (aVR):** RA is connected to the non-inverting input while LA and LL are summed at the inverting input. The unipolar right arm lead faces the atria and cavity of ventricles.

      By Kirchoff’s law \( a_{VR} = -V_I - V_{III}/2 \)

   2. **Augmented voltage left arm (aVL):** LA is connected to the non-inverting input while RA and LL are summed at the inverting input. The unipolar left arm lead faces the upper side of the heart.

      By Kirchoff’s law \( a_{VL} = V_I - V_{II}/2 \)

   3. **Augmented voltage foot (aVF):** LL is connected to the non-inverting input while RA and LA are summed at the inverting input. The left leg lead faces interior surface of heart.

      By Kirchoff’s law \( a_{VF} = V_{II} - V_I/2 \)
3. **Unipolar chest or precordial leads:**

The chest electrodes are placed on six predesignated points on the chest close to the heart. These chest positions are designated V1 to V6. The figure shows the unipolar chest leads. The signals from any of the six chest electrodes is applied to non-inverting input and the three active limb electrodes (LA,RA,LL) are used to summed in a resistor Wilson network at the inverting input. The three resistances are equal.

Intercostal means between the ribs
V₁ = Fourth intercostal space, at right sternal margin
V₂ = Fourth intercostal space, at left sternal margin
V₃ = Midway between V₂ and V₄
V₄ = Fifth intercostal space, at mid clavicular line
V₅ = Fifth intercostal space, on anterior axillary line
V₆ = Fifth intercostal space, on mid axillary line

V₁ and V₂ reflect RV activity.
V₃ and V₄ reflect activity from intraventricular septum
V₅ and V₆ reflect left ventricular activity.
Out of the ECGs recorded from these 12 selections, the leads I and II resembles most closely the idealized waveform.

Marriot Lead:
In addition to the lead systems already discussed, there are other lead modifications for use in coronary care unit. The most widely used modification is modified chest lead I (MCL₁) or Marriot lead. This lead system simulates the V₁ position with electrode placement as follows: Positive electrode in the four intercostal space, right sternal border, negative electrode just below the outer portion of the left clavicle and ground usually below the right clavicle. The monitor is set on lead I for this bipolar tracing. It is very useful in differentiating left ventricular ectopic rhythms from aberrant right ventricular or supraventricular rhythms.

ECG MACHINE / RECORDER

The following figure shows the block diagram of an ECG machine. The frequency selective network is an RC network which provides necessary damping of the pen motor. The auxiliary circuits provide 1mV calibration signal and automatic blocking of the amplifier when switch is moved.
The figure shows the principle units or building blocks of an ECG recorder.
**Patient cable:**
One end of this cable plugs into the ECG recorder and the connecting wires for the patient electrodes originate from the other end.

**Lead selector switch:** The wires from the patient electrode are connected to this switch. It has resistors needed for unipolar leads. The switch is used to select the leads. A push button allows insertion of standardization voltage of 1mV to calibrate the recorder, before or after each recording.

**Preamplifier:** From the lead selector switch the ECG signal goes to a preamplifier. It is a three or four stage differential amplifier with large negative current feedback and high CMRR. It is AC coupled to avoid problems with small dc voltage originating from polarization of electrodes. It has a ‘gain’ switch to set the sensitivity or gain.

**Pen amplifier:** It is a DC amplifier which provides power to drive the pen motor that records the actual ECG trace. The ‘position’ control is used for centering the pen on paper. A special contact turns off the amplifier when the switch is moved, because it causes artifacts in the trace.

**Recorder:** It uses an electrically heated stylus as pen and heat-sensitive paper. The ‘stylus heat control’ is used to adjust the temperature of the stylus for optimal recording trace. The ‘marker stylus’ is used to mark a coded indication of the lead being recorded at the margin of paper. The coded indication has short marks (dots) and long marks (dashes). The paper speed is 25mm/s normally, 50mm/s is provided for better resolution of QRS complex at very high heart rates or when particular waveform detail is desired.

**Power switch:** When the switch is in the ON position, the power to the amplifier is turned on but paper drive is not running. In the RUN position the paper drive is started.

**Polarity test:** In the older machines it is used to check whether the recorder is connected to the power line with right polarity before connecting electrodes to the patient. The modern machines have line plugs with grounding pins and hence do not require polarity test.
Buffer amplifier: The above figure shows the input circuit of modern ECG machine. It is provided for each patient lead, to increase the input impedance and thus reduce the effect of variations in electrode impedance.

Overvoltage protection: The network of resistors and neon lamps protect the transistors in the buffer amplifiers from overvoltages that occur when the electrocardiograph is used during surgery in conjunction with high frequency devices for cutting and coagulation.

Driven right leg lead: A summing network obtains the sum of voltages from all other electrodes and a driving amplifier whose output is connected to the right leg of the patient. This forces the reference connection at the right leg to assume a voltage equal to the sum of voltages at other leads. This arrangement increases the CMRR of the overall system, reduces interference and reduces the current flow in the right leg electrode.

**TYPES OF ECG RECORDERS**

(i) **Single channel recorders:**

The single channel machines have one amplifier channel and one recording system. Hence only one lead can be recorded at a time. The portable single-channel unit is usually mounted on a cart so as to be wheeled to patient bedside easily. If 12 lead configurations are used, then the paper strip is 3 to 6 feet long. The lead for each trace is encoded using short marks (dots) and long marks (dashes) at the margin of the paper, with marker pen. The strip is cut and the sections are inserted into pockets of a special folder. The recordings from the three limb leads (leads I, II, III) are longer than those from the other lead selections in order to show several QRS complexes and are called rhythm strips.
(ii) Multichannel ECG machine or three-channel recorder:
The multi-channel ECG machines have several amplifier channels and a corresponding number of recording pens.

In three-channel recorder, an ECG with 12 standard leads can be recorded automatically as a sequence of four groups of three leads each. It records three leads simultaneously and switch automatically to the next group of three leads. The time required for the actual recording is only 10 seconds.

The figure shows the block diagram of a microprocessor based three channel ECG machine. An operating program for controlling the lead selection and other operations is stored in a ROM. The lead selector is sequenced to switch between four groups of three lead signals each, every few seconds.

The ECG signals selected by the microprocessor are amplified, filtered and sent to a three-channel multiplexer. The multiplexed analog signals are then given to an analog to digital converter. The digitized signals are stored in a RAM. D-A converter reconstructs the analog signals from the digitized signals. The analog signals are demultiplexed and passed to the video display or chart recorder.

**Advantages:**

1. Since several ECG leads can be recorded simultaneously, the time required to complete the recordings is reduced and different waveforms can be shown in their proper time relationship with respect to each other. This is useful if large numbers of ECGs are recorded and mounted daily.

2. The number of personnel required is reduced and mounting of ECG is simplified because there is no cutting or mounting of individual lead selections.

**Disadvantages:**
Although the actual recording time is reduced, more time is required to apply the electrodes to the patient because separate electrodes must be used for each chest position.

3. Vector electrocardiographs or Vectorcardiographs:

In ECG described so far, only the magnitude of the voltage generated by the activity of the heart is recorded. Vectorcardiography, presents an image of both magnitude and spatial orientation of heart vector.

Vectorcardiography is the technique of analyzing the electrical activity of the heart by obtaining ECGs along three axes at right angles to one another and displaying any two of these ECGs as a vector display on an X-Y oscilloscope. In contrast, the ECG displays the electrical potential in any one single axis.

Since the heart vector is a three-dimensional variable, three views or projections on orthogonal planes are necessary to describe it fully in two-dimensional figures. The signal is resolved into three images corresponding to frontal, sagittal and transverse planes.

The VCG appears as loops in each plane, on a CRT, which are then photographed with a Polaroid camera. In case of any heart disease such as myocardial infarction, the loops are altered. The figure shows the normal VCG in the frontal, sagittal and transverse planes.

VCG illustrates the phase differences between the voltages and also the various leads from which it is derived.
Frank system is the most frequently used special lead placement system to pickup the ECG signals for vector electrocardiograms. VCG provides information about the direction of depolarization and repolarization of the atria and ventricles. It is effective in detecting atrial and ventricular hypertrophy, myocardial infarction, infarctions in the presence of fascicular and bundle branch blocks.

4. Electrocardiograph systems for stress testing:
In the Masters test or two-step exercise test, physiological stress is imposed on the cardiovascular system by letting the patient repeatedly walk up and down a special pair of 9 inch high steps before recording his ECG. It uses a regular single-channel ECG.
In the exercise stress test, the patient walks at a specified speed on a treadmill whose inclination can be changed. Special system used for exercise stress test consists of the following.
   a. A treadmill with automatic programmer to change the speed and inclination so as to apply a specific physiological stress.
   b. ECG radiotelemetry system to record the ECG without artifacts while the patient is on the treadmill.
   c. An ECG monitor with CRT display and heart rate meter.
   d. An ECG recorder.
   e. An automatic or semiautomatic sphygmomanometer for indirect measurement of blood pressure.

5. Electrocardiographs for computer processing:
The ECG signals are recorded on a tape for later computer entry or can be directly transmitted to the computer through special lines or regular telephone lines using a special acoustical coupler. The information regarding the patient is entered with thumbwheel switches or from a keyboard and is transmitted along with the ECG signal.

6. Continuous ECG recording (Holter recording):
Continuous ECG recording technique introduced by Norman Holter captures arrhythmias which occur intermittently or only under certain conditions e.g. emotional stress. A special magnetic tape recorder records the ECG of a patient. The smallest device of this type is actually worn in a shirt pocket and allows recordings of the ECG for four hours. Other recorders about the size of a camera case, is worn over the shoulder and can record for up to 24 hours.
A special scanner which plays back the tape at a higher speed than that used for recording, so that a 24-hour tape can be reviewed in 12 minutes. During the playback, the beat-to-beat interval of the ECG is displayed on a CRT as a picket-fence-like pattern in which arrhythmia episodes are visible. When an arrhythmia is detected, the tape is slowed down to obtain ECG strip for the time interval during which the arrhythmia is discovered.

Uses:
It is used for diagnosing various diseases and conditions associated with the heart e.g. arrhythmias and myocardial infarction and also as timing reference for other measurements.

Disadvantages of ECG:
Certain disorders e.g. those involving heart valves cannot be diagnosed from the ECG.