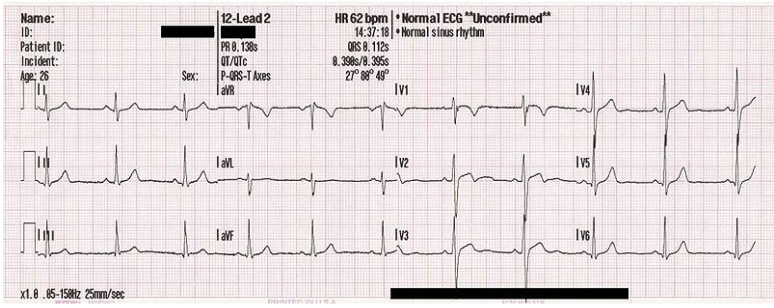
Electrocardiography



12 Lead ECG of a 26-year-old male.

Electrocardiography (**ECG** or **EKG**) is a transthoracic interpretation of the electrical activity of the heart over time captured and externally recorded by skin electrodes.[1] It is a noninvasive recording produced by an electrocardiographic device. The etymology of the word is derived from the Greek *electro*, because it is related to electrical activity, *cardio*, Greek for heart, and *graph*, a Greek root meaning "to write" .

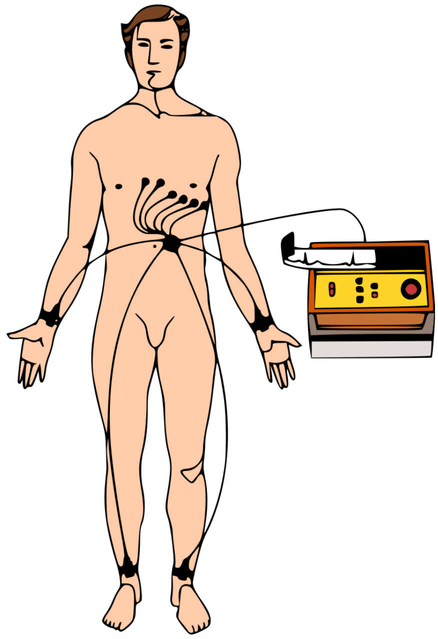


Image showing a patient connected to the 10 electrodes necessary for a 12-lead ECG

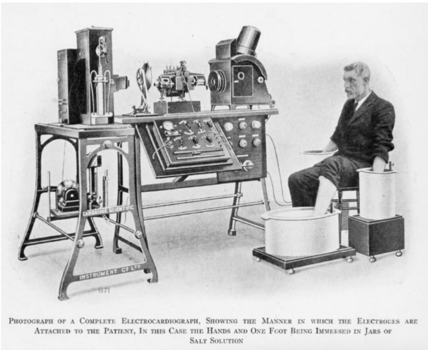
The ECG works by detecting and amplifying the tiny electrical changes on the skin that are caused when the heart muscle "depolarises" during each heart beat. At rest, each heart muscle cell has a charge across its outer wall, or cell membrane. Reducing this charge towards zero is called de-polarisation, which activates the mechanisms in the cell that cause it to contract. During each heartbeat a healthy heart will have an orderly progression of a wave of depolarisation that is triggered by the cells in the sinoatrial node, spreads out through the atrium, passes through "intrinsic conduction pathways" and then spreads all over the ventricles. This is detected as tiny rises and falls in the voltage between two electrodes placed either side of the heart which is displayed as a wavy line either on a screen or on paper. This display indicates the overall rhythm of the heart and weaknesses in different parts of the heart muscle.

Usually more than 2 electrodes are used and they can be combined into a number of pairs. (For example: Left arm (LA),right arm (RA) and left leg (LL) electrodes form the pairs: LA+RA, LA+LL, RA+LL) The output from each pair is known as a **lead**. Each lead is said to look at the heart from a different angle. Different types of ECGs can be referred to by the number of leads that are recorded, for example 3-lead, 5-lead or 12-lead ECGs (sometimes simply "a 12-lead"). A 12-lead ECG is one in which 12 different electrical signals are recorded at approximately the same time and will often be used as a one-off recording of an ECG, typically printed out as a paper copy. 3- and 5-lead ECGs tend to be monitored continuously and viewed only on the screen of an appropriate monitoring device, for example during an operation or whilst being transported in an ambulance. There may, or may not be any permanent record of a 3- or 5-lead ECG depending on the equipment used.

It is the best way to measure and diagnose abnormal rhythms of the heart,[2] particularly abnormal rhythms caused by damage to the conductive tissue that carries electrical signals, or abnormal rhythms caused by electrolyte imbalances.[3] In a myocardial infarction (MI), the ECG can identify if the heart muscle has been damaged in specific areas, though not all areas of the heart are covered.[4] The ECG cannot reliably measure the pumping ability of the heart, for which ultrasound-based (echocardiography) or nuclear medicine tests are used. It is possible to be in cardiac arrest with a normal ECG signal (a condition known as pulseless electrical activity).

History

Alexander Muirhead is reported to have attached wires to a feverish patient's wrist to obtain a record of the patient's heartbeat while studying for his Doctor of Science (in electricity) in 1872 at St Bartholomew's Hospital.[5] This activity was directly recorded and visualized using a Lippmann capillary electrometer by the British physiologist John Burdon Sanderson.[6] The first to systematically approach the heart from an electrical point-of-view was Augustus Waller, working in St Mary's Hospital in Paddington, London.[7] His electrocardiograph machine consisted of a Lippmann capillary electrometer fixed to a projector. The trace from the heartbeat was projected onto a photographic plate which was itself fixed to a toy train. This allowed a heartbeat to be recorded in real time. In 1911 he still saw little clinical application for his work.



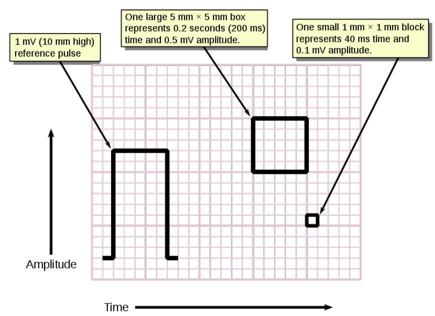
Einthoven's ECG device

An initial breakthrough came when Willem Einthoven, working in Leiden, Netherlands, used the string galvanometer that he invented in 1903.[8] This device was much more sensitive than both the capillary electrometer that Waller used and the string galvanometer that had been invented separately in 1897 by the French engineer Clément Ader.[9] . Rather than using today's self-adhesive electrodes Einthoven's subjects would immerse each of their limbs into containers of salt solutions from which the ECG was recorded.

Einthoven assigned the letters P, Q, R, S and T to the various deflections, and described the electrocardiographic features of a number of cardiovascular disorders. In 1924, he was awarded the Nobel Prize in Medicine for his discovery.[10]

Though the basic principles of that era are still in use today, there have been many advances in electrocardiography over the years. The instrumentation, for example, has evolved from a cumbersome laboratory apparatus to compact electronic systems that often include computerized interpretation of the electrocardiogram.[11]

ECG graph paper



One second of ECG graph paper

The output of an ECG recorder is a graph (or sometimes several graphs, representing each of the leads) with time represented on the x-axis and voltage represented on the y-axis. A dedicated ECG machine would usually print onto graph paper which has a background pattern of 1mm squares (often in red or green), with bold divisions every 5mm in both vertical and horizontal directions. It is possible to change the output of most ECG devices but it is standard to represent each mV on the y axis as 1cm and each second as 25mm on the x-axis (that is a paper speed of 25mm/s). Faster paper speeds can be used - for example to resolve finer detail in the ECG. At a paper speed of 25 mm/s, one small block of ECG paper translates into 40 ms. Five small blocks make up one large block, which translates into 200 ms. Hence, there are five large blocks per second. A calibration signal may be included with a record. A standard signal of 1 mV must move the stylus vertically 1 cm, that is two large squares on ECG paper.

Layout

By definition a 12-lead ECG will show a short segment of the recording of each of the 12-leads. This is often arranged in a grid of 4 colums by three rows, the first columns being the limb leads (I,II and III), the second column the augmented limb leads (aVR, aVL and aVF) and the last two columns being the chest leads (V1-V6). It is usually possible to change this layout so it is vital to check the labels to see which lead is represented. Each column will usually record the same moment in time for the three leads and then the recording will switch to the next column which will record the heart beats after that point. It is possible for the heart rhythm to change between the columns of leads. Each of these segments is short, perhaps 1-3 heart beats only, depending on the heart rate and it can be difficult to analyse any heart rhythm that shows changes between heart beats. To help with the analysis it is common to print one or two "rhythm strips" as well. This will usually be lead II (which shows the electrical signal from the atrium, the P-wave, well) and shows the rhythm for the whole time the ECG was recorded (usually 5-6 seconds). The term "rhythm strip" may also refer to the whole printout from a continuous monitoring system which may show only one lead and is either initiated by a clinician or in response to an alarm or event.

Leads

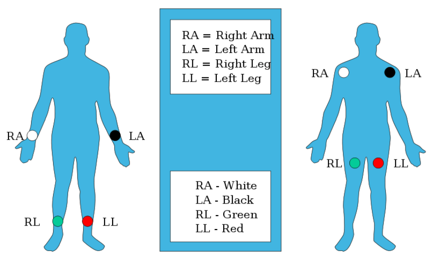
The term "lead" in electrocardiography causes much confusion because it is used to refer to two *different* things. In accordance with common parlance the word lead may be used to refer to the electrical cable attaching the electrodes to the ECG recorder. As such it may be acceptable to refer to the "left arm lead" as the electrode (and its cable) that should be attached at or near the left arm. There are usually ten of these electrodes in a standard "12-lead" ECG.

Alternatively (and some would say properly, in the context of electrocardiography) the word *lead* may refer to the tracing of the voltage difference between two of the electrodes and is what is actually produced by the ECG recorder. Each will have a specific name. For example "Lead I" (lead one) is the voltage between the right arm electrode and the left arm electrode, whereas "Lead II" (lead two) is the voltage between the right limb and the feet. (This rapidly becomes more complex as one of the "electrodes" may in fact be a composite of the electrical signal from a combination of the other electrodes. (See later.) Twelve of this type of lead form a "12-lead" ECG

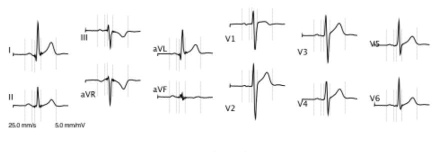
To cause additional confusion the term "limb leads" usually refers to the tracings from leads I, II and III rather than the electrodes attached to the limbs.

Placement of electrodes

Ten electrodes are used for a 12-lead ECG. The electrodes usually consist of a conducting gel, embedded in the middle of a self-adhesive pad onto which cables clip. Sometimes the gel also forms the adhesive. [12] They are labeled and placed on the patient's body as follows:[13] [14]



Proper placement of the limb electrodes, color coded as recommended by the American Health Association (a different colour scheme is used in Europe). Note that the limb electrodes can be far down on the limbs or close to the hips/shoulders, but they must be even (left vs right).[15]



12 leads

Electrode label (in the USA)	Electrode placement
RA	On the right arm, avoiding bony prominences.
LA	In the same location that RA was placed, but on the left arm this time.
RL	On the right leg, avoiding bony prominences.
LL	In the same location that RL was placed, but on the left leg this time.
V_1	In the *fourth* intercostal space (between ribs 4 & 5) just to the *right* of the sternum (breastbone).
V_2	In the *fourth* intercostal space (between ribs 4 & 5) just to the *left* of the sternum.
V_3	Between leads V_2 and V_4.
V_4	In the fifth intercostal space (between ribs 5 & 6) in the mid-clavicular line (the imaginary line that extends down from the midpoint of the clavicle (collarbone).
V_5	Horizontally even with V_4, but in the anterior axillary line. (The anterior axillary line is the imaginary line that runs down from the point midway between the middle of the clavicle and the lateral end of the clavicle; the lateral end of the collarbone is the end closer to the arm.)
V_6	Horizontally even with V_4 and V_5 in the midaxillary line. (The midaxillary line is the imaginary line that extends down from the middle of the patient's armpit.)

Additional electrodes

The classical 12-lead ECG can be extended in a number of ways in an attempt to improve its sensitivity in detecting myocardial infarction involving territories not normally "seen" well. This includes an rV_4 lead which uses the equivalent landmarks to the V_4 but on the *right* side of the chest wall and extending the chest leads onto the back with a V_7, V_8 and V_9

Limb leads

In both the 5- and 12-lead configuration, leads I, II and III are called *limb leads*. The electrodes that form these signals are located on the limbs—one on each arm and one on the left leg.[16] [17] [18] The limb leads form the points of what is known as *Einthoven's triangle*.[19]

- Lead I is the voltage between the (positive) left arm (LA) electrode and right arm (RA) electrode:

$$I = LA - RA.$$

- Lead II is the voltage between the (positive) left leg (LL) electrode and the right arm (RA) electrode:

$$II = LL - RA.$$

- Lead III is the voltage between the (positive) left leg (LL) electrode and the left arm (LA) electrode:

$$III = LL - LA.$$

Simplified electrocardiograph sensors designed for teaching purposes at e.g. high school level are generally limited to three arm electrodes serving similar purposes. [20]

Unipolar vs. bipolar leads

There are two types of leads: *unipolar* and *bipolar*. Bipolar leads have one positive and one negative pole.[21] In a 12-lead ECG, the limb leads (I, II and III) are bipolar leads. Unipolar leads also have two poles, as a voltage is measured; however, the negative pole is a composite pole (Wilson's central terminal) made up of signals from lots of other electrodes.[22] In a 12-lead ECG, all leads besides the limb leads are unipolar (aVR, aVL, aVF, V_1, V_2, V_3, V_4, V_5, and V_6).

Wilson's central terminal V_W is produced by connecting the electrodes, RA; LA; and LL, together, via a simple resistive network, to give an average potential across the body, which approximates the potential at infinity (i.e. zero):

$$V_W = \frac{1}{3}(RA + LA + LL).$$

Augmented limb leads

Leads aVR, aVL, and aVF are *augmented limb leads*. They are derived from the same three electrodes as leads I, II, and III. However, they view the heart from different angles (or vectors) because the negative electrode for these leads is a modification of Wilson's central terminal. This zeroes out the negative electrode and allows the positive electrode to become the "exploring electrode". This is possible because *Einthoven's Law* states that I + (−II) + III = 0. The equation can also be written I + III = II. It is written this way (instead of I − II + III = 0) because Einthoven reversed the polarity of lead II in Einthoven's triangle, possibly because he liked to view upright QRS complexes. Wilson's central terminal paved the way for the development of the augmented limb leads aVR, aVL, aVF and the precordial leads V_1, V_2, V_3, V_4, V_5 and V_6.

- Lead **augmented vector right (aVR)** has the positive electrode (*white*) on the right arm. The negative electrode is a combination of the left arm (black) electrode and the left leg (red) electrode, which "augments" the signal strength of the positive electrode on the right arm:

$$aVR = RA - \frac{1}{2}(LA + LL).$$

- Lead **augmented vector left (aVL)** has the positive (*black*) electrode on the left arm. The negative electrode is a combination of the right arm (white) electrode and the left leg (red) electrode, which "augments" the signal strength of the positive electrode on the left arm:

$$aVL = LA - \frac{1}{2}(RA + LL).$$

- Lead **augmented vector foot (aVF)** has the positive (*red*) electrode on the left leg. The negative electrode is a combination of the right arm (white) electrode and the left arm (black) electrode, which "augments" the signal of the positive electrode on the left leg:

$$aVF = LL - \frac{1}{2}(RA + LA).$$

The augmented limb leads aVR, aVL, and aVF are amplified in this way because the signal is too small to be useful when the negative electrode is Wilson's central terminal. Together with leads I, II, and III, augmented limb leads aVR, aVL, and aVF form the basis of the *hexaxial reference system*, which is used to calculate the heart's electrical axis in the *frontal plane*. The aVR, aVL, and aVF leads can also be represented using the I and II limb leads:

$$aVR = -\frac{I + II}{2}$$

$$aVL = I - \frac{II}{2}$$

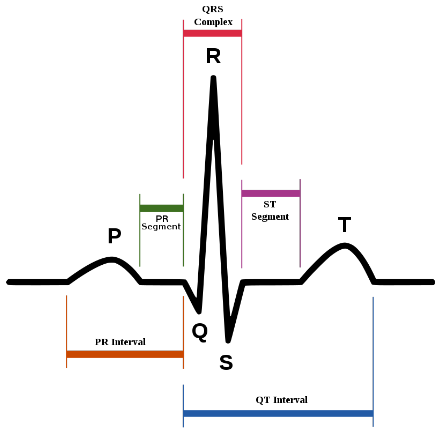
$$aVF = II - \frac{I}{2}$$

Precordial leads

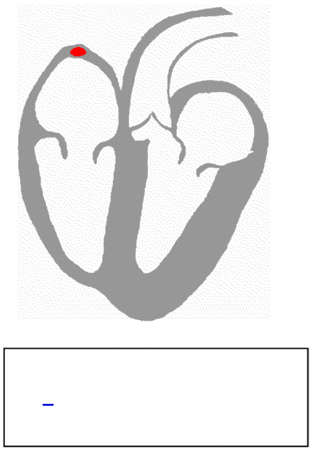
The electrodes for the precordial leads (V_1, V_2, V_3, V_4, V_5 and V_6) are placed directly on the chest. Because of their close proximity to the heart, they do not require augmentation. Wilson's central terminal is used for the negative electrode, and these leads are considered to be *unipolar* (recall that Wilson's central terminal is the average of the three limb leads. This approximates common, or average, potential over the body). The precordial leads view the heart's electrical activity in the so-called *horizontal plane*. The heart's electrical axis in the horizontal plane is referred to as the *Z axis*.

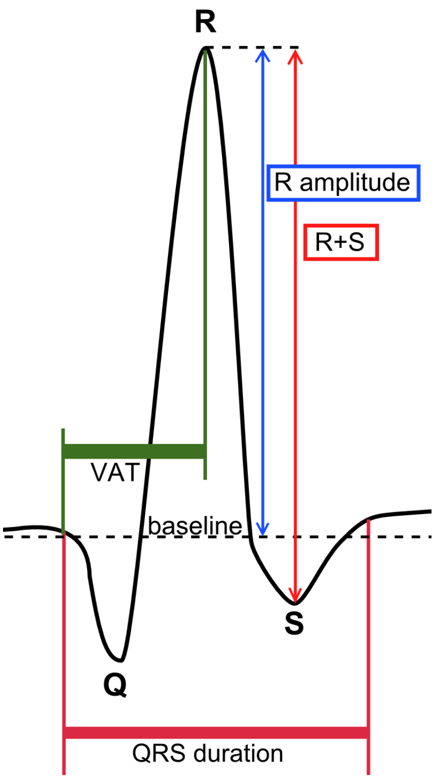
Waves and intervals

A typical ECG tracing of the cardiac cycle (heartbeat) consists of a P wave, a QRS complex, a T wave, and a U wave which is normally visible in 50 to 75% of ECGs.[23] The baseline voltage of the electrocardiogram is known as the *isoelectric line*. Typically the isoelectric line is measured as the portion of the tracing following the T wave and preceding the next P wave.



Schematic representation of normal ECG


Animation of a normal ECG wave.



Detail of the QRS complex, showing ventricular activation time (VAT) and amplitude.

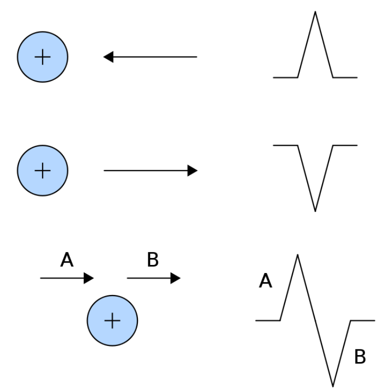
Feature	Description	Duration
RR interval	The interval between an R wave and the next R wave is the inverse of the heart rate. Normal resting heart rate is between 50 and 100 bpm	0.6 to 1.2s
P wave	During normal atrial depolarization, the main electrical vector is directed from the SA node towards the AV node, and spreads from the right atrium to the left atrium. This turns into the P wave on the ECG.	80ms
PR interval	The PR interval is measured from the beginning of the P wave to the beginning of the QRS complex. The PR interval reflects the time the electrical impulse takes to travel from the sinus node through the AV node and entering the ventricles. The PR interval is therefore a good estimate of AV node function.	120 to 200ms
PR segment	The PR segment connects the P wave and the QRS complex. This coincides with the electrical conduction from the AV node to the bundle of His to the bundle branches and then to the Purkinje Fibers. This electrical activity does not produce a contraction directly and is merely traveling down towards the ventricles and this shows up flat on the ECG. The PR interval is more clinically relevant.	50 to 120ms
QRS complex	The QRS complex reflects the rapid depolarization of the right and left ventricles. They have a large muscle mass compared to the atria and so the QRS complex usually has a much larger amplitude than the P-wave.	80 to 120ms
J-point	The point at which the QRS complex finishes and the ST segment begins. Used to measure the degree of ST elevation or depression present.	N/A
ST segment	The ST segment connects the QRS complex and the T wave. The ST segment represents the period when the ventricles are depolarized. It is isoelectric.	80 to 120ms
T wave	The T wave represents the repolarization (or recovery) of the ventricles. The interval from the beginning of the QRS complex to the apex of the T wave is referred to as the *absolute refractory period*. The last half of the T wave is referred to as the *relative refractory period* (or vulnerable period).	160ms
ST interval	The ST interval is measured from the J point to the end of the T wave.	320ms

QT interval	The QT interval is measured from the beginning of the QRS complex to the end of the T wave. A prolonged QT interval is a risk factor for ventricular tachyarrhythmias and sudden death. It varies with heart rate and for clinical relevance requires a correction for this, giving the QTc.	300 to 430ms
U wave	The U wave is not always seen. It is typically low amplitude, and, by definition, follows the T wave.	

There were originally four deflections, but after the mathematical correction for artifacts introduced by early amplifiers, five deflections were discovered. Einthoven chose the letters P, Q, R, S, and T to identify the tracing which was superimposed over the uncorrected labeled A, B, C, and D.[24]

Vectors and views

Interpretation of the ECG relies on the idea that different leads (by which we mean the ECG leads I,II,III, aVR, aVL, aVF and the chest leads) "view" the heart from different angles. This has two benefits. Firstly, leads which are showing problems (for example ST segment elevation) can be used to infer which region of the heart is affected. Secondly, the overall direction of travel of the wave of depolarisation can also be inferred which can reveal other problems. This is termed the cardiac **axis** . Determination of the cardiac axis relies on the concept of a vector which describes the motion of the depolarisation wave. This vector can then be described in terms of its components in relation to the direction of the lead considered. One component will be in the direction of the lead and this will be revealed in the behaviour of the QRS complex and one component will be at 90 degrees to this (which will not). Any net positive deflection of the QRS complex (i.e. height of the R-wave minus depth of the S-wave) suggests that the wave of depolarisation is spreading through the heart in a direction that has some component (of the vector) in the same direction as the lead in question.



Graphic showing the relationship between positive electrodes, depolarization wavefronts (or mean electrical vectors), and complexes displayed on the ECG.

Axis

The heart's *electrical axis* refers to the general direction of the heart's depolarization wavefront (or *mean electrical vector*) in the frontal plane. With a healthy conducting system the cardiac axis is related to where the major muscle bulk of the heart lies. Normally this is the left ventricle with some contribution from the right ventricle. It is usually oriented in a right shoulder to left leg direction, which corresponds to the left inferior quadrant of the hexaxial reference system, although −30° to +90° is considered to be normal. If the left ventricle increases its activity or bulk then there is said to be "left axis deviation" as the axis swings round to the left beyond -30°, alternatively in conditions where the right ventricle is strained or hypertrophied then the axis swings round beyond +90° and "right axis deviation" is said to exist. Disorders of the conduction system of the heart can disturb the electrical axis without neccesarily reflecting changes in muscle bulk.

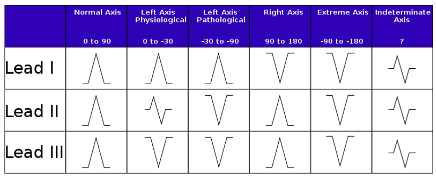


Diagram showing how the polarity of the QRS complex in leads I, II, and III can be used to estimate the heart's electrical axis in the frontal plane.

Normal	−30° to 90°	Normal	Normal
Left axis deviation	−30° to −90°	May indicate left anterior fascicular block or Q waves from inferior MI.	Left axis deviation is considered normal in pregnant women and those with emphysema.
Right axis deviation	+90° to +180°	May indicate left posterior fascicular block, Q waves from high lateral MI, or a right ventricular strain pattern.	Right deviation is considered normal in children and is a standard effect of dextrocardia.
Extreme right axis deviation	+180° to −90°	Is rare, and considered an 'electrical no-man's land'.	

In the setting of right bundle branch block, right or left axis deviation may indicate bifascicular block.

Clinical lead groups

There are twelve leads in total, each recording the electrical activity of the heart from a different perspective, which also correlate to different anatomical areas of the heart for the purpose of identifying acute coronary ischemia or injury. Two leads that look at neighbouring anatomical areas of the heart are said to be *contiguous* (see color coded chart). The relevance of this is in determining whether an abnormality on the ECG is likely to represent true disease or a spurious finding.

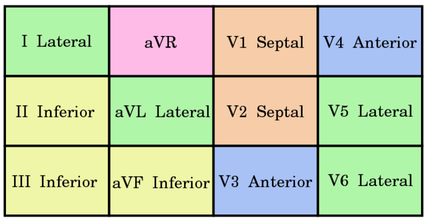


Diagram showing the contiguous leads in the same color

Category	Color on chart	Leads	Activity
Inferior leads	Yellow	Leads II, III and aVF	Look at electrical activity from the vantage point of the inferior surface (diaphragmatic surface of heart).
Lateral leads	Green	I, aVL, V_5 and V_6	Look at the electrical activity from the vantage point of the lateral wall of left ventricle. • The positive electrode for leads I and aVL should be located distally on the left arm and because of which, leads I and aVL are sometimes referred to as the *high lateral leads*. • Because the positive electrodes for leads V5 and V6 are on the patient's chest, they are sometimes referred to as the *low lateral leads*.
Septal leads	Orange	V_1 and V_2	Look at electrical activity from the vantage point of the septal wall of the ventricles (interventricular septum).
Anterior leads	Blue	V_3 and V_4	Look at electrical activity from the vantage point of the anterior surface of the heart (sternocostal surface of heart).

In addition, any two precordial leads that are next to one another are considered to be contiguous. For example, even though V4 is an anterior lead and V5 is a lateral lead, they are contiguous because they are next to one another.

Lead aVR offers no specific view of the left ventricle. Rather, it views the inside of the endocardial wall to the surface of the right atrium, from its perspective on the right shoulder.

Filter selection

Modern ECG monitors offer multiple filters for signal processing. The most common settings are monitor mode and diagnostic mode. In monitor mode, the low frequency filter (also called the high-pass filter because signals above the threshold are allowed to pass) is set at either 0.5 Hz or 1 Hz and the high frequency filter (also called the low-pass filter because signals below the threshold are allowed to pass) is set at 40 Hz. This limits artifact for routine cardiac rhythm monitoring. The high-pass filter helps reduce wandering baseline and the low-pass filter helps reduce 50 or 60 Hz power line noise (the power line network frequency differs between 50 and 60 Hz in different countries). In diagnostic mode, the high-pass filter is set at 0.05 Hz, which allows accurate ST segments to be recorded. The low-pass filter is set to 40, 100, or 150 Hz. Consequently, the monitor mode ECG display is more filtered than diagnostic mode, because its passband is narrower.[25]

Some pathological entities which can be seen on the ECG

Shortened QT interval	Hypercalcemia, some drugs, certain genetic abnormalities.
Prolonged QT interval	Hypocalcemia, some drugs, certain genetic abnormalities.
Flattened or inverted T waves	Coronary ischemia, left ventricular hypertrophy, digoxin effect, some drugs.
Hyperacute T waves	Possibly the first manifestation of acute myocardial infarction.
Prominent U waves	Hypokalemia.

Electrocardiogram heterogeneity

Electrocardiogram (ECG) heterogeneity is a measurement of the amount of variance between one ECG waveform and the next. This heterogeneity can be measured by placing multiple ECG electrodes on the chest and by then computing the variance in waveform morphology across the signals obtained from these electrodes. Recent research suggests that ECG heterogeneity often precedes dangerous cardiac arrhythmias.

Future applications

In the future, implantable devices may be programmed to measure and track heterogeneity. These devices could potentially help ward off arrhythmias by stimulating nerves such as the vagus nerve, by delivering drugs such as beta-blockers, and if necessary, by defibrillating the heart.[26]

Equipment

Electrocardiogram machines have been reduced in size and cost over the years. Hand held versions are sold for $800 each. [27]

See also

- Advanced cardiac life support (ACLS)
- Angiogram
- HEART scan
- Ballistocardiograph
- Bundle branch block
- Cardiac cycle
- Echocardiogram
- Electrical conduction system of the heart
- Electrocardiogram technician

- Electroencephalography
- Electrogastrogram
- Electropalatograph
- Electroretinography
- Heart rate monitor
- Holter monitor
- Intrinsicoid deflection
- Magnetic field imaging
- Magnetocardiography
- Myocardial infarction
- Open ECG project
- Treacherous technician syndrome

External links

- Electrocardiogram, EKG, or ECG [28] – Explanation of what an ECG is, who needs one, what to expect during one, etc. Written by the National Heart Lung and Blood Institute (a division of the NIH)
- University of Maryland School of Medicine Emergency Medicine Interest Group [29] – Introduction to EKGs as written by a medical student and a cardiologist
- ECG in 100 steps: Slideshow [30]
- ECG Lead Placement [31] – A teaching guide "designed for student nurses who know nothing at all about Cardiology"
- ECGpedia: Course for interpretation of ECG [32]
- 12-lead ECG library [33]
- Simulation tool to demonstrate and study the relation between the electric activity of the heart and the ECG [34]
- Minnesota ECG Code [35]
- openECGproject - help develop an open ECG solution [36]
- EKG Review: Arrhythmias [37] – A guide to reading ECGs not written for a university biology (anatomy and physiology) course.

References

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[3] "The clinical value of the ECG in noncardiac conditions." *Chest* 2004; **125(4)**: 1561-76. PMID 15078775

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