An electrocardiogram (ECG) is a quick bedside investigation that assesses the electrical activity of the heart. It is a non-invasive, cheap technique that provides critical information about heart rate and rhythm, and helps assess for cardiac disease. ECG monitoring is used often in many different healthcare settings, including acute care, cardiac care and pre-operative assessment.

This article, the first in a three-part series, discusses cardiac electrophysiology, indications for an ECG, monitoring and troubleshooting. Part 2 of the series will take a methodical approach to interpretation, with a focus on cardiac ischaemia; part 3 will explore cardiac rhythm and conduction abnormalities.

**Electrophysiology and mechanical events in the heart**

The heart is an organ that acts as a mechanical pump; it consists of four chambers (right and left atria, and right and left ventricles) that contract sequentially during the cardiac cycle and are regulated by an electrical conducting system. To understand the basics of an ECG, it is important to consider the normal electrophysiology of the heart, in which a cardiac electrical impulse is generated and transmitted to the heart muscle, leading to contractions (the heartbeat).

**Electrophysiology of cardiac cells**

There are two main cell types in the heart:

- Those that conduct electrical impulses (electrical cells);
- Cardiomyocytes (cardiac muscle cells).

Cardiomyocytes contract and relax in response to an electrical stimulus. During their resting state, inside the cells there are high internal levels of potassium ions (K$^+$), compared with outside the cells; along with negatively charged proteins, which creates a chemical gradient. Outside the cardiomyocytes there are more sodium ions (Na$^+$) and calcium ions (Ca$^{2+}$) compared with inside the cell. Overall, this means there is a voltage difference across the cell membrane, called transmembrane potential (TMP). When there is net movement of Na$^+$ and Ca$^{2+}$ into the cell, TMP becomes more positive; when there is net movement of positive ions out of it, TMP becomes more negative.

In response to an electrical stimulus, cardiomyocytes become depolarised and fast Na$^+$ channels open on the cell membrane, allowing Na$^+$ into the cell; because this is positively charged, the TMP becomes more positive, increasing to ~70 millivolts (mV) (resting potential is ~90mV). This is the point at which enough...
**Electrical monitoring of the heart**

The ECG’s origin dates back to the discovery of the heart muscle’s electric activity. In 1901, Willem Einthoven made a breakthrough that facilitated the first steps towards electrocardiography, for which he subsequently won a Nobel Prize in 1924 (Yang et al, 2015).

ECGs are used as a technique to diagnose cardiac disease and to detect abnormal heart rhythm. They may also be used as a general health assessment in certain occupations, including aviation, diving and the military (Chamley et al, 2019). According to professional societies, adequate education for medical staff is critical for ECG monitoring and developing skills in interpreting waveforms and ECG data (Sandau et al, 2017).

In routine clinical practice, there are four main approaches to monitoring cardiac rhythm:

- 12-lead ECG – the gold standard for cardiac monitoring, it provides information about the heart’s electrical activity in three dimensions;
- Basic continuous ECG – less detailed but provides ongoing information about heart rate and rhythm;

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**Electrical pathways of the heart**

The heart’s electrical conducting system (Fig 1) regulates its overall electrical activity and includes the following components:

- Sinoatrial node (SAN);
- Atrioventricular node (AVN);
- Bundle of His;
- Bundle branches;
- Purkinje fibres.

Each heartbeat is initiated by an electrical impulse generated by the SAN; this impulse passes through the atria to the AVN, then through the right and left ventricles, the bundle of His, subsequent bundle branches and the Purkinje fibres. As a result, the atria and ventricles contract sequentially as the impulse is conducted through the different regions of the heart. In normal circumstances, the SAN is the heart’s pacemaker; however, if there is a problem with the SAN, another conducting region centre – such as the AVN, bundle of His or bundle branches – can assume the role of the pacemaker in an occurrence known as an escape rhythm (Jarvis and Saman, 2018; Newby and Grubb, 2018).

**Cardiac cycle**

In healthy individuals, the chambers of the heart contract and relax in a coordinated manner, referred to as systole and diastole respectively. The right and left atria synchronise during atrial systole and diastole, while the right and left ventricles synchronise during ventricular systole and diastole. One complete cycle of these events is called the cardiac cycle, during which the pressure in the cardiac chambers rises and falls, causing the opening and closure of heart valves that regulates blood flow between the chambers.

Pressures on the left side of the heart are around five times higher than those on the right side, but the same volume of blood is pumped per cardiac beat. In the cardiac cycle, blood moves from high- to low-pressure areas (Marieb and Keller, 2018).

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**Fig 1. Electrical conducting system of the heart**

- Sinoatrial node
- Atrioventricular node
- Bundle of His
- Bundle branches
- Purkinje fibres
- Left and right bundle branches

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Box 1. Indications for a 12-lead ECG
- Any cardiac symptoms (palpitations, chest pain, syncope)
- Critical illness
- Peri- or post-cardiac arrest
- History of arrhythmias
- During invasive cardiac procedures
- During sedation or anaesthesia
- Conduction abnormalities
- Toxic insults, such as drug overdose or electrolyte abnormalities
- Respiratory disease, such as pulmonary embolism

ECG = electrocardiogram.

- Holter-tape ECG – uses a portable device to enable continuous monitoring of various electrical activities over 1-7 days as a diagnostic tool;
- Exercise ECG – used to assess the heart’s response to exercise or stress and useful in diagnosing ischaemia.

The 12-lead ECG is a non-invasive method of monitoring the heart’s electrical activity. This bedside test can provide important diagnostic information or be used as part of a baseline assessment; Box 1 outlines some indications for using it.

If there is a concern that a patient’s acute symptoms may have a cardiac cause, continuous cardiac monitoring might be used in a hospital setting. This may help with:
- Immediate recognition of any cardiac rhythm disorder preceding a cardiac arrest;
- Recognition of deteriorating conditions that may lead to life-threatening arrhythmias (in which the heart beats with an irregular or abnormal rhythm);
- Diagnosis and management of arrhythmias (Sandau et al, 2017).

Continuous cardiac monitoring is also an important component of non-invasive monitoring of vital signs, with clinical benefits in medical ward settings (Sun et al, 2020).

How does a 12-lead ECG work?

Normal ECG waveforms

The ECG is a graphical representation of the heart’s electrical activity, plotting its voltage on a vertical axis against time on a horizontal axis. It is recorded onto ECG paper, which runs at a speed of 25mm per second. Standard pink ECG paper is made up of 5 x 5mm squares, each containing 25 smaller 1 x 1mm squares. The 1mm width of each small square represents 40 milliseconds. On the vertical axis, the height of an ECG wave or deflection represents its amplitude (Prutkin, 2020). Fig 2 shows what a normal ECG looks like and its relationship with the stages of the cardiac cycle.

During the normal cardiac cycle, the atrial contraction that takes place is associated with a P-wave (atrial depolarisation) and is of low amplitude because the muscle is relatively thin in the atria. This contrasts with the QRS complex, which represents the electrical impulse as it spreads through the ventricles (ventricular depolarisation). The first deflection of the QRS complex is the Q-wave, which is a negative wave that begins septal depolarisation. The R-wave represents depolarisation of the left ventricular myocardium and the next negative deflection is the S-wave, which represents terminal depolarisation. The T-wave occurs after that and represents the repolarisation of the ventricles.

The ECG also records a number of other parameters:
- PR interval – the duration of time from the start of the P-wave to the start of the QRS complex, this represents the conduction through the AVN.
- QT interval – the time duration between the onset of the QRS complex and the end of the T-wave, this represents the time taken for the ventricles to depolarise and repolarise; it is calculated using lead II or chest leads V5-6 (described later in this piece).
- ST segment – the flat line (isoelectric line) on the ECG between the end of the S-wave and the start of the T-wave; when there is a lack of blood supply (myocardial infarction) or reduced blood supply (ischaemia), the ST segment may be elevated or depressed respectively.

- Exercise ECG – used to assess the heart’s response to exercise or stress and useful in diagnosing ischaemia.
- Holter-tape ECG – uses a portable device to enable continuous monitoring of various electrical activities over 1-7 days as a diagnostic tool.
- Conduction abnormalities
- Toxic insults, such as drug overdose or electrolyte abnormalities
- Respiratory disease, such as pulmonary embolism

Fig 2. Relationship between ECG and cardiac cycle stages

ECG = electrocardiogram.
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It is important to know the normal ranges for the various ECG parameters (Table 1): if any measurements are outside the normal range, thought and investigation are needed to ascertain why and decide on a course of action. Parts 2 and 3 of this series will discuss this in more detail.

**Lead positioning**

It is important to remember that the electrical ‘lead’ actually represents the differences in electrical potentials measured in two points in space. The conduction of electrical impulses between these two points in space can be detected via electrodes that are positioned at various points on the body; this is then displayed as a waveform on the ECG machine/monitor.

There are several configurations of electrode positioning; continuous ECG monitoring uses a 3-lead configuration but the standard 12-lead ECG comprises:

- Six chest (precordial) leads, which are referred to as leads V1, V2, V3, V4, V5 and V6 (Fig 3a);
- Six limb leads, referred to as leads I, II, III, aVR, aVL, and aVF (Fig 3b).

To position the chest electrodes accurately, it is important to first identify the sternal angle (angle of Louis); this is done by feeling the bony prominence at the top of the sternum, which articulates with the second rib above the second intercostal space. By moving the fingers downwards, the fourth intercostal space can be felt: here, the electrodes for V1 and V2 should be placed to the right and left of the sternum respectively. By feeling the fifth intercostal space and moving the fingers to the middle of the clavicle, V4 can be placed on the midclavicular line. V3 should then be placed midway between V2 and V4. V5 is placed in the fifth intercostal space, more lateral to the anterior axillary line, and V6 is placed in the fifth intercostal space in the midaxillary line.

To record the limb leads (Fig 3b), four electrodes are placed on the body. In the upper limbs, an electrode pad is placed...
**Table 2. Troubleshooting in ECG monitoring**

<table>
<thead>
<tr>
<th>Problem</th>
<th>Considerations</th>
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| Incorrect paper speed, which will alter the ECG's appearance and affect proper assessment | - Ensure paper speed is 25mm per second  
- Ensure gain is 10mm per millivolt |
| ECG not reading properly or intermittent signal   | - Check cables, leads, connections and settings  
- Replace electrode, cable or lead wire if needed  
- Check electrodes are securely attached to patient  
- Check for electrode gel dry-out  
- Remove possible static charge by touching metal before touching the patient |
| Wandering baseline, caused by the patient moving excessively due to:  
- Nervousness  
- Shivering | - Ensure patient is comfortable  
- Ask them to relax  
- Keep them warm if cold  
- Ensure electrodes are placed over bone, not muscle |

ECG = electrocardiogram; mV = millivolts.

Below the right clavicle (arm), the next electrode pad is placed below the left clavicle (arm); in the lower limbs, a cable is connected to an electrode pad placed on the left hip/ankle (LL) and on the right hip/ankle (RL).

It is important to follow local policy. All of the limb electrodes are placed on bony areas, rather than muscle, to avoid motion artifacts caused by muscle oscillation. Positioning electrodes in this formation allows the heart to be electrically mapped in three dimensions.

**Technical aspects of recording an ECG**

When undertaking any cardiac monitoring, the first step is to give the patient a simple explanation of the purpose of the test and what they should expect, as well as gaining their informed consent. It is important to ensure they are not allergic to the gel used on the ECG electrodes by asking if they have had any previous reactions.

It is critical that the health professional can accurately place the electrodes – this will help avoid inaccurate diagnosis and treatment – and it is important to ensure good contact between the electrode and the skin, which should be clean and dry. Excessive hair may need to be shaved and oily skin cleaned with alcohol or gauze. The electrodes are then attached to the patient in line with the machine’s instructions. The ECG is displayed on the machine’s monitor and should be checked for clarity, wave size and any interference.

Inadequate ECG monitoring can be dangerous; for example, misreading artifacts (electrocardiographic impulses unrelated to cardiac electrical activity) during ECG monitoring can be costly and cause delays to care. Other potential problems and how to resolve them are listed in Table 2.

An excellent ECG trace must be acquired to aid appropriate interpretation and provide the best care. The Society of Cardiological Science and Technology’s (2020) ECG guidance has more information about the reporting standards used by professional societies.

**Conclusion**

ECG monitoring is standard for patients in a variety of settings. Understanding the basic physiology underpinning the electrical and mechanical events of the heart is crucial for ECG interpretation. Part 2 of this series will focus on this and present important ischaemic pathologies, while part 3 will cover cardiac rhythm disorders and conduction defects. NT

Selina Jarvis was a recipient of the Mary Seacole Development Award and is focused on improving care for patients with cardiac disease.

**References**


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