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Understanding the ECG. Part 2: ECG basics

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Introduction

The 12 lead ECG is one of the most commonly performed cardiac investigations and provides a wealth of clinical data (Whitbread 2006). Correct interpretation of this data, however, requires that practitioners have a good understanding of how it is presented, and approach the data in a methodical and thorough fashion (Gregory 2006). Equally important is a recognition of the factors that can influence recording accuracy, and a knowledge of how each aspect of the recording relates to the structure and function of the heart (Crawford & Doherty 2008). Normal and abnormal values must be understood and applied to the clinical context (Garcia 2015).

Our previous article explored and discussed the anatomy and physiology that underpins the ECG. We discussed the way in which cardiac electrical activity arises from the movement of electrolytes and outlined the main features of the cardiac conduction system. We then introduced the principal waveforms and considered different types of ECG recording. In this second article, we now take a more detailed look at the 12 lead ECG. Our aim is to familiarise you with the layout of the 12 lead ECG, and to help you to understand the relationship between ECG leads and the different areas of the heart. We also consider common factors that affect the accuracy of recording and offer the reader a method of interpretation that we believe facilitates systematic analysis of the ECG. Finally, we describe the first step in this system of interpretation; the assessment of heart rate, rhythm and intervals.
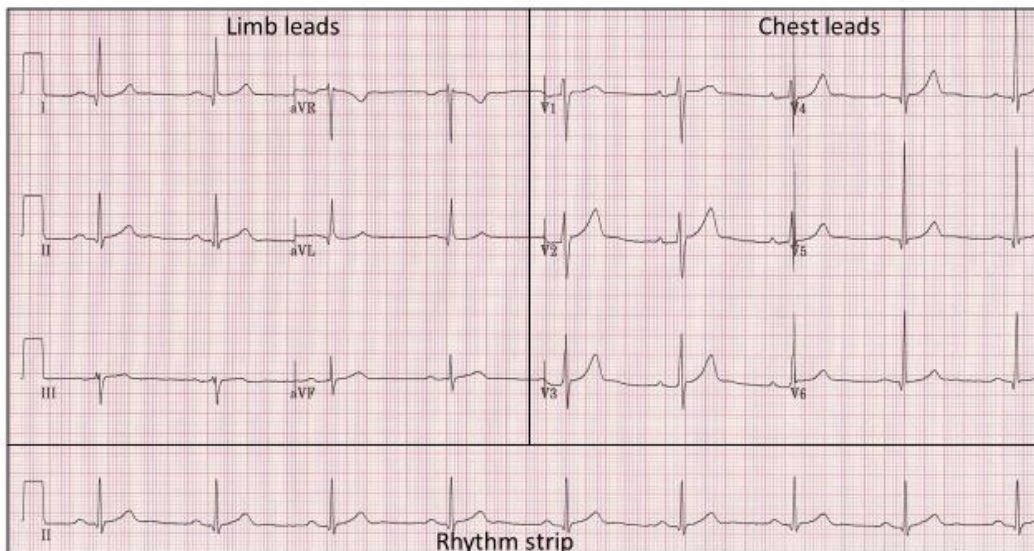
Leads

I remember once being approached by a junior member of staff in the Emergency Department who informed me that the ECG machine was broken. "There are only 10 leads" she told me, "instead of the 12 that there should be". After a simple explanation of what *lead* means in ECG terms, she realised that she had a fully functioning piece of equipment.

To put it simply, an ECG lead is not an electrical cable but a recording of the heart's electrical activity, seen from one particular perspective (Garcia 2015). Therefore, when we carry out a 12 lead ECG we are recording cardiac electrical activity from 12 different perspectives (Hampton 2013). Imagine you're visiting an historic building and taking photographs of it. If you take 12 photographs from around the building, each one will show a different aspect, for example the front, the sides and

the back of the building. Together, they build up a three-dimensional record of the buildings shape and appearance. A 12 lead ECG builds up a three-dimensional picture of the heart's electrical activity in a similar way.

Let's look at an ECG more closely and hopefully you'll see what we mean. Figure 1 shows a normal 12 lead ECG. The first thing to note is that there are two groups of six leads, one group to the left and one to the right. Below them is a longer printout of lead II which is called a rhythm strip. Most ECGs are laid out in this fashion, although some may print a different lead for the rhythm strip, typically V1, and others may not print a rhythm strip at all (Eldridge & Richley 2014). You'll see from figure 1 that the leads to the left have either a roman numeral or three letters starting with "a". These six leads are derived from the four electrodes placed on the arms and legs. For this reason, they are called the *limb* leads. The limb leads can be further divided into the *basic limb leads* (I, II, III) and the *augmented limb leads* (aVR, aVL, aVF) (Houghton & Gray 2014).

**Figure 1. Layout of the 12 lead ECG**

Moving to the right-hand side of the ECG, we can see that the six leads on that side all start with the letter V followed by a number: V1 through to V6. These leads are called the *chest* or *precordial leads*. Each one corresponds with a single electrode placed on the chest wall. On some machines these leads are labelled as C1 to C6 (Garcia 2015).

The final lead on the ECG is our rhythm strip. As we mentioned earlier, this is a longer printout of one of the 12 leads, usually lead II.   A rhythm strip is useful in evaluating heart rate and rhythm because it gives you a longer recording in which to evaluate the pattern of ECG waveforms (Bennett 2013).

The 12 views

The next step in getting to know the 12 lead ECG is to think about which parts of the heart the 12 leads are "seeing" electrically. The heart is complex structure and if we required a truly three-dimensional picture we would need a lot more than 12 leads. Imagine trying to interpret a 48 or 60 lead ECG - this would be impractical. Therefore the 12 leads are predominantly grouped around the left ventricle (LV) as this is the most important chamber in terms of maintaining cardiac output (Aaronson et al 2013). The two sets of leads view the heart in two different planes; the limb leads in a frontal plane, and the chest leads in a transverse plane (Kligfield et al 2007).

Figure 2 shows how the limb leads view the heart. You can see that all six leads look in from the sides of the body. Leads I and aVL look in from near the left arm and see the *lateral* (side) wall of the LV. Leads II, III and aVF look in from below, as if you were looking up the legs. These three leads see the *inferior* surface of the LV, the part that rests on the diaphragm. Finally, lead aVR looks in from the area of the right arm so sees predominantly the right atrium (Garcia 2015). As you can see, the limb leads do not see the front surface of the heart which is why the chest leads are necessary (Houghton & Gray 2014).


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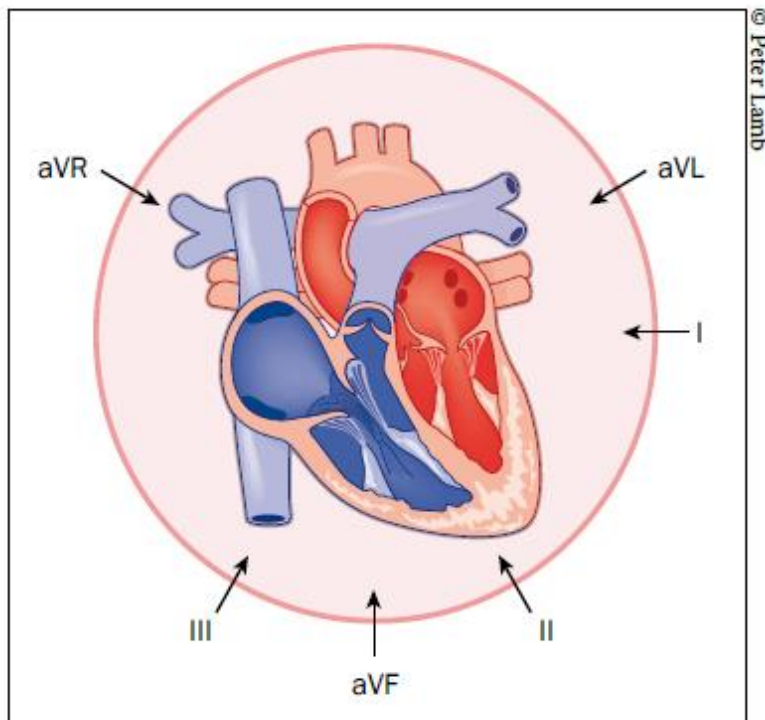
Figure 2. The limb leads

The chest leads look in through the front of the chest wall. As the electrodes are now closer to the heart, the waveforms are generally larger. However, this is not always the case. Conditions such as obesity and lung disease may increase the distance between the heart and the recording electrodes, which in turn reduces the size of the waveforms (Low et al 2012).

Figure 3 shows the relationship between the chest leads and the heart. In this image we are looking down on the heart from above, with the sternum at the front and the spine at the back. You can see that the right ventricle is towards the front of the body, and the left ventricle more towards the

back. This anatomical arrangement of the chambers is not obvious when the heart is depicted from the front, as it is in most textbooks. From this perspective we can see that V1 and V2 are looking in at part of the right ventricle, however their main view is of the septum between the two ventricles. We can therefore refer to these leads as the *septal* leads. Leads V3 and V4 are further around towards the left side of the body, and see the anterior or front surface of the LV. These leads can therefore be referred to as the *anterior* leads. More commonly, leads V1 to V4 are grouped together as the *anteroseptal* leads (Jowett & Thompson 2007). Finally, leads V5 and V6 look in from the left side of the chest and see the *lateral* wall of the LV. The area they see is similar to leads I and aVL (Hampton 2013).

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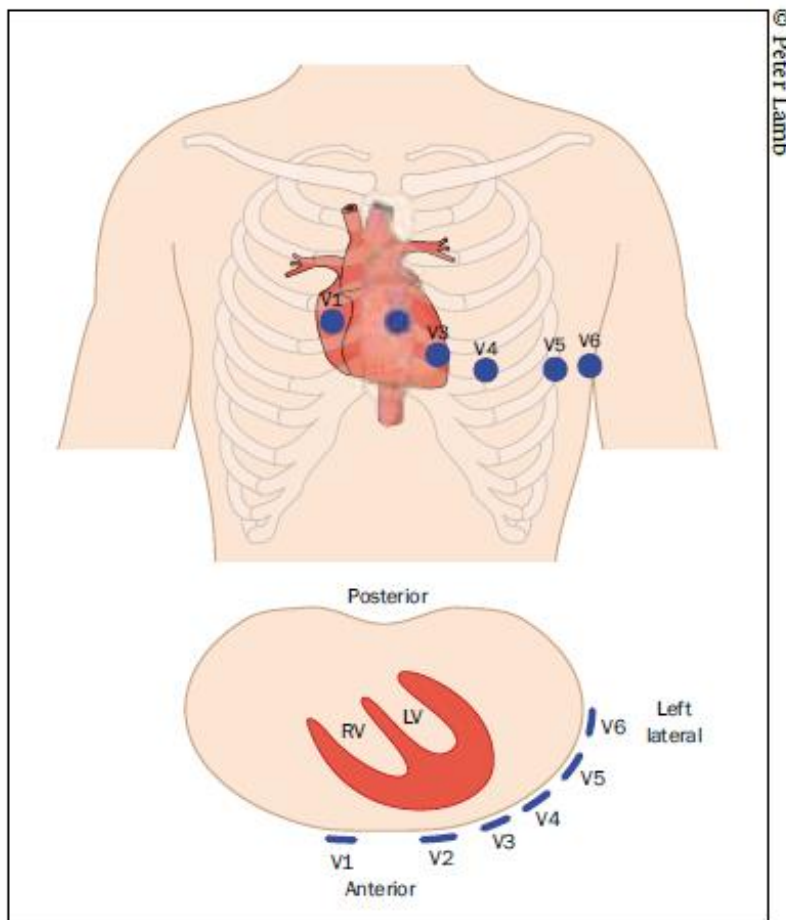
Figure 3. The chest leads

It is important that you develop a full understanding of what each group of leads sees if you are to assess the ECG for signs of structural heart disease, for example hypertrophy or ischaemia (Jabbour & Touquet 2014). Our aim is to provide a more detailed overview of these areas in a future article.

ECG paper

We are fortunate that the graph paper on which the ECG is recorded can provide us with a great deal of information. The way in which the paper is laid out allows the interpreter to measure the timing of events, as well as the size of the various waveforms. It is important to note that accurate interpretation of both timing and size relies on the machine being properly set up, and the electrodes being placed correctly. Let's now consider these points in turn.
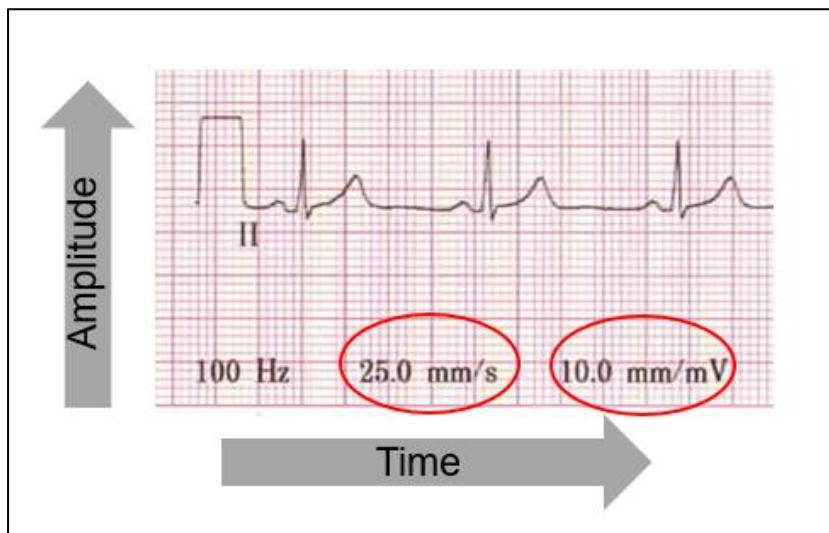

Figure 4. ECG paper

When you look at ECG paper you note that it is divided into small and large squares (see figure 4). Each small square is 1mm x 1mm, and each large square 5mm x 5mm.   Time is measured along the horizontal (x) axis.   Each small square represents 0.04 seconds (40 milliseconds) and each large square 0.2 seconds (200 milliseconds) (Garcia 2015). Therefore, if events on the ECG are five large squares apart, then one second separates them in time. These timings assume that the paper speed of the ECG machine is set up normally. Standard paper speed is 25mm/second (Eldridge & Richley 2014). If the paper speed is increased, waveforms on the ECG will be wider and further apart which will confuse your analysis. When you are interpreting an ECG, it is important that you check the speed. This is printed out in the bottom left corner of the paper (see figure 4).

The vertical, or Y axis, of the ECG measures the amplitude of the waveforms in millivolts. The amplitude, or size, of the waveforms reflects the size of the chambers that are depolarising. The QRS complex is much taller than the P wave because the ventricles are much larger, and thicker walled, than the atria (Klabunde 2012). From a clinical perspective, the ECG of a patient with an enlarged heart, for example because of long standing hypertension, may show QRS complexes that are taller than normal. This is because the thickened walls of the ventricles contain many more cells than a normal heart (Gosse et al 2012). The standard calibration for amplitude is 10mm per millivolt, in other words one millivolt of electricity will move the stylus up or down by 10mm on the paper (Kligfield et al 2007). As with paper speed, amplitude settings can be altered on the ECG machine. Increasing the setting to 20mm/mv will double the size of the waveforms on the ECG. The amplitude calibration is printed in the bottom left corner of the ECG, next to the paper speed. This should also be checked when you are interpreting the ECG.

A second factor to consider when assessing the accuracy of waveform amplitude is electrode placement. Electrodes that are placed in the wrong position can result in increased or decreased amplitude of the ECG waveforms. In a study of 120 healthcare practitioners, Rajaganeshan et al (2008) found that errors in chest electrode placement were especially common, with V1/V2 and V5/V6 often placed too high on the chest. Limb electrodes may also be incorrectly placed. Eldridge & Richley (2014) point out that these electrodes should be placed on the wrists and ankles, not on the upper limbs or torso. Practitioners who are unsure of correct lead placement should consult a more experienced colleague, or a suitable written guide. Crawford & Doherty (2008), for example, discuss the subject in depth and provide an excellent step by step guide to correct lead placement.

Systematic ECG interpretation

The strength of the 12 lead ECG is the amount of detail that it contains, however this also poses its greatest challenge. A structured approach to interpretation is recommended, and reduces the chance that you will miss important information (Whitbread 2006). Research suggests that the use of interpretation tools improves accuracy in both experienced and novice practitioners (Sibbald et al 2013). Whilst we acknowledge that there are a number of systems of interpretation available, we propose to use a modified version of the RPQRST system. This system was devised by Gregory (2006) and has the advantage of being simple and memorable (see figure 5). We believe that using a tool ensures that you work through each aspect in turn before making a diagnosis. This then ensures a thorough and systemic evaluation of the information contained on the ECG, which in turn reduces the risk of jumping to conclusions or reaching an incorrect diagnosis. Let's now consider the first step in the RPQRST system; the evaluation of heart rate, rhythm and intervals.
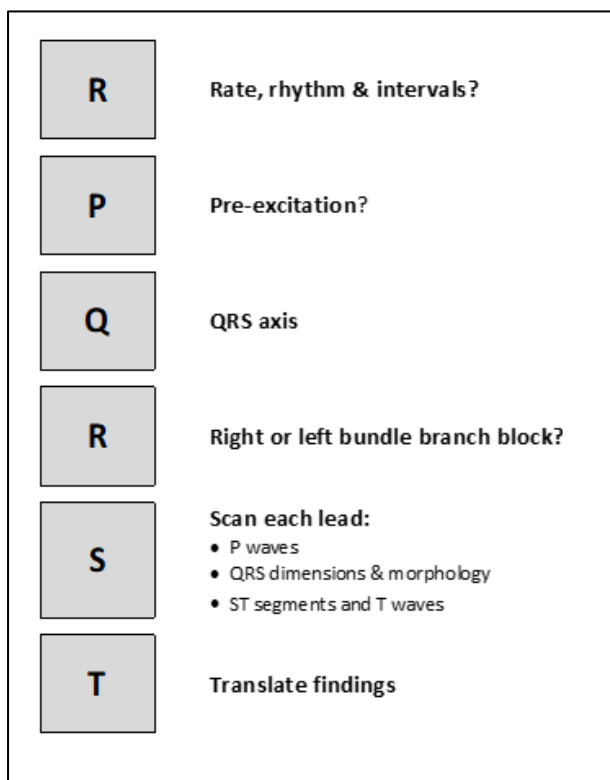

R	Rate, rhythm & intervals?
P	Pre-excitation?
Q	QRS axis
R	Right or left bundle branch block?
S	Scan each lead: • P waves • QRS dimensions & morphology • ST segments and T waves
T	Translate findings

Figure 5. System of interpretation adapted from Gregory (2006) with permission
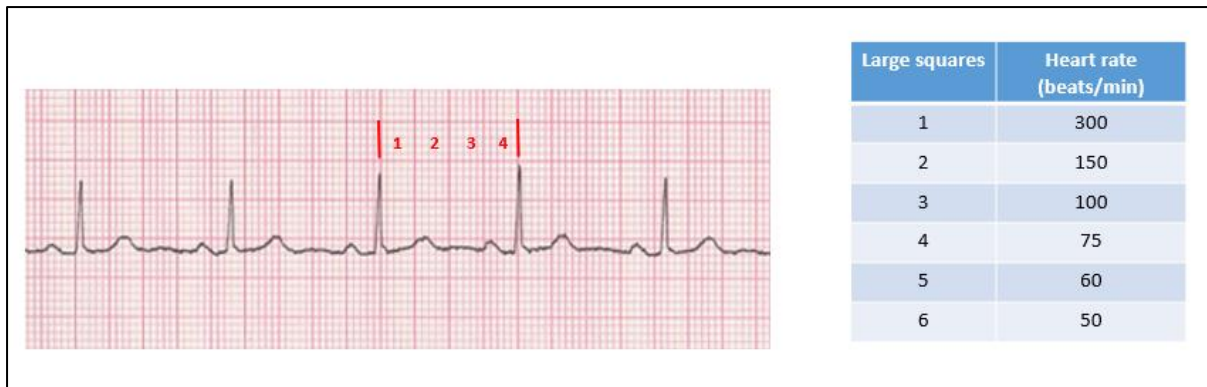
Evaluating heart rate

The heart rate is an important piece of information not only from a diagnostic point of view, but also in terms of patient safety. Extremely low or high heart rates suggest serious rhythm abnormalities, and the possibility of patient decompensation or cardiac arrest (Resuscitation Council UK 2015). Heart rate is therefore an important factor in overall patient assessment, as well as one aspect to be considered when assessing the ECG (Jevon 2010). The first step in evaluating heart rate is to understand the normal range of values.

During sinus rhythm, the heart rate is set by how quickly the sinus node depolarises (Levick 2010). We discussed various factors that influence sinus rate last month, including the autonomic nervous system, hormones and medications. At rest, normal sinus rate is usually defined as 60 to 100 beats per minute (Bennett 2013; Garcia 2015; Hampton 2013, Houghton & Gray 2014). Rates below 60 are described as bradycardia, although there is evidence that rates as low as 50 are both normal and common, especially in physically fit individuals. Spodick et al (1992) measured the resting heart rate of 500 healthy, un-medicated individuals and found a range of 46 to 93 beats per minute in men, and 51 to 95 beats per minute in women. Sinus bradycardia is also common during sleep, when the heart slows due to decreased demand for cardiac output (Marieb & Hoehn 2015). Rates above 100 are described as tachycardia (Garcia 2015). Sinus tachycardia is normal during exercise, and increases cardiac output to meet the demand of working muscles (Wilmore et al 2008). Other causes of sinus tachycardia include pain, anxiety, fever and blood loss. Sinus tachycardia should always be investigated to determine and treat the underlying cause, for example giving analgesia for pain (Bench & Brown 2011).

Once we understand the normal values for heart rate, we are ready to evaluate them on the ECG. At first glance it would appear that the easiest way to determine the heart rate is to use the figure calculated by the machine. Whilst this is acceptable in most circumstances, there are several potential pitfalls that must be considered. Firstly, ECG machines are not infallible and may miscalculate the heart rate (Southern & Arnsten 2009). It is important therefore that practitioners should be able to calculate rate manually to check the machine's findings. Secondly, practitioners may need to calculate heart rate from a rhythm strip that has no rate printed on it. There are a number of ways of calculating heart rate from the ECG, some of which require a calculator. However we would like to propose two simple methods that require no equipment. The first is the "R-R method", and the second the "30 large square" method.
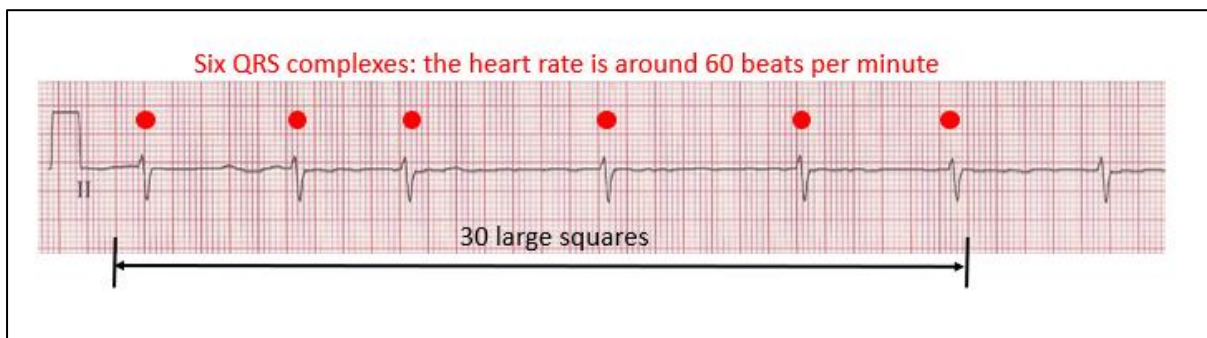
R-R method

The R-R method gives a quick estimate of heart rate based on the number of large squares between each QRS complex (see figure 6). The number of large squares is divided into 300 to give the approximate heart rate. The more squares between the QRS complexes, the lower the heart rate (Hampton 2013). In figure 6 we can see that there are four large squares between QRS complexes. 300 divided by four gives us a heart rate of 75 beats per minute. Some people prefer to memorise the heart rate for a given number of large squares, as shown in figure six. The advantage of the R-R method is that it gives a very quick and easy estimate of heart rate. The disadvantages are that the rate is only a very rough estimate, and that the system cannot be used when the rhythm is irregular. This is because in irregular rhythms the interval between QRS complexes is not the same for each beat (Garcia 2015).

Figure 6. The R-R method of estimating heart rate

30 large square method

For a more accurate estimate of heart rate, or when the rhythm is irregular, the 30 large square method is better (Hampton 2013). To use this method, mark a point on the rhythm strip and count off 30 large squares before making another mark. Now count the number of QRS complexes between the marks. Multiply this number by ten to give the heart rate. In the example in figure 7 there are six QRS complexes between the marks. Six multiplied by ten gives us a heart rate of 60 beats per minute.

Figure 7. The 30-square method of estimating heart rate

Evaluating rhythm

Once we know the heart rate, the next step is to evaluate the rhythm. The normal rhythm of the heart is sinus rhythm. We can understand the ECG appearance of sinus rhythm by reflecting on our knowledge of the cardiac conduction system. The sinus node depolarises at regular intervals. Sinus rhythm therefore has a regular pattern. The electrical signal spreads through the atria, creating the P wave on the ECG, and then spreads through the ventricles to create the QRS complex. The P wave therefore comes in front of the QRS complex, and there should only be one P wave to every QRS. Because each P wave comes from the same place in the heart, each one should be the same size and shape (Bennett 2013). P waves should also be upright (positive) in all leads except aVR, which is usually negative, and leads III and V1 which may have positive or negative P waves (Garcia 2015). This can be explained by the way in which ECG machines record electrical activity. An electrical impulse moving towards an ECG lead creates an upright waveform, while an impulse moving away

results in a negative one.   The sinus node is at the top of the heart, while most of the recording leads are lower down. The impulse from the sinus node is therefore travelling towards most of the leads, and causes a positive P wave (Hampton 2013).

The QRS is also upright in most leads, although various abnormalities in cardiac structure or electrical function can alter this, as we shall see as we progress through this series of articles. From a rhythm perspective, a more important consideration when assessing the QRS is its width or duration. We know that the electrical impulse spreads through the ventricles very rapidly because of the extensive His-Purkinje system (Tortora & Nielson 2014). The QRS is therefore narrow in normal health, and occurs in less than 0.12 seconds (less than 3 small squares of ECG paper) (Hampton 2013). A wide QRS suggests one of two possibilities. Either the electrical impulse has not travelled normally through the conduction system, for example because of heart block, or more alarmingly the rhythm itself has originated in the ventricles. Because broad complex arrhythmias can cause cardiac arrest, any ECG with a wide QRS complex must be carefully evaluated (Tough 2008).

The final major consideration from a rhythm point of view is the time taken for the electrical impulse to pass through the conduction system. This is measured from the start of the P wave to the start of the QRS complex, and is called the PR interval. The normal PR interval is between 0.12 and 0.2 seconds (3 to 5 small squares) (Klabunde 2013).

Checking if all these normal features are present will tell you whether the rhythm is sinus or not. Box 1 lists the key questions that you need to ask. If any answer is no, either the rhythm is not sinus or a variation of sinus rhythm is present, for example sinus tachycardia. Recognising abnormal rhythms will be the focus of the next two articles in this series.


Rhythm evaluation questions

1. Is the rhythm regular?

2. Is the heart rate between 60 and 100 beats per minute?

3. Are there upright P waves, and are they all the same shape?

4. Is there one P wave in front of each QRS complex?

5. Is the PR interval normal (3 to 5 small squares?)

6. Is the QRS complex narrow (less than 3 small squares wide?)

**Box 1. Rhythm evaluation questions**

Intervals

The final element in this first stage of ECG interpretation is to evaluate the time intervals on the ECG. We have already considered the PR interval and the QRS duration in our discussion of rhythm. The other important time measurement is the QT interval (Houghton & Gray 2014). The QT interval is the time from the beginning of the QRS complex to the end of the T wave, and represents the entire process of ventricular depolarisation and repolarisation (see figure 9). Prolongation of the QT interval increases the risk of ventricular arrhythmias, particularly a type of ventricular tachycardia called Torsades de Pointes (Attin & Davidson 2011). A prolonged QT interval may occur because of a genetic abnormality in ion channel function, creating a condition known as long QT syndrome (Martin et al 2012). The QT interval may also be increased by cardiac drugs such as amiodarone, flecainide and sotalol, as well as by many non-cardiac drugs including eythromycin and haloperidol (Fogoros 2007; Nachimuthu et al 2012).
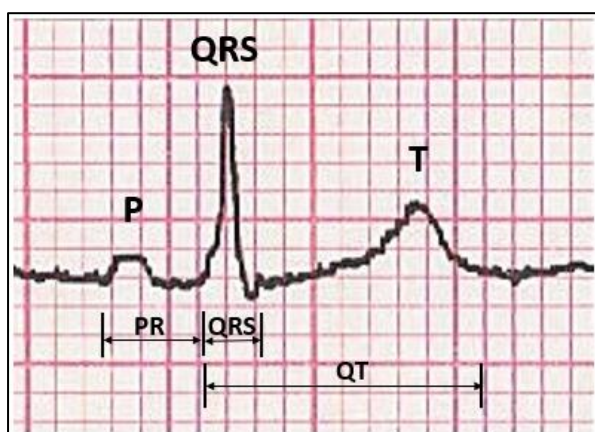
**Figure 8: Time intervals of the ECG**

Measurement of the QT interval is more complex than assessment of the PR interval or QRS duration for several reasons. Firstly, the QT interval appears longer in some ECG leads than others. The American Heart Association recommends simultaneous analysis of all 12 leads to determine the earliest QRS complex and the latest T wave, thereby measuring the longest possible QT interval (Rautaharju et al 2009). Yaldren & Richley (2014) point out that this is not feasible in everyday practice, and suggest that the most important aspect of accurate QT measurement is selecting a lead in which the end of the T wave is clearly visible. They suggest using lead II if the T wave is clearly defined, otherwise leads I, III or V5.

The second complication with QT measurement is variability with heart rate. As heart rate increases, the QT interval shortens. This makes comparison with normal values difficult. QT interval is therefore *corrected* for heart rate to give QT*c*. QTc represents the QT interval as it would be at 60 beats per minute (Hampton 2013). A number of formulae are available to calculate QTc, of which Bazett's is the most widely used (Yaldren & Richley 2014). Bazett's formula states that the QTc is equal to the QT interval (in millseconds) divided by the square root of the R-R interval (in seconds). An example of a QTc calculation using Bazett's formula is shown in Figure 10. Suggested maximum values for QTc are 450 milliseconds for men, and 460 milliseconds for women (Rautaharju et al 2009; NICE 2010).
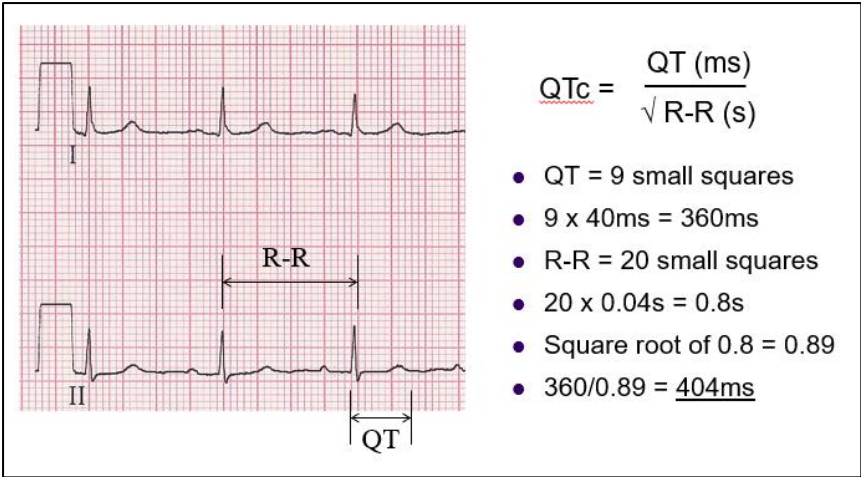
Figure 10. Calculating QTc using Bazett's formula

Measuring QTc manually is quite time consuming so many practitioners rely on the ECG machine's calculation. While this is usually highly accurate, a quick visual check is essential in case of machine error. Garcia (2015) points out that the normal QT is less than half of the R-R distance and suggests this method as a quick visual check. Figure 11 compares ECGs with normal and prolonged QT intervals.
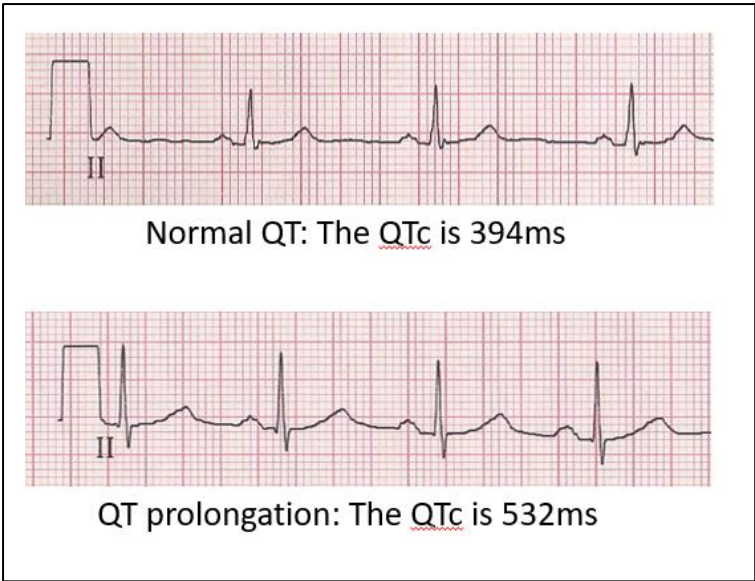
Figure 11: Comparison of normal and prolonged QT intervals

Conclusion

The 12 lead ECG provides detailed information about the heart's electrical activity. Use of a structured interpretation tool is recommended to ensure that the information from the ECG is handled in a systematic and thorough fashion. In this article we have provided you with one system of analysis as well as the essential building blocks for a deeper understanding of the ECG and how it is recorded. We have also endeavoured to provide you with a better understanding of the layout of the ECG, and the orientation of the various leads. We believe that this is an essential first step in developing your 12 lead interpretation skills. Next month, we aim to consolidate and develop your knowledge further by examining in detail the common rhythm abnormalities.

Key points

- The 12 leads of the ECG build a three-dimensional picture of the heart's electrical activity and are divided into the six limb leads and six chest leads.

- ECG leads can also be grouped according to the area of the left ventricle that is seen: Inferior, lateral and anteroseptal. This becomes important when assessing for structural heart disease and ischaemia.

- The ECG is printed on graph paper with small and large squares. Time is shown along the horizontal axis, and amplitude up the vertical axis.

- Paper speed and amplitude must be correctly set on the machine for accurate interpretation. Incorrect electrode placement will also affect accuracy.

- The use of a system of interpretation ensures that the 12 lead ECG is evaluated thoroughly, and that important details are not overlooked. We propose the use of the RPQRST system.

- The first stage in this system is to evaluate heart rate, rhythm and conduction intervals.

- The normal heart rate is 60-100 beats per minute, with slower rates described as bradycardia and faster rates as tachycardia.

- Normal sinus rhythm has a number of key features including regularity, P waves that are consistent and upright in most leads, one P wave in front of every QRS, and a normal PR interval. The QRS is usually narrow.

- In addition to evaluating QRS width and PR interval, the QT interval should also be measured. QTc is used due to variability of the interval at different heart rates.

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