Understanding the ECG Part 2: ECG basics

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Understanding the ECG
Part 2: ECG basics

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The 12-lead electrocardiogram (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 and Doherty, 2008). Normal and abnormal values must be understood, and applied to the clinical context (Garcia, 2015).

The first article in this series explored and discussed the anatomy and physiology that underpins the ECG (Sampson and McGrath, 2015). 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 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 are visiting a 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 building's 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 and Richley, 2014). You'll see from *Figure 1* that the leads to the left are marked with 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'. These can be further divided into the basic limb leads (I, II, III) and the augmented limb leads (aVR, aVL, aVF) (Houghton and Gray, 2014).

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).
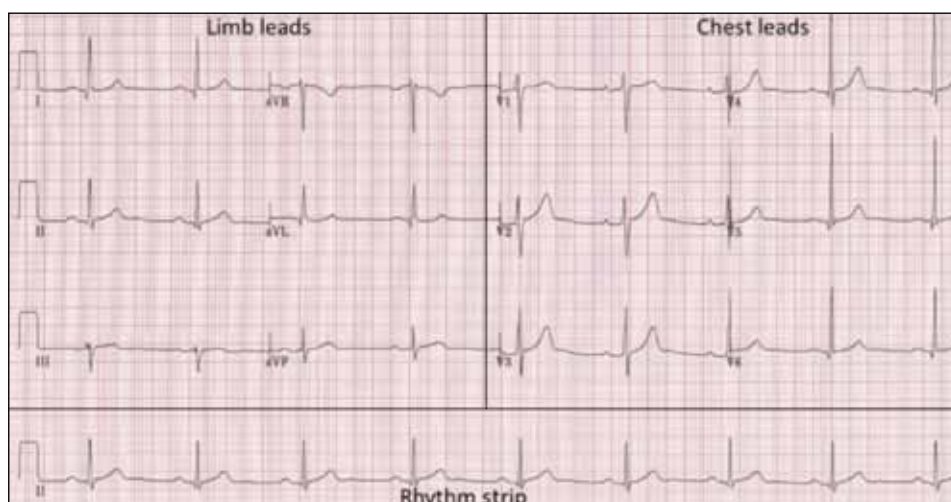

Figure 1. Layout of the 12-lead ECG

The final lead on the ECG is our rhythm strip. As mentioned, this is a longer print-out 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 through 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 a 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 (Kligfield et al, 2007):

* The limb leads in a frontal plane
* The chest leads in a transverse plane.

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, seeing 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 and Gray, 2014).

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 and 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). It is important that cardiac nurses develop a full understanding of what each group of leads sees in order to be able to assess the ECG for signs of structural heart disease, such as hypertrophy or ischaemia (Jabbour and 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 us now consider these points in turn.

When you look at ECG paper, you note that it is divided into small and large squares (*Figure 4*). Each small square is 1 mm x 1 mm, and each large square 5 mm x 5 mm. 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 25 mm/second (Eldridge and Richley, 2014). If the paper speed is increased,
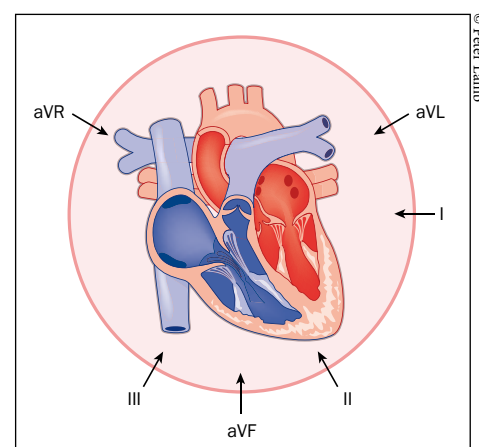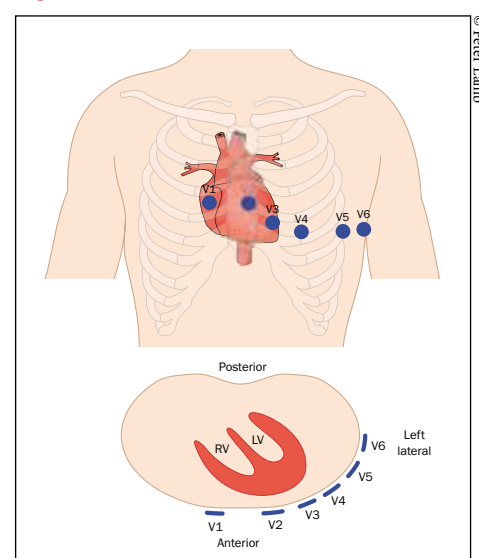

Figure 2. The limb leads

Figure 3. The chest leads

Figure 4. ECG paper

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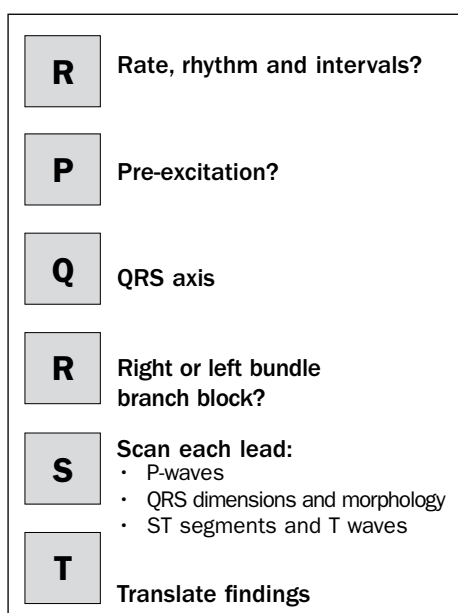
R	Rate, rhythm and intervals?
P	Pre-excitation?
Q	QRS axis
R	Right or left bundle branch block?
S	Scan each lead: • P-waves • QRS dimensions and morphology • ST segments and T waves
T	Translate findings

Figure 5. System of interpretation adapted from Gregory (2006), with kind permission

because the ventricles are much larger, and thicker-walled, than the atria (Klabunde, 2012). Clinically, this can be useful when assessing the ECG for enlargement of the heart. The ECG of a patient whose heart has enlarged, because of long-standing hypertension, for example, 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 10 mm per millivolt. In other words, one millivolt of electricity will move the stylus up or down by 10 mm on the paper (Kligfield et al, 2007). As with paper speed, amplitude settings can be altered on the ECG machine. Increasing the setting to 20 mm/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 health-care 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 and 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 and Doherty (2008), for example, provide an in-depth, 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 the use of interpretation tools improves accuracy in both experienced and novices (Sibbald et al, 2013). While 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 (*Figure 5*). We believe using a tool ensures you work through each aspect in turn before making a diagnosis. This ensures a thorough and systematic evaluation of the information contained on the ECG, which in turn reduces the risk of jumping to conclusions or reaching an incorrect diagnosis. Let us now consider the first step in the RPQRST system; the evaluation of heart rate, rhythm and intervals.
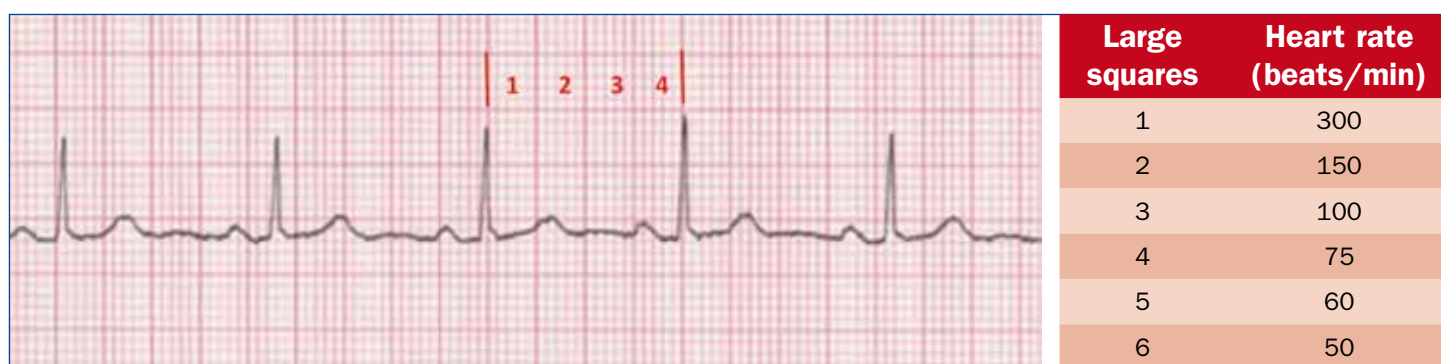
Large squares	Heart rate (beats/min)
1	300
2	150
3	100
4	75
5	60
6	50

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

Six QRS complexes: the heart rate is around 60 beats per minute
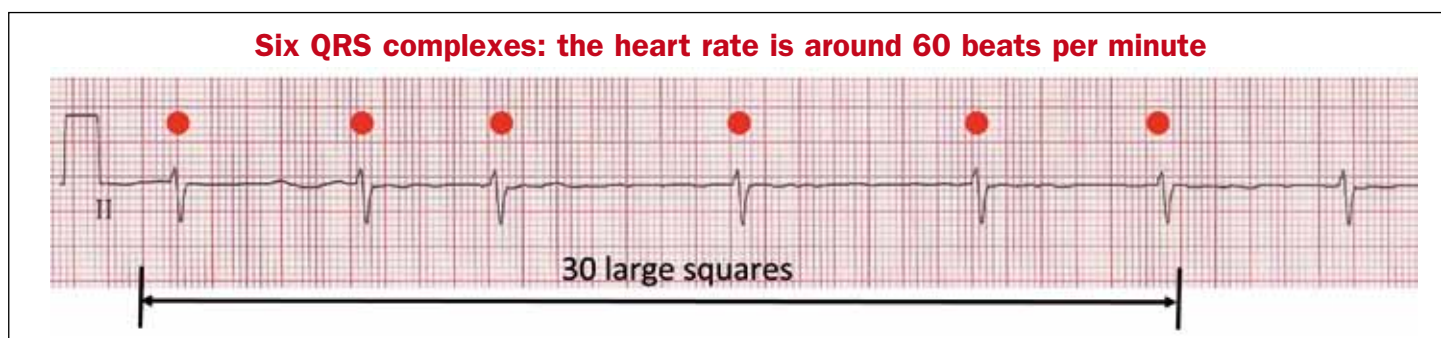
30 large squares

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

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 (Pitcher and Nolan, 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 (Sampson and McGrath, 2015). At rest, normal sinus rate is usually defined as 60–100 beats per minute (Bennett, 2013; Hampton, 2013; Houghton and Gray, 2014; Garcia, 2015). 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, unmedicated individuals and found a range of 46–93 beats per minute in men, and 51–95 beats per minute in women. Sinus bradycardia is also common during sleep, when the heart slows as a result of decreased demand for cardiac output (Marieb and 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 (Kenney et al, 2015). 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 and 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. While this is acceptable in most circumstances, there are several potential pitfalls that must be considered. First, ECG machines are not infallible and may miscalculate the heart rate (Southern and Arnsten, 2009). It is important therefore that practitioners should be able to calculate rate manually to check the machine's findings. Second, 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
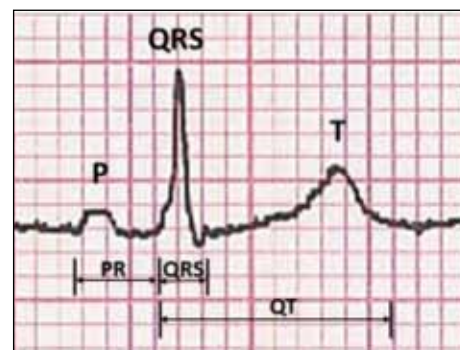
Figure 8. Time intervals of the ECG

Box 1. 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?)
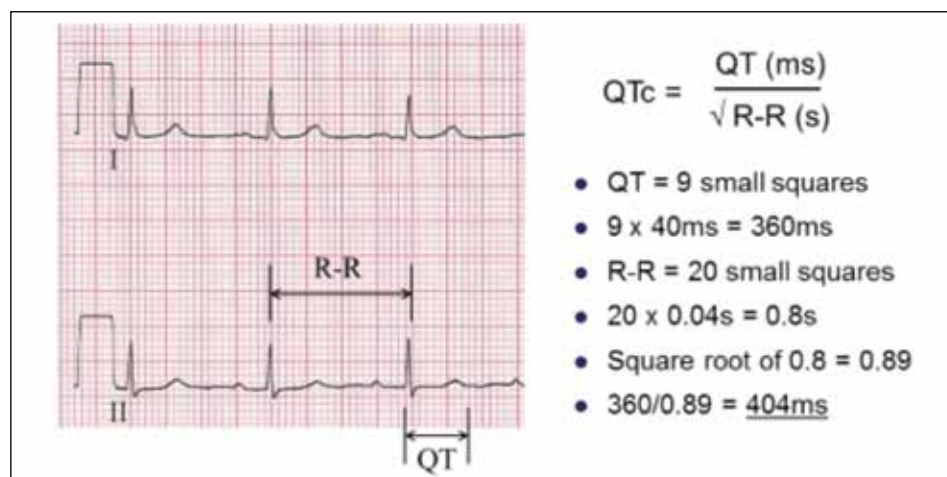6. Is the QRS complex narrow (less than 3 small squares wide?)

$$QTc = \frac{QT\ (ms)}{\sqrt{R\text{-}R\ (s)}}$$

- QT = 9 small squares
- 9 x 40ms = 360ms
- R-R = 20 small squares
- 20 x 0.04s = 0.8s
- Square root of 0.8 = 0.89
- 360/0.89 = <u>404ms</u>

Figure 9. Calculating QTc using Bazett's formula

Normal QT: The QTc is 394 ms

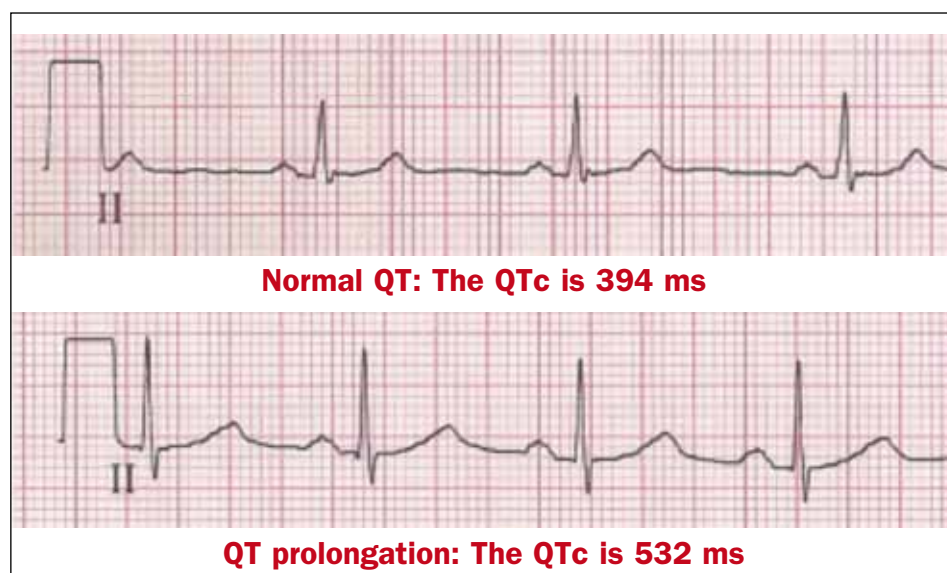**QT prolongation: The QTc is 532 ms**

Figure 10. Comparison of normal and prolonged QT intervals

equipment. The first is the 'R-R method', 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 (*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 6*.

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).

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.

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 and Nielsen, 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 (3–5 small squares) (Klabunde, 2012).

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, such as sinus tachycardia. Recognising abnormal rhythms will be the focus of the next article in this series.

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 and 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 (*Figure 8*). Prolongation of the QT interval increases the risk of ventricular arrhythmias, particularly a type of ventricular tachycardia called Torsades de Pointes (Attin and 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 noncardiac drugs including erythromycin and haloperidol (Fogoros, 2007; Nachimuthu et al, 2012).

Measurement of the QT interval is more complex than assessment of the PR interval or QRS duration for several reasons. First, 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 and 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 QTc. 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 and Richley, 2014). Bazett's formula states that the QTc is equal to the QT interval (in milliseconds) 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 9*. Suggested maximum values for QTc are 450 milliseconds for men, and 460 milliseconds for women (Rautaharju et al, 2009; National Institute for Health and Care Excellence (NICE), 2010). 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 10* compares ECGs with normal and prolonged QT intervals.

Conclusion

The 12-lead ECG provides detailed information about the heart's electrical activity. The use of a structured interpretation tool is recommended to ensure that this information 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. **BJCN**

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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 (i.e. inferior, lateral or 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 on 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 owing to variability of the interval at different heart rates

BHF Resources

The British Heart Foundation (BHF) is committed to sharing our knowledge to prevent heart disease devastating people's lives. We have created a range of resources that can be used by health professionals to support people with a heart or circulatory condition. Resources relevant to this article are listed below: A wealth of online information on a variety of heart conditions, tests and treatments—Find out more at **bhf.org.uk/tests**

- **Tests**—A booklet for adults describing the tests that are commonly used to help diagnose heart diseases or assess the current condition of people with a heart condition

- **Electrocardiogram**—Your quick guide. A short illustrated leaflet that helps adults understand what to expect if they're having an ECG. It explains the different types of ECG, including Holter monitoring and exercise stress tests

- **Your guide to heart tests and treatments**—A series of films following 18 real people's journeys through a variety of cardiac tests and treatments. By seeing the actual procedures, patients know what to expect and how to prepare. Available online at **bhf.org.uk** or on DVD, there are three films covering ECG: *Your guide to ECG*; *Your guide to 24 hour blood pressure and Holter monitoring tests*; and *Your guide to exercise ECG (stress test)*. The DVD version includes subtitles in English, Bengali, Hindi, Gujarati, Punjabi and Urdu, and optional in-vision BSL interpretation

View, download and order these items free at **bhf.org.uk/publications**

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BHF Doctor's comment

Achieving optimal clinical outcomes requires accurate diagnosis, and this in turn is dependent on accurate interpretation of tests, as well as precision in undertaking the test in the first place. This review, the second in the series, provides a clear understanding of the principles and practice needed to record and interpret the ECG.

Dr Mike Knapton
BHF Medical Director

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