

RESTING 12-LEAD ECG ELECTRODE PLACEMENT AND ASSOCIATED PROBLEMS.

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While Waller is credited with recording the first human electrocardiogram (ECG) in 1887 (1), it was not until a few years later that Einthoven introduced the limb leads. In the Einthoven Museum in Leiden, in the Netherlands, there is a tracing of what is said to be Einthoven's first recording dated 1902.



Fig I. An example of limb electrode connections from the early days of ECG recording (after Lewis 1925).

In those days, electrodes took the form of a conducting solution into which limbs were placed and therefore there was little difficulty in deciding where, to attach the electrode!

Throughout the 20th Century, the process of ECG recording has been one of gradual change. The initial three standard limb leads have been extended with the introduction of unipolar chest leads and augmented unipolar limb leads. In addition, the recording apparatus has gradually changed in size and complexity so that nowadays a briefcase sized

electrocardiograph can record a 12-lead ECG, produce a chart with the waveforms and, indeed, print out a computer assisted ECG interpretation.

It may be as well to state at this stage for the avoidance of doubt that the machine which records the waveforms generated by the electrical activity of the heart is called an electrocardiograph while the collection of waveforms produced is called an electrocardiogram. It is surprising how often there is confusion about these terms even among physicians (see Reference 5!).

Despite the enormous strides in technology which have facilitated the recording of the ECG, there still remains the human element in ensuring a satisfactory technical recording. The single biggest problem with ECG recording at the present time is undoubtedly the difficulty of ensuring that electrodes are properly positioned and securely attached to a patient. The purpose of this paper is to review the correct positions of the electrodes and to highlight problems which arise from faulty electrode positioning of connections. Particular emphasis is placed on electrode positioning for recording the standard resting 12-lead electrocardiogram. Electrode positioning for the exercise ECG and patient monitoring is different.

ECG ELECTRODE PLACEMENT.

Standard Limb Leads:

In the original recordings of Einthoven, it was the wrists and the patient's foot which were inserted into the jars containing the conducting solution (see Figure 1). This is a strong indication that ECG electrodes of modern design should also be attached to the patient's wrists and ankle if data accumulated in earlier years is to be utilised.

It is common practice in some centres to use adhesive tab electrodes particularly for the arm connections and it is therefore very convenient to attach these to the forearms. It has been shown (2), however, that there is a small difference in potential between the upper arm and the wrists; hence, a Lead I recorded with electrodes on the wrists will differ very slightly in amplitude from a Lead I with electrodes placed on the forearms. Clearly, the closer the arm electrodes are moved to the trunk, the greater the difference in amplitudes there will be compared to leads which are recorded with electrodes on the wrists; ultimately, as in the case of the exercise ECG, if the right arm left arm electrodes are placed on the thorax, in accordance with the Mason-Likar system (3), the Lead I so recorded will be significantly different from that obtained using the conventional electrode positions. These variations in arm electrode positions have been investigated with respect to their effect on the exercise ECG (4). In addition, the significant differences between the conventional 12-lead ECG recording and that made using the Mason-Likar system have been highlighted elsewhere (5). These include a rightward shift of the mean QRS axis and a consequent reduction in R wave amplitude in I and aVL together with an increase in R wave amplitude in II, III and aVF. Chest leads are also affected because of the altered potential of the central terminal.

To record a resting 12-lead ECG properly, it is important that the patient is lying comfortably with the inner aspect of the wrists close to but not touching the waist and the electrodes attached to the outer aspect of the wrists particularly if plate electrodes are used. On occasions where a patient may have uncontrolled tremor, it may be necessary to place the electrodes on the forearm in order to minimise the baseline noise on the ECG. This is one of the few occasions on which electrodes should be shifted. Another example would be if the patient had a limb in plaster! Any such departure from the conventional pattern of electrode placement must be clearly noted on the ECG printout. There is an opinion that an electrode placed over bone gives less somatic tremor than an electrode placed over muscle. This concept is irrelevant if the recommendations in this paper are observed. Indeed, it is more important for the patient to be relaxed. It is unrealistic to expect a good recording of the limb leads from a patient lying in a cold environment perhaps on a narrow plinth in an Outpatient Clinic.

In summary, therefore, the limb lead electrodes should be placed on the right and left wrists and the right and left ankles. The outer aspect of the wrist should be used to ensure that the patient does not have to rotate the arms. Similarly, for ease of connection, the ankle electrodes should be placed on the outer aspect of each ankle. When the electrodes are in place, the following leads are obtained: ,

$$\text{Lead I} = E_L - E_R \quad \text{Lead II} = E_F - E_R \quad \text{Lead III} = E_F - E_L$$

where E_L is the potential at the left arm, E_R is the potential at the right arm and E_F is the potential at the left leg. These leads are called bipolar limb leads because they measure the potential difference between two limbs.

It follows from the above that at any instant in the cardiac cycle the sum of the potentials in Leads I and III is equal to the potential in Lead II, i.e.

$$I + III = II$$

This is known as Einthoven's Law. The significance of this relationship will become apparent later but it is essential that the competent practitioner is aware of this most basic relationship between the limb leads.

Precordial Leads:

Wilson, an American physician, introduced a terminal (6) which connected the right and left arms and the left leg. Effectively, this central terminal (ct) records the average potential of these three limbs, i.e.

$$E_{ct} = \frac{1}{3} (E_R + E_L + E_F)$$

The central terminal potential is non-zero but is relatively constant throughout the cardiac cycle and hence, if the potential difference is obtained between a point P on the body and the terminal, the waveform essentially reflects the variation in potential at the electrode P on the body. Hence, such a lead is called a unipolar lead. Theoretically, the relationship is as follows:

$$\begin{aligned} V_p &= E_p - E_{ct} \\ &= E_p - \frac{1}{3} (E_R + E_L + E_F) \end{aligned}$$

where E_p is the potential at the so-called exploring electrode P

When Wilson and colleagues introduced these leads for unipolar chest recordings, they used a variety of points on the thorax, including The xiphisternum, However, between 1938 and 1943, agreement was reached between the British Cardiac Society and American cardiologists on the placement of six electrodes on the chest (7-9) the locations of which are shown in Figure 2. The leads derived from these electrodes are known as V1 to V6.

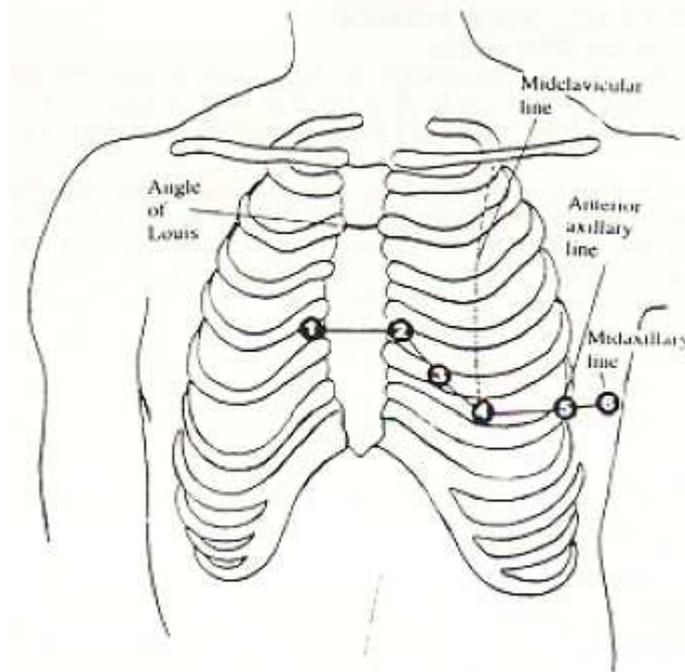


Fig 2. The positions of the six precordial electrodes. Note that the junction of sternum and manubrium is called the Angle of Louis

The critical aspect of precordial lead positioning is to locate the fourth intercostal space. In early textbooks of electrocardiography, e.g. Goldberger (10), It was recommended that the fourth intercostal space be located with reference to the angle of Louis (Figure 2). This angle, otherwise known as the sternal angle, marks the position of the manubriosternal junction and is located where the body of the sternum proper joins the structure known as the manubrium. At this junction, there is a transverse ridge which must be identified by palpation. If the finger is moved along the ridge, it will slide downwards into the second intercostal space.

It has become commonplace for some of those who record ECGs to locate the first intercostal space by finding the clavicle and then taking the first space below as being the required interspace. Careful examination of Figure 2 will show that there is a danger in locating the small space between the clavicle and the first rib and of designating this as the first intercostal space; the first intercostal space will then be identified as the second, and so on, downwards. For this reason, it is essential to locate interspaces using the bony ridge of the angle of Louis. The consequences of not locating the fourth interspace correctly are quite significant as will be shown.

When the fourth Intercostal space is Identified, the six chest electrodes are then located as follows:

- V1: In the fourth intercostal space at the right sternal border.
- V2: in the fourth intercostal space at the left sternal border.
- V3: mid-way between V2 and V4.
- V4: in the fifth Intercostal space in the mid-clavicular line.

V5: in the left anterior axillary line at the level of V4.
V6: In the left mid-axillary line at the level of V4.

For the avoidance of doubt in women where there may be difficulty with electrode placement on account of pendulous breasts, it should be noted that the electrodes should be placed under the breast and not on top. Correct placement may be impossible which on occasion will account for normal variants of ECG waveforms in the precordial leads in healthy women.

It is felt worthwhile to insert a further historical note at this point. In their original paper of 1938 (8), the American Heart Association stated that the V3-V6 electrodes should be placed "on a line drawn from the left sternal margin in the 4th intercostal space to the outer border of the apex beat (or to a point at the junction of the midclavicular line and the fifth intercostal space) and continued around the left side of the chest at the level of the apex beat or of the junction mentioned". This is what may have led a committee of the British Cardiac Society to state (11), perhaps somewhat strangely, in 1949 that "there is so far only one position for the precordial leads defined as standard". This short paper then recommended the use of the six locations for precordial electrodes described above. There was no reference whatsoever to the apex beat as a landmark for electrode positioning.

Textbooks of then and now are often confusing. Goldberger in his 1953 text (10) quoted precordial positions also as defined by V1-V6 above. However, Paul White, an eminent American cardiologist of the day, stated in the 1951 edition of his book (12) on heart disease, that V5 and V6 should be in the 5th intercostal space which is quite different from being at the same level as V4. White also indicated that the use of the apex beat as a reference point was unsatisfactory because of the variability of its location in health and disease. It is thus even more perplexing to read his statement that V5 and V6 should be located in the sixth or seventh interspace if the cardiac apex were correspondingly in one of these interspaces. In the 1988 edition of Cecil's textbook on medicine (13), the section on electrocardiography also incorrectly refers to the use of the 5th intercostal space for V5 and V6.

The competent practitioner should always bear the foregoing in mind if involved in discussions with medical or other colleagues, confused over correct lead positioning through being taught by senior cardiologists or physicians who themselves may have been "brought up" to believe in incorrect lead positioning.

Right Sided Chest Leads:

On occasions, right sided chest leads are required. These leads are denoted V3R to V6R and effectively are reflections of the left sided chest leads V3 to V6 about the mid-line, e.g. V4R is positioned in the right mid-clavicular line in fifth intercostal space.

In paediatric electrocardiography, lead V4R is often used to the exclusion of lead V3. This is because of the normal right ventricular preponderance in early infancy.

If a patient is known to have mirror image dextrocardia, it is common practice to reverse the chest leads completely. In other words, the V1 electrode would be positioned in the fourth intercostal space at the left sternal margin (=V2). The V2 electrode would be placed in the fourth intercostal space at the right sternal margin (= V1). The electrodes used for V3 to V6 would be positioned similarly in the V3R to V6R positions as described above. Right arm left arm connections should also be interchanged and for completeness, although there is little effect, the right and left leg electrode connections should also be swapped over. Thus, there is a complete switch of electrodes from one side of the body to the other. In this event, it is imperative that the ECG printout be marked with a statement that the limb and chest electrode connections were reversed.

It may be of interest to note that in adults, it is occasionally recommended that right sided chest leads should be recorded in patients with suspected inferior myocardial infarction which might involve the right ventricle (14).

Augmented Unipolar Limb Leads:

The availability of circuitry to record a unipolar chest lead allowed unipolar limb leads to be recorded by placing the exploring electrode on the right or left arm or the left (e.g. However, in 1942, Goldberger(15) modified the Wilson central terminal to augment the voltage of the unipolar limb leads by 50% and thereby introduced the augmented unipolar limb leads. These are designated aVR, aVL and aVF. An augmented unipolar limb lead measures the difference between one limb and the average of the potentials at the other two. For example, aVL measures the potential at the left arm minus the average of the potentials at the right arm and the left leg. Mathematically, this is written as follows:

$$aVL = E_L - \frac{1}{2} (E_R + E_F)$$

By symmetry, the other leads are as follows:

$$aVF = E_F - \frac{1}{2} (E_L + E_R)$$

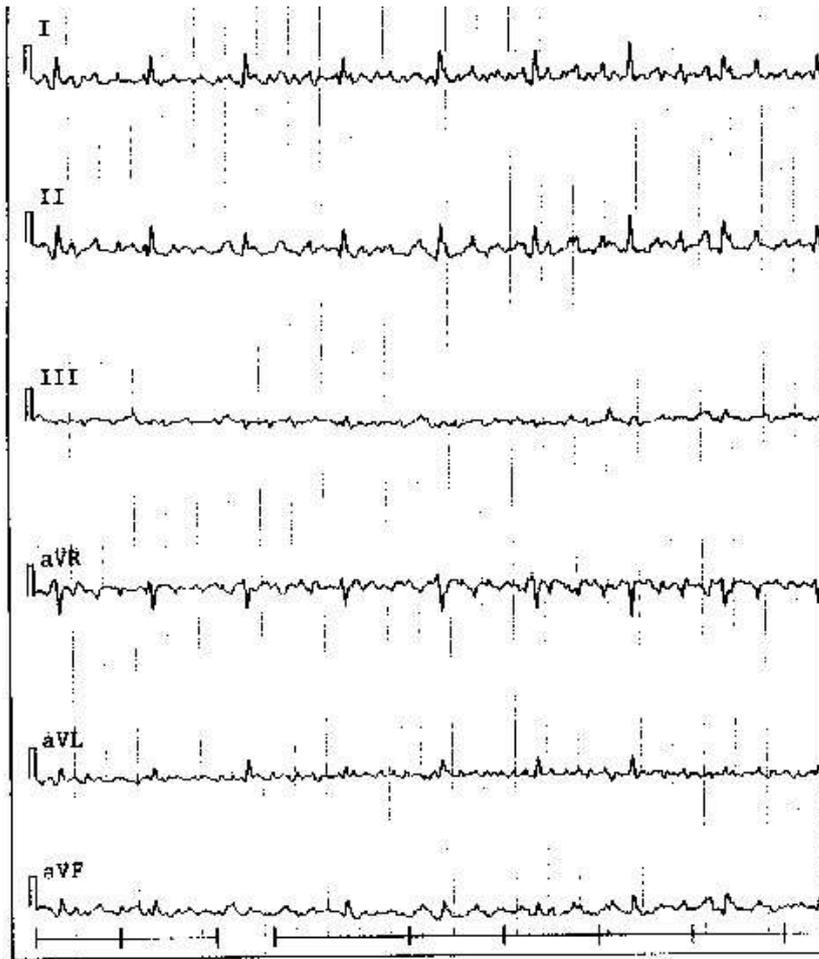
$$aVR = E_R - \frac{1}{2} (E_L + E_F)$$

For completeness, it should be noted that $aVR + aVL + aVF = 0$ at any instant in the cardiac cycle.

ELECTRODES.

A variety of electrodes is now available for ECG recording. They range from the conventional electrode and strap or a suction electrode to the modern adhesive electrode with a conducting tag. An important point to note is that electrodes of different metal composition should not be mixed. It is likely that if plate electrodes are used on the limbs together with adhesive electrodes on the chest, the electrocardiograph may fail to give a recording. If plate electrodes are used together with suction electrodes, they should be obtained from the same manufacturer and be made from the same metals. An excellent technical review can be found elsewhere (16).

PROBLEMS WITH ECG RECORDING - THE PATIENT.



• • • • Fig 3 Example of somatic tremor where there is excessive random fluctuations of the signal, best seen in the T - P, P R segments

The patient must be placed outside the immediate field of an AC current source. If a patient is not completely relaxed, then there will be interference of a random nature (somatic tremor) on the limb leads in particular. This is illustrated in Figure 3. Occasionally, this is unavoidable if a patient has a neurological problem leading to tremor but more often it is a result of anxiety or discomfort. It is therefore essential to ensure that the patient is reassured, warm, comfortable, with arms and legs fully supported on the couch or bed. Note that an ECG should be recorded with a patient in the recumbent position, i.e. lying with the head supported on a large pillow or on a plinth with the back section slightly raised. On occasion, particularly with elderly patients, it may be necessary to record an ECG with the patient sitting upright in a chair. In that event, the position of the heart within the thorax will be different from that of the patient in a recumbent position and therefore different waveforms will be recorded. Any unusual recording position should be noted on the ECG printout to assist the physician with the ECG interpretation. This comment is also applicable to exercise electrocardiography in that the precordial leads in a patient walking on a treadmill will differ from those recorded on the same patient in a recumbent position. As mentioned previously, exercise ECG waveforms will differ from resting ECG waveforms because of different limb lead electrode placement (5).

PROBLEMS WITH ECG RECORDING - ELECTRODE PLACEMENT.
Colour Coding of Electrode Cables:

There are two different colour coding and labelling schemes in use for identifying electrode connections, One is recommended by the International Electrotechnical Commission (IEC) while the other is recommended by the American Heart Association (AHA). Experienced staff will, for example, automatically check for R or RA being inscribed on the right arm electrode connection in addition to knowing that the colour code is red In the IEC scheme or white in the AHA code (table 1). The variation in colour coding is one source of faulty electrode connections but if a department standardises on a single system, the problem can be minimised.

Location	AHA		IEC	
	Inscription	Colour	Inscription	Colour
Right Arm	RA	White	R	Red
Left Arm	LA	Black	L	Yellow
Right Leg	RL	Green	N	Black
Left Leg	LL	Red	F	Green
Chest	V1	Brown/Red	C1	White/Red
Chest	V2	Brown/Yellow	C2	White/Yellow
Chest	V3	Brown/Green	C3	White/Green
Chest	V4	Brown/Blue	C4	White/Brown
Chest	V5	Brown/Orange	C5	White/Black
Chest	V6	Brown/Purple	C6	White/Violet

Table 1. Colour Code and Inscriptions on Electrodes Connections

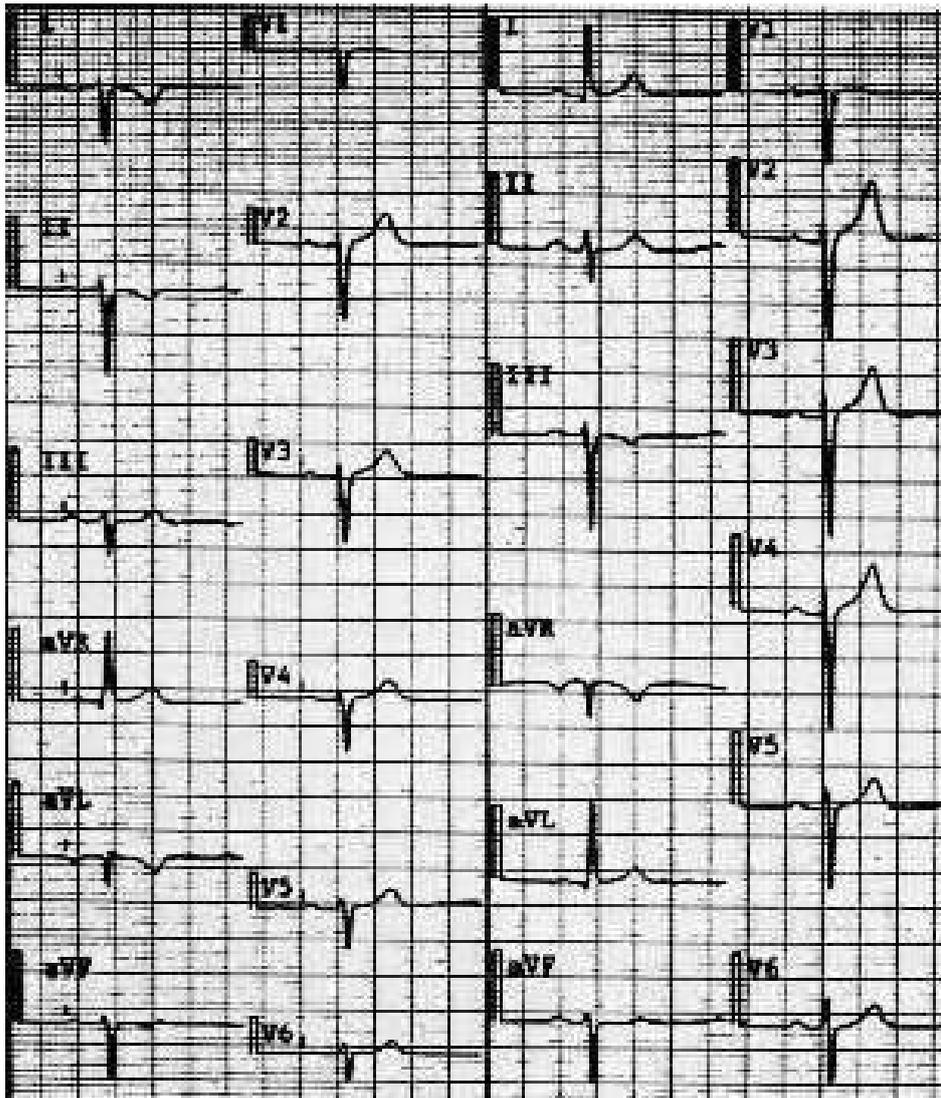


Fig 4 LH Panel: Right and left arm electrode connection reversal RH Panel: The correct recording from one year earlier

Reversal of Arm Lead Electrode Connections:

The most easily recognised error in recording the limb leads is that of interchanging the right and left arm electrode connections. Characteristically in Lead I (Figure 4), in sinus rhythm, the P wave is usually inverted and the QRS complex mainly negative, i.e. has a QS or rS configuration. The T wave may or may not be inverted depending upon the underlying pathology. In atrial fibrillation, a check should be made between appearances in Lead I and V6 and if the QRS in Lead I appears inverted compared to V6, then the probability is that arm lead connections have been reversed.

Reversal of Arm and Leg Lead Electrode Connections:

Recently, Haisty et al (17) pointed out the effects of interchanging the right arm and right leg electrode connections. Recall that: Lead II = EF - ER. If the right arm electrode connection is attached to the right leg electrode in error, then: Lead II = EF - ERL where ERL is the potential at the right leg. Because the potential on the left and right leg is essentially similar there is only a very small potential difference recorded by Lead II in this case (see Fig. 5&127).

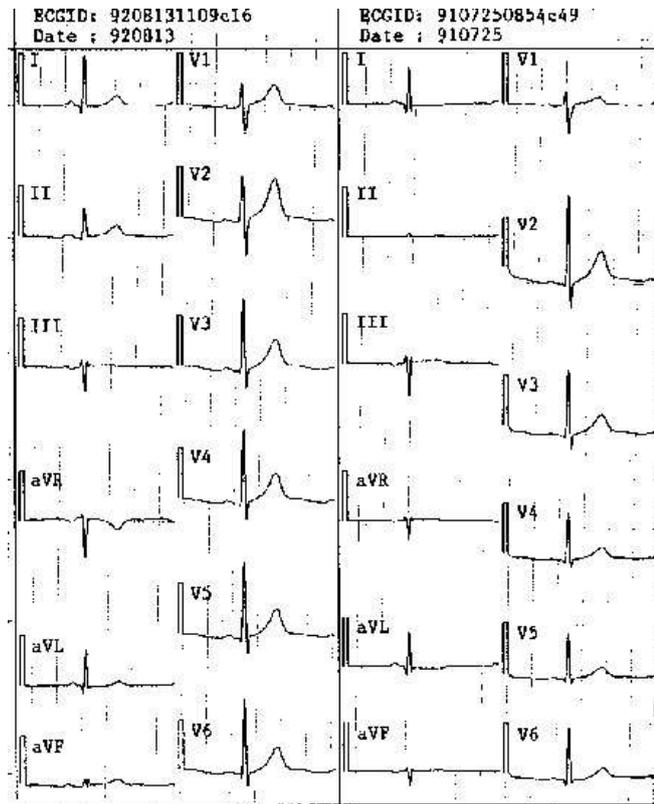


Fig 5 RH Panel: An almost isoelectric lead II caused by the right arm and leg connections being Interchanged. Note that aVL, aVF and the Wilson Central Terminal (and hence V1- V6) are affected by this error. LH Panel: The correct recording from one year later is also shown.

While the experienced individual will rarely make such an error, the occurrence of an essentially isoelectric Lead II should immediately draw attention to the possibility that the right arm and right leg electrode connections have been interchanged by mistake. Because of Einthoven's law, it follows that when Lead II is essentially zero, Leads I and III are mirror images of each other, i.e. in this case,

$$I + III = II = 0 \quad I = -III$$

It is, of course, also possible to interchange the right arm and left leg electrode connections although this is extremely uncommon. Nevertheless, Figure 6

gives an example of careless electrode connection illustrating this particular fault. This error produces a pattern resembling that of inferior myocardial infarction as aVF has the appearances of aVR. The experienced reviewer might suspect a problem from the inverted P in aVF but this is a difficult error to detect on a single ECG.

A much more difficult error to detect is faulty placement of the left arm and left leg electrode connections. If these are interchanged, then what is thought to be aVL will, of course, be aVF and vice versa. Furthermore, Lead III is inverted compared to the correct recording. What appears as Lead I is really Lead II and what appears as Lead II is actually Lead I (Figure 7).

Indeed, this can be missed by an experienced operative and by an experienced cardiologist interpreting ECGs. The problem generally comes to light when serial ECGs are recorded as is often the case following myocardial infarction or in a research study where ECGs are recorded annually. In the case of the latter, it is often less experienced staff who are recording the ECGs and there is therefore all the more need to be careful when connecting electrodes.

Finally, the left arm and right leg electrode connections could be interchanged. The reader is encouraged to work out the consequences. It should be concluded that aVL will resemble aVF, I will be similar to II, and Lead III will be virtually isoelectric. Figure 8 illustrates this problem. It should also be recalled that the Wilson Central Terminal is derived from ER+EL+EF. If two of these potentials are similar. e.g. when the right arm and leg electrodes are interchanged (and the recorded ER = EF approximately), the central terminal potential is faulty and chest leads will also be distorted (17).

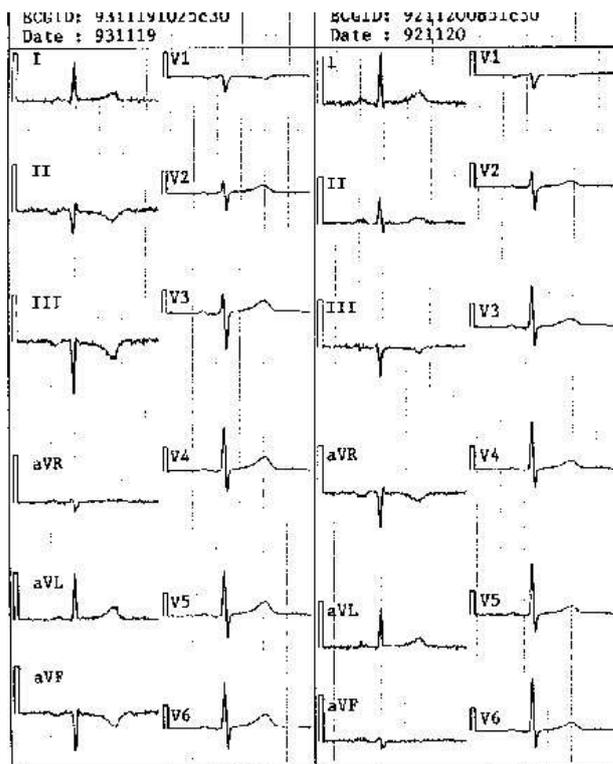


Fig 6 LH Panel: An example of the right arm and left leg electrodes being interchanged producing the false positive appearance of inferior myocardial infarction.

RH panel: The correct recording from one year earlier is also shown. Note how aVR and aVF are interchanged between the two recordings.

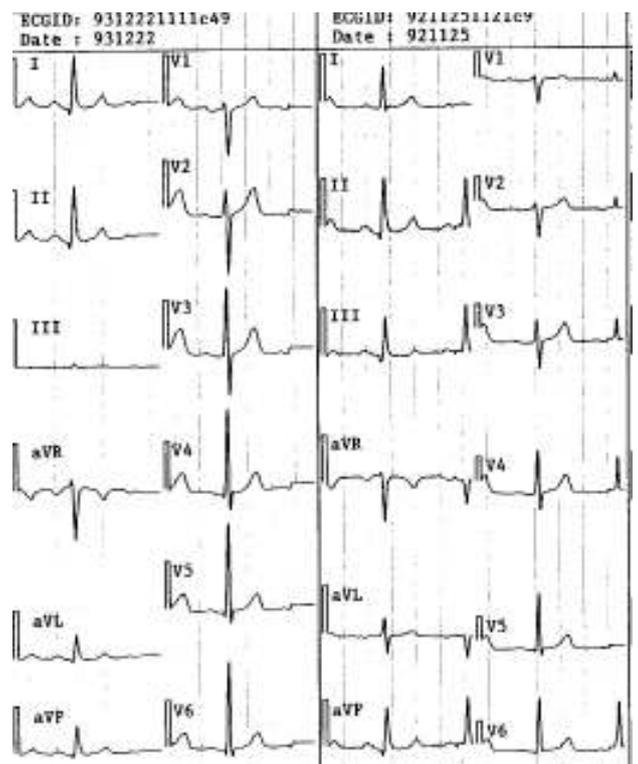


Fig 8 LH Panel: An example of reversal of the left arm and right leg electrode connections. The consequences are that aVL and aVF as well as I and II are similar and lead III is essentially isoelectric.

RH panel: The correct recording one year later.

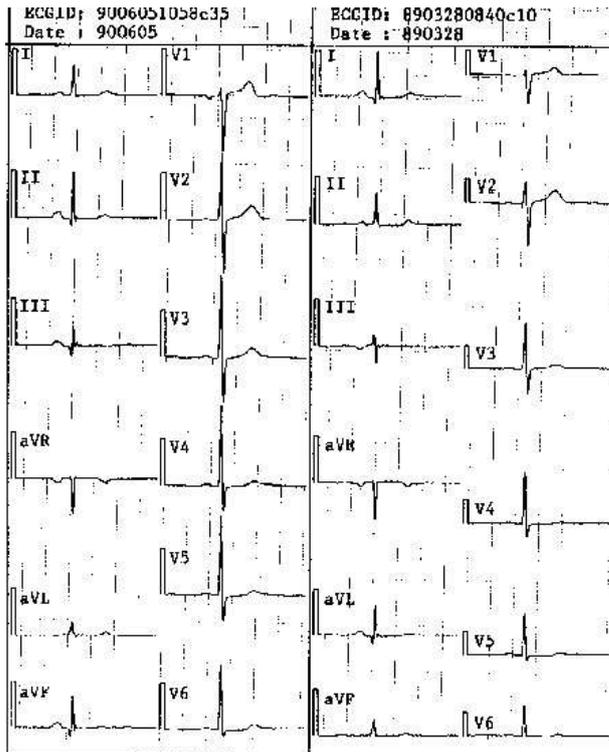


Fig 7 RH panel: An example of left arm and left leg electrode connection reversal
LH panel: The correct recording one year later.

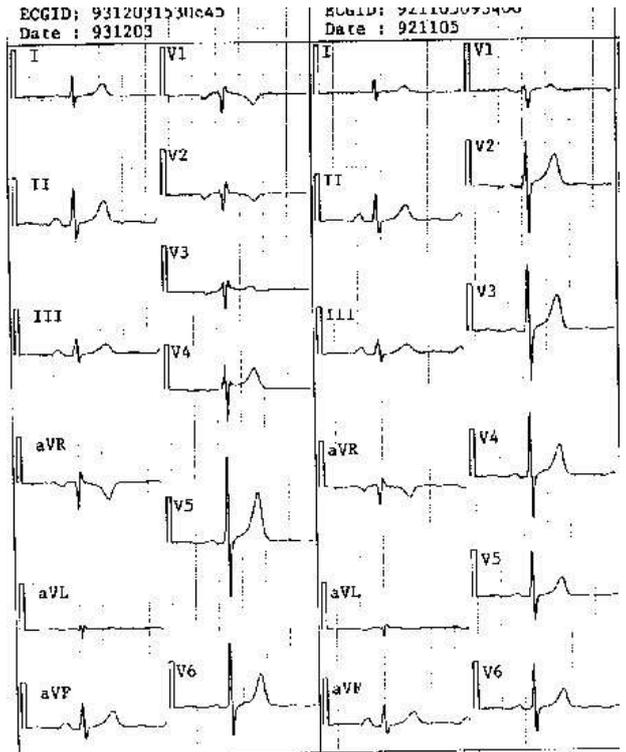


Fig 9 The effect of recording V1 and V2 one interspace too high (left-hand panel) can be seen in these comparative recordings. The P and T waves are both clearly inverted and there is an rSr' complex in V1 and V2

Chest Lead Electrode Placement Errors:

As indicated earlier, the fourth intercostal space must be located accurately. If this is not done, the probability is that the V1 and V2 electrodes will be positioned in the third intercostal space with resultant knock-on effects on the other precordial leads. In general terms, when this happens, V1 and V2 tend to show an rSr' configuration with inverted P waves and inverted T waves (Figure 9). If this morphology is noted in V1 and V2, a check should be made on electrode placement. There is no doubt that in cases of right ventricular hypertrophy, rSr' with inverted T waves can be found in these leads but in general, these appearances should not be accompanied by inverted P waves. Likewise, anyone reviewing a batch of ECGs for interpretation should be aware that, if there is a frequent incidence of incomplete right bundle branch block patterns in V1 and V2, then most probably the electrode placement is at fault.

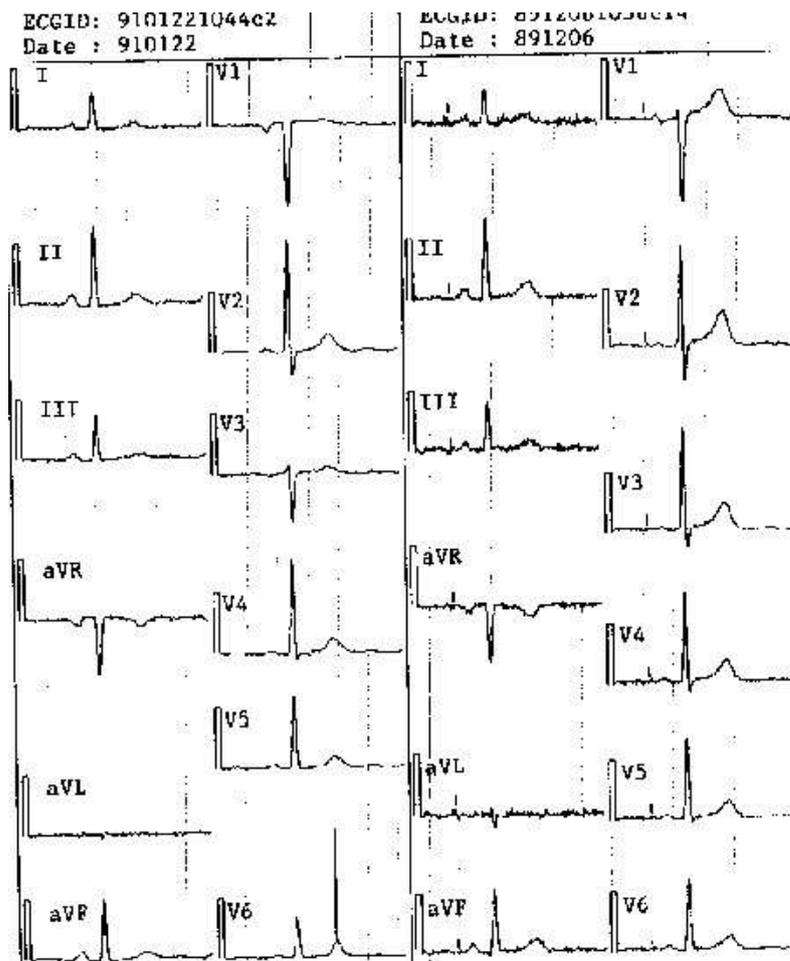


Fig 10. LH Panel: Precordial lead reversal Involving V2 and V3 RH Panel: A recording from the same patient one year earlier

Another quite common error is to interchange precordial leads. For example, the V2 and V3 electrodes may be reversed so that there is an apparent lack of progression of R waves (Figure 10). This should always be suspected if the S amplitude in V3 is larger than in V2 and the R wave has lower amplitude. Another clue will be the lack of progression of T wave amplitude which, in general terms, increases from V2 to V3 to V4.

DISCUSSION.

Experience derived from serial electrocardiographic studies, and from the formal testing of the practical skills of individuals in training, suggests that errors in ECG recording are common and widespread. This communication seeks to draw attention to several of these errors in ECG recording, and to the diagnostic mistakes that may follow. Although, there is a wide range of possible error in limb lead recording, we suspect that the challenge which daily defeats many individuals is the accurate location of the chest electrode positions.

Practitioners in busy cardiology departments are often under pressure to record large numbers of ECGs each day. To avoid the possibility of error, it is suggested that even the most experienced reader should take a few minutes to study the examples presented in this paper to learn the common patterns of electrode misplacement or electrode connection error. Many of the changes described are of an extremely subtle nature and go unrecognised in routine recording.

Likewise, with physicians under pressure to report ECGs or check computer based ECG interpretations, If indeed ECGs are reported at all on a routine basis within a hospital, there is often a tendency not to look at serial recordings which would enable change or errors in electrode placement to be uncovered. Physicians might also do well to take a minute or two to look at some of the problems highlighted in this paper!

Computer-based electrocardiographs can nowadays check criteria for limb lead connection errors where the left and right arm electrode connections have been interchanged or where the right arm and leg connections have been interchanged although diagnostic algorithms are open to error. Thus, even computer reported ECGs should be very carefully checked to ensure that the ECG has been recorded properly. Furthermore, the computer is unlikely to be specific in reporting the possibility of electrode misplacement at the fourth intercostal space although the example highlighted does suggest that it could be worthwhile to include such criteria in a computer program.

The message from this short communication should be clear. All those involved in ECG recording, whether it be for routine purposes in hospital or for research purposes elsewhere, should ensure that limb leads are connected properly and that chest leads are located correctly - otherwise there may be significant errors in reporting with perhaps unfortunate consequences for the patient. The need is urgent for those who record and those who report electrocardiograms to be constantly vigilant for those suspicious signs which point to an incorrect recording.

Marriott has warned (18) that "heart disease of electrocardiographic origin" should be avoided. To this end, whoever records the electrocardiogram of any patient must exercise the greatest care to ensure the highest standards of accuracy.

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