Einthoven's Triangle Transparency: A Practical Method to Explain Limb Lead Configuration Following Single Lead Misplacements

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Limb lead switches remain a significant source of electrocardiographic error that may lead to faulty diagnosis and improper clinical action. Methods to identify such errors have been the subject of many prior publications. A brief review of the mathematical derivation of the limb lead system is presented here, together with an additional method to help understand limb lead reversals using a transparency of the Einthoven's triangle.

[Rev Cardiovasc Med. *2010;11(1):33-38 doi: 10.3909/ricm0506*]

Key words: Einthoven triangle • Electrocardiogram • Lead reversal

Electrode cable switches and misplacements during the recording of an electrocardiogram (ECG) are not uncommon despite the mandatory color coding standard of lead wires.[1] Lead misplacement errors include improper positioning of precordial leads,[2] a problem reported to be shared by physicians and nurses (although less so by technicians),[3] use of the Likar-Mason configuration of the limb leads (exercise electrode placement),[4] and inadvertent reversal of leads.

Although the first 2 types of errors may be decreased by extra training in the correct lead positioning and its importance, the third type is unintentional and probably depends on the intensity of the clinical setting.[5] Many factors may influence the prevalence of lead misplacement. One study reported approximately 2% lead misplacement in more than 10,000 ECGs analyzed.[6] Another study reported the incidence of lead misplacement in 0.4% of ECGs performed in an outpatient cardiology clinic and in 4% of ECGs performed in the intensive care unit.[5] The grave ramifications of lead misplacement are evident, including incorrect diagnosis and improper treatment. Incorrect diagnoses include, but are not limited to, new appearance or resolution of infarcts[7-9] and rhythm changes such as atrial or junctional rhythms replacing sinus rhythm, or vice versa.[10] Several reviews have been published[11-13] describing ways to identify ECG lead misplacements. Artificial neural networks have been applied to aid in the recognition of lead misplacements with high reported sensitivity and specificity.[6,14,15] Although some lead misplacements are obvious and can be readily recognized even by electronic ECG machines (eg, arm lead reversal), others may not be so apparent, and in many cases will need a baseline ECG recording with the correct lead placement for comparison. Complex and more challenging lead misplacements have been reported, such as precordial and limb lead reversal,[16] and lead misplacement without reversal.[17] Fortunately such errors are rare. Both P-wave and QRS axis analysis appear to be important in analyzing the likelihood of lead misplacement.[18,19] It is important to be able to identify not only the presence of lead misplacement but also the location of such misplacement, because this may be caused by an erroneous hook-up of the terminal clamp to the lead wire,[20] a problem that may perpetuate in several ECGs unless promptly recognized and corrected.

A simple and practical method for identifying single-limb lead reversal and deducing its effect on the remaining limb leads is suggested here; using a cut-out transparency of the Einthoven triangle (Figure 1). This may also help as a control to check whether the proposed lead misplacement is compatible with the anticipated change in morphology of the other leads secondary to such misplacement.

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Mathematical Derivation of the Limb Leads

A brief review of the mathematical derivation of the limb lead system helps clarify their interdependence. This aids in the visualization of what the proper lead placement should be from an ECG with misplaced limb leads, thereby allowing corrective action. This may be especially helpful if a repeat ECG cannot be performed in a timely manner, such as after a patient has been discharged.

The heart acts as a dipole of positive and negative charges in the center of the chest, creating variable electrical potentials (Φ) at various points surrounding it.[21] The potential difference (voltage) between the electrical potentials at any 2 of the 3 leads is a vector quantity based on the assumption (by convention) that the augmented vector foot (aVF) is positive and the augmented vector right (aVR) is negative; augmented vector left (aVL) is positive in relation to aVR, but negative in relation to aVF. Kirchhoff's second law states that the algebraic sum of all the voltages around any closed path in a circuit equals zero[22]:

$$\mathrm{I} + \mathrm{III} + (-\mathrm{II}) = 0; \text{ therefore } \mathrm{I} + \mathrm{III} = \mathrm{II}$$

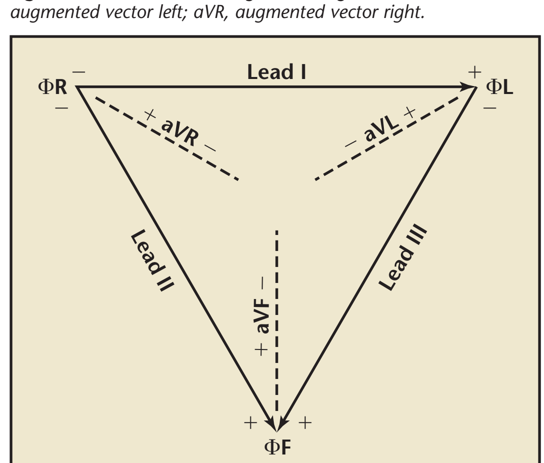
Stated differently, the potential difference (vector displacement) between any 2 points is equal to the sum of any number of potential differences (vector displacements) causing the same net displacement.

The same conclusion can be arrived at by examining the potential differences between any 2 points:

$$\begin{aligned} \mathrm{I} &= \Phi\mathrm{L} - \Phi\mathrm{R} \\ \mathrm{II} &= \Phi\mathrm{F} - \Phi\mathrm{R} \\ \mathrm{III} &= \Phi\mathrm{F} - \Phi\mathrm{L} \\ \mathrm{I} + \mathrm{III} &= (\Phi\mathrm{L} - \Phi\mathrm{R}) + (\Phi\mathrm{F} - \Phi\mathrm{L}) \\ &= \Phi\mathrm{F} - \Phi\mathrm{R} = \mathrm{II} \\ \mathrm{III} &= \mathrm{II} - \mathrm{I} \end{aligned}$$

The augmented unipolar lead vectors measure the potential difference between a frontal cable lead

Figure 1. *The Einthoven triangle. aVF, augmented vector foot; aVL, augmented vector left; aVR, augmented vector right.*



and the corresponding Goldberger-modified Wilson central terminal, which is essentially the average of the remaining (opposite) terminal potentials[23]:

$$aVR = \Phi R - \tfrac{1}{2}(\Phi L + \Phi F)$$

by algebraic rearrangement:

$$aVR = \tfrac{1}{2}(2\Phi R - \Phi L - \Phi F) = \tfrac{1}{2}\{[-(\Phi L - \Phi R)] + [-(\Phi F - \Phi R)]\} = \tfrac{1}{2}\{(-I) + (-II)\}$$

Similarly;

$$aVL = \Phi L - \tfrac{1}{2}(\Phi R + \Phi F)$$

and by algebraic rearrangement:

$$aVL = \tfrac{1}{2}(2\Phi L - \Phi R - \Phi F) = \tfrac{1}{2}\{[(\Phi L - \Phi R)] + [-(\Phi F - \Phi L)]\} = \tfrac{1}{2}\{(I) + (-III)\}$$

Finally;

$$aVF = \Phi F - \tfrac{1}{2}(\Phi R + \Phi L)$$

and by algebraic rearrangement:

$$aVF = \tfrac{1}{2}(2\Phi F - \Phi R - \Phi L) = \tfrac{1}{2}\{(\Phi F - \Phi R) + (\Phi F - \Phi L)\} = \tfrac{1}{2}\{(II) + (III)\}$$

Therefore, taking polarity and magnitude into account, the voltage of an augmented unipolar lead corresponds to the average of the voltages (vector displacements) of the 2 adjacent bipolar leads.

Replacing III with II − I in the above equations will yield:

$$III = II - I$$
$$aVR = (-\tfrac{1}{2}I) + (-\tfrac{1}{2}II)$$
$$aVL = \tfrac{1}{2}\{(I) + (-III)\} = \tfrac{1}{2}\{(I) + (-(II - I))\} = \tfrac{1}{2}\{(I) + (I - II)\} = (I) + (-\tfrac{1}{2}II)$$
$$aVF = \tfrac{1}{2}\{(II) + (III)\} = \tfrac{1}{2}\{(II) + (II - I)\} = (-\tfrac{1}{2}I) + (II)$$

Such derivation makes it clear that it takes any 2 of the bipolar leads—usually I and II are recorded by ECG machines[21]—to mathematically derive the remaining 4 leads. Having all 6 leads graphed, however, facilitates identifying patterns and pathologies according to the segment of the heart (center dipole) from which they are coming.

The Einthoven Triangle Transparency

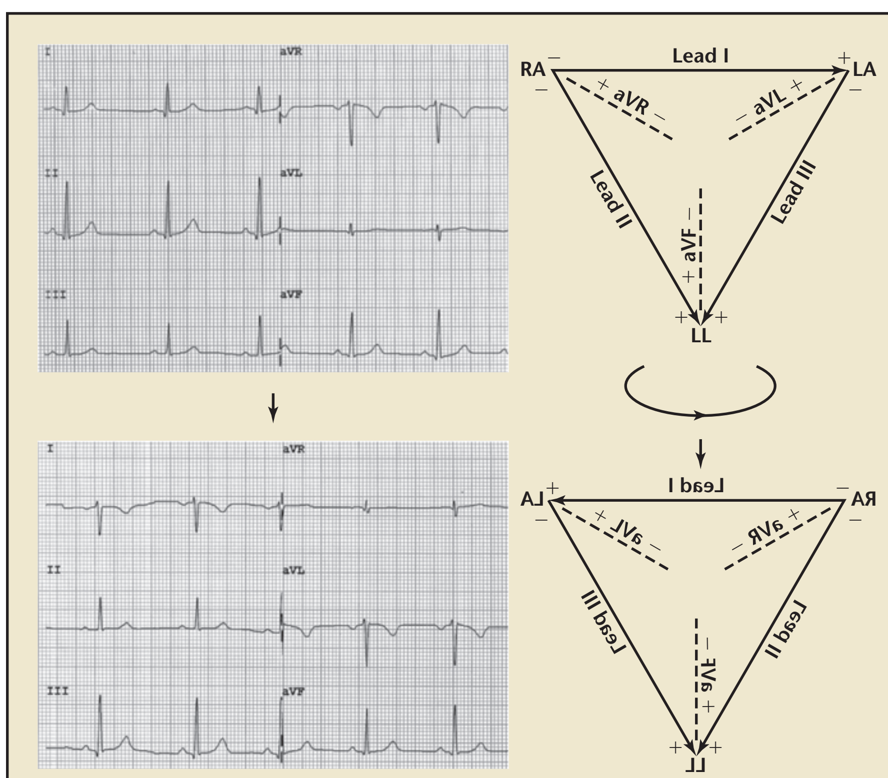
The Einthoven triangle is an important tool that has been used as the basis for facilitating the recognition and understanding of lead misplacements.[19,24,25] We suggest here another practical method utilizing the Einthoven triangle to further help in understanding the effects of limb lead reversals. To demonstrate the outcome of any single limb lead reversal, we recommend the use of a cut-out transparency and a regular print (as a reference) of the Einthoven triangle.

Starting with the more obvious arm lead reversal (Figure 2), the changes become clear from the flipped Einthoven triangle transparency: lead I changes polarity only (upside down) to become reverse lead I. Lead II becomes lead III and lead III becomes lead II. aVF (fulcrum around which the transparency was flipped) is unchanged; aVR becomes aVL and aVL becomes aVR.

Second, the effect of right arm (RA) and left leg (LL) lead reversal is demonstrated in the next diagram

To demonstrate the outcome of any single limb lead reversal, we recommend the use of a cut-out transparency and a regular print (as a reference) of the Einthoven triangle.

Figure 2. *Arm lead reversal. aVF, augmented vector foot; aVL, augmented vector left; aVR, augmented vector right; LA, left arm; LL, left leg; RA, right arm.*



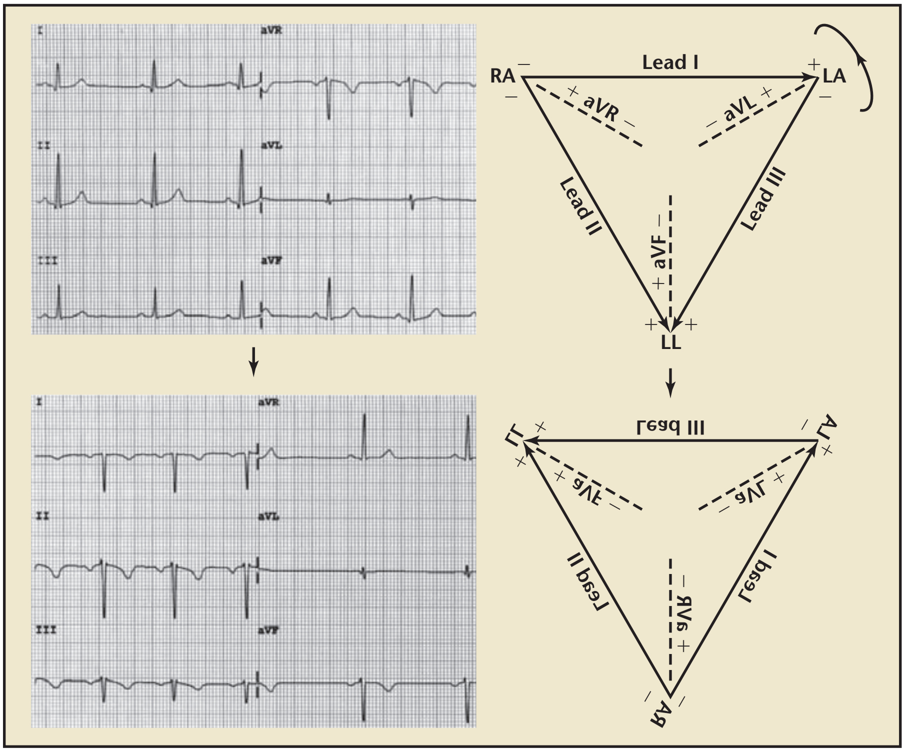


Figure 3. *Right arm and left leg lead reversal. aVF, augmented vector foot; aVL, augmented vector left; aVR, augmented vector right; LA, left arm; LL, left leg; RA, right arm.*

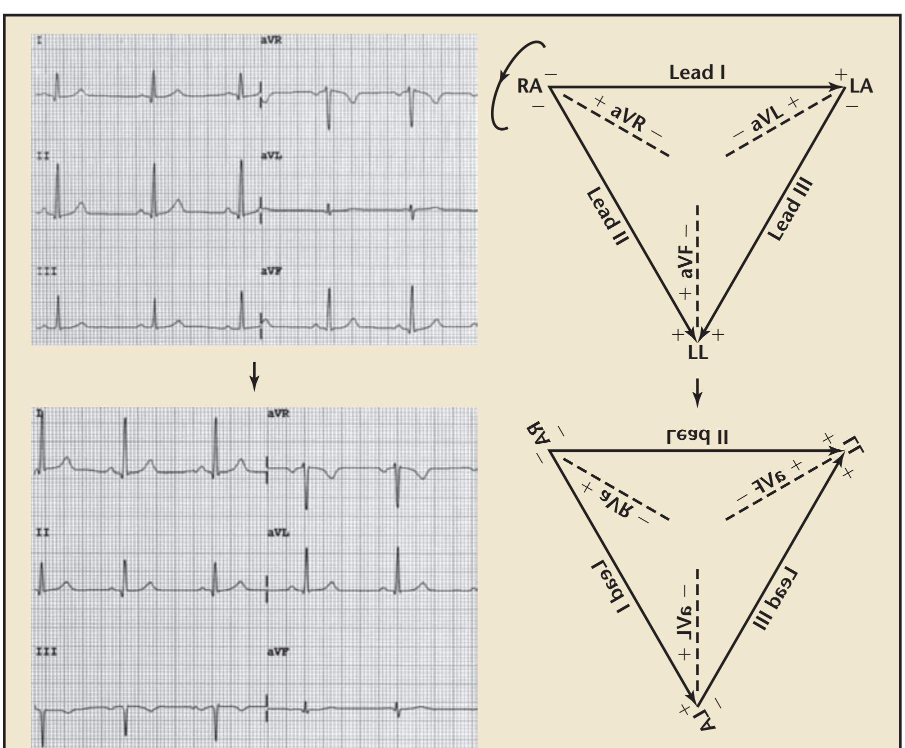


Figure 4. *Left arm and left leg lead reversal. aVF, augmented vector foot; aVL, augmented vector left; aVR, augmented vector right; LA, left arm; LL, left leg; RA, right arm.*

(Figure 3). Again, it can be seen that lead II changes polarity only (upside down) to become reverse lead II. Lead I becomes reverse lead III. Lead III becomes reverse lead I. aVL (fulcrum around which the transparency was flipped) is unchanged; aVR becomes aVF and aVF becomes aVR.

Third, the effect of left arm (LA) and LL lead reversal is demonstrated in the next diagram (Figure 4).

Here, it can be seen that lead III changes polarity only (upside down). Lead I becomes lead II. Lead II becomes lead I. aVR (fulcrum around which the transparency was flipped) is unchanged; aVL becomes aVF and aVF becomes aVL. Therefore, the unipolar lead that acts as the fulcrum around which the transparency is flipped remains unchanged, and the opposite bipolar lead reverses direction. The remaining 2 unipolar leads are swapped, maintaining the same polarity; the remaining 2 bipolar leads are swapped, and change polarity only when aVL is the fulcrum.

Grounding Errors

Methods to identify right leg (RL) (ground) lead reversals have been the subject of previous reviews.[26-28] Here we briefly discuss the effect of such reversals on the remaining limb leads. To understand the effect of lead reversal involving RL (grounding lead) it is important to realize that there is no potential difference between RL and LL.[29] Therefore, if RL and LL are swapped, no change is seen on the ECG. For the discussion below, we will replace RA or LA with RL, which may be done either by imagination or with a small removable sticker placed on the transparency.

If RL is swapped with RA (Figure 5):

Lead III is unchanged

$$\text{Lead II} = \text{LL} - \text{RL} = 0$$

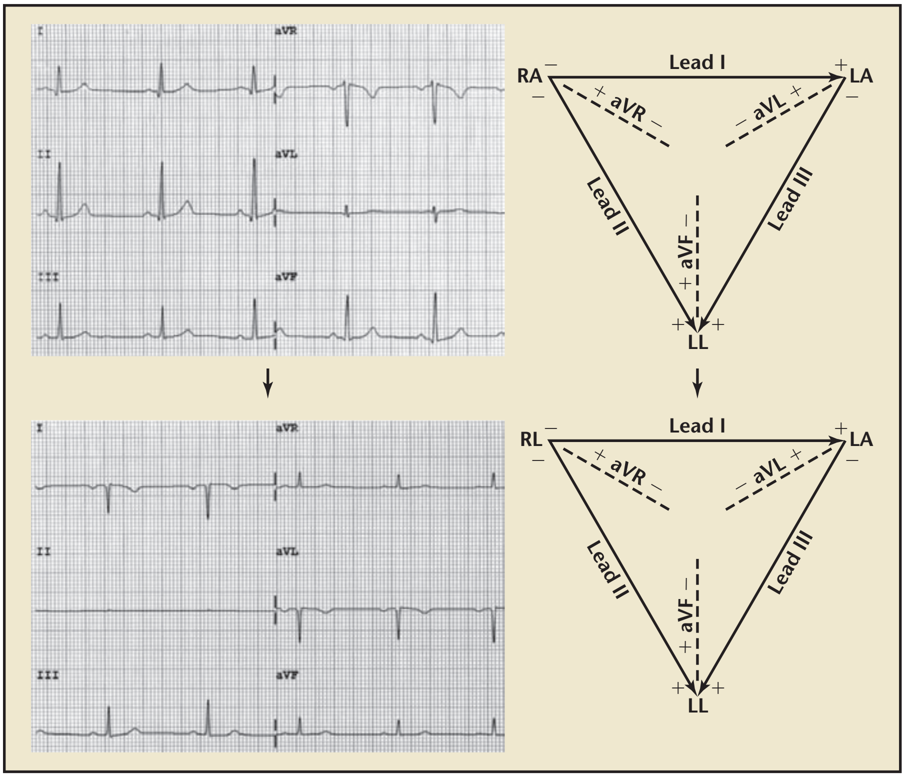


Figure 5. *Right leg and right arm (ground) lead reversal. aVF, augmented vector foot; aVL, augmented vector left; aVR, augmented vector right; LA, left arm; LL, left leg; RA, right arm; RL, right leg.*

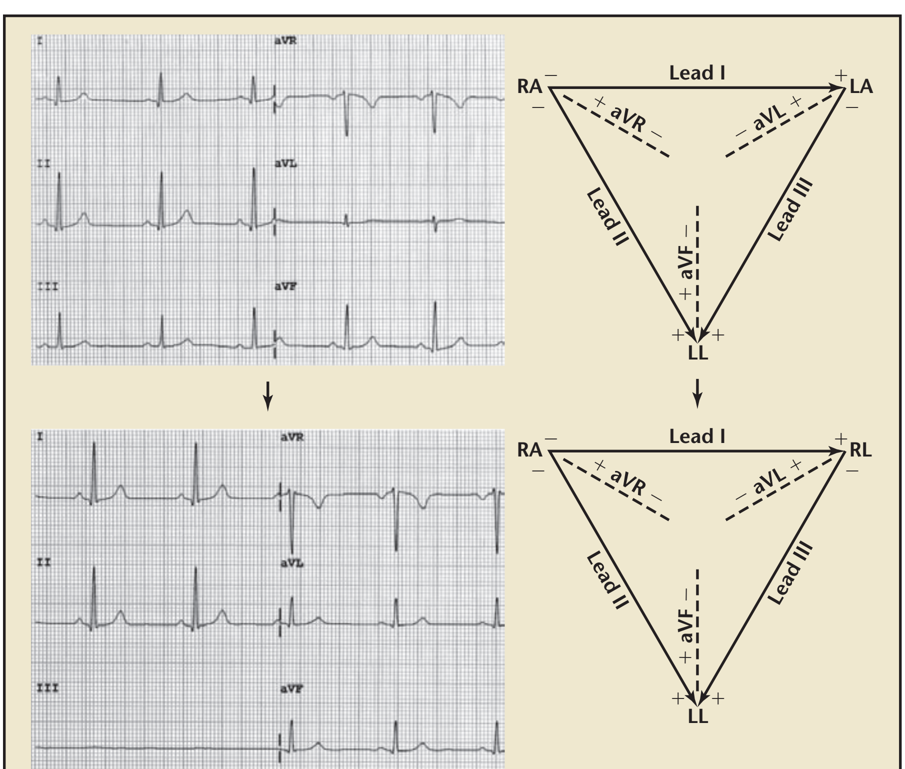


Figure 6. *Right leg and left arm lead reversal. aVF, augmented vector foot; aVL, augmented vector left; aVR, augmented vector right; LA, left arm; LL, left leg; RA, right arm; RL, right leg.*

Therefore Lead I = − Lead III

$$\begin{aligned} aVR &= \tfrac{1}{2}\{(-I) + (-II)\} \\ &= \tfrac{1}{2}(-I) \text{ or } \tfrac{1}{2}\,III \\ aVL &= \tfrac{1}{2}\{(I) + (-III)\} = I \text{ or } -III \\ aVF &= \tfrac{1}{2}\{(II) + (III)\} = \tfrac{1}{2}(-I) \text{ or } \tfrac{1}{2}\,III \end{aligned}$$

Therefore aVR = aVF. Note that this may be mistaken for arm lead reversal due to the negative QRS and P-waves in leads I and aVL. However, the isoelectric lead II should give a clue to the grounding error.

If RL is swapped with LA (Figure 6):

Lead II is unchanged
Lead III = LL − RL = 0

Therefore Lead I = Lead II

$$\begin{aligned} aVR &= \tfrac{1}{2}\{(-I) + (-II)\} = -I \text{ or } -II \\ aVL &= \tfrac{1}{2}\{(I) + (-III)\} = \tfrac{1}{2}\,I \text{ or } \tfrac{1}{2}\,II \\ aVF &= \tfrac{1}{2}\{(II) + (III)\} = \tfrac{1}{2}\,II \text{ or } \tfrac{1}{2}\,I \end{aligned}$$

Therefore aVL = aVF

Although this method may also help elucidate change with multiple limb lead misplacements or reversals, such discussion is beyond the scope of this article.

Conclusions

ECG lead misplacement is an important and potentially detrimental source of error that has received fair attention in the literature. Computerized ECG machines may only be able to identify a limited number of misplacements. Therefore, the proofreading physician should be able to not only recognize the remaining misplacements, but also to reconstruct what the proper placement would look like so timely corrective action can be implemented in case a serious diagnosis is suspected, especially if a repeat ECG cannot be obtained in a timely manner. An Einthoven's triangle transparency may yet be another gadget worthwhile to carry around to help in this endeavor. ■

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Main Points

- Electrode cable switches and misplacements during the recording of an electrocardiogram are not uncommon despite the mandatory color coding standard of lead wires.
- The ramifications of lead misplacement are evident and quite serious, including incorrect diagnosis and improper treatment.
- Using a cut-out transparency of the Einthoven triangle is a simple and practical method for identifying single-limb lead reversal and deducing its effect on the remaining limb leads.
- Physicians should be able to recognize lead misplacements and also reconstruct what the proper placement would look like so corrective action can be taken.