Part I

Few subjects related to 12 lead ECG interpretation provoke more controversy (or anxiety) than axis determination.

It is controversial in that not everyone agrees it is a necessary skill for prehospital providers to learn. It is anxiety provoking in that it can be difficult to understand, especially when taught poorly.

I am of the opinion that axis determination is a critical skill to master. I would even go so far as to say that you cannot be competent at 12 lead ECG interpretation if you don’t understand the heart’s electrical axis.

In many classes, to the extent that axis is discussed at all, the instructor goes straight to providing a cheat sheet for axis determination. The most commonly taught method is the quadrant method that uses leads I and aVF. I don’t think this holds much value for the student. On the one hand, it’s perfectly true that leads I and aVF can place the QRS axis into one of four quadrants in the frontal plane. On the other hand, it leaves the student with a feeling of “so what?” The axis becomes a piece of “gee whiz” information that doesn’t lend itself to a deeper understanding of the 12 lead ECG.

I do teach the quadrant method (and other speed methods for axis determination), but only after I teach the hexaxial reference system, and my students can place the QRS axis within 10 to 15 degrees. This is not particularly difficult, and once it is well understood, it’s the gift that keeps on giving for the rest of your career. It is similar to using the large block method for rate determination in this respect. Once you know it, you know it, and you can estimate the heart rate at a glance. And yet, most paramedics have never bothered to commit this simple method for calculating the heart rate to memory, so they are dependent on the computer, or they have to count out the QRS complexes in a 6 second strip and multiply by 10.

Before we begin looking at the hexaxial reference system, there’s a man we need to discuss, and his name was Willem Einthoven, winner of the Nobel Prize in Physiology or Medicine in 1924 for his invention of the string galvanometer, which was the first reliable electrocardiograph.

You’ll notice in the image to the right that Einthoven’s arms and his left leg are immersed in buckets of salt water. At the time, this was the only way to obtain a signal for the electrocardiograph. Even after the invention of the electrode, they continued to be placed on the subject’s arms and legs. From this configuration, leads I, II, and III were born, and they are called the “limb leads” to this day.

Leads I, II, and III have been around for a long time (over 100 years). I always laugh when I hear people suggest that using leads I, II, and III to estimate the heart’s electrical axis is somehow a new thing! It’s been happening long before any of us were born.

These first 3 leads of the 12 lead ECG form what came to be known as Einthoven’s Triangle or Einthoven’s Equilateral Triangle.
If you’re like me, you’re reading this and it sounds very confusing. After all, if you look at the image on the left, it’s clear that anatomically, leads I, II, and III form a scalene triangle, not an equilateral triangle. So what in the world was Einthoven talking about?

Einthoven meant that electrically speaking, leads I, II, and III form an equilateral triangle. He expressed this with Einthoven’s Law, which states:

\[ I + (-II) + III = 0 \]

I know what you’re thinking. This equation is scary. I’ve just lost you. Take a deep breath! Everything is going to be okay.

What is lead I? It is a dipole, with the negative electrode at the right arm (white electrode) and the positive electrode at the left arm (black electrode).

What is lead III? It is a dipole with the negative electrode at the left arm (black electrode) and the positive electrode at the left leg (red electrode). Sometimes I wonder why Einthoven didn’t call this lead II.

What is lead II? Continuing clockwise as you look at the patient, you’d think it would be a dipole with the negative electrode at the left leg (red electrode) and the positive electrode at the right arm (white electrode), but it’s not. For reasons known only to Einthoven (perhaps because he liked to view upright QRS complexes), he made lead II a dipole with the negative electrode at the right arm (white electrode) and the positive electrode at the left leg (red electrode).

Had Einthoven not switched the polarity of lead II, Einthoven’s Law would be written like this:

\[ I + II + III = 0 \]

But he did, and there’s no point in crying over spilled milk.

I still know what you’re thinking. You’re feeling anxious because you still don’t understand what the equation is referring to! That’s okay. We’re getting there. Take another deep breath and relax. Everything is still going to be okay.

Rather than explain to you why Einthoven’s Law works, I’m simply going to prove to you that it does work.

Look at the image to the right and come up with a numerical value for the signal recorded in lead I. The R wave is about 7 1/2 mm tall, and the S wave is about 2 1/2 mm deep. Subtract the S wave from the R wave, and you come up with 5 mm.

Let’s do the same thing for the signal in lead II. This is easier, because it’s essentially a monophasic QS complex. It’s about -10 mm.

Do you see where this is going?

Now how about lead III? There’s a little nub of an R wave that is about 1 mm high, and the S wave is about 16 mm
deep. Subtract the R wave from the S wave, and you get a complex that measures approximately -15 mm.

Now let’s plug these values into the equation for Einthoven’s Law.

\[ I + (-II) + III = 0 \]

\[ 5 + 10 - 15 = 0 \]

As you can see, when you plug in the measurements, you end up with an electrical value of zero.

You can try this trick on virtually any ECG.

Because this is true, leads I, II, and III can be represented as an electrically equilateral triangle.

As you will see in Part II, this is the key to understanding the formation of the hexaxial reference system, and understanding the heart’s electrical axis in the frontal plane.

**Part II**

In Part I, we looked at Einthoven’s Equilateral Triangle and Einthoven’s Law, and I told you that it was the key to understanding the formation of the hexaxial reference system. But before we delve further into the hexaxial reference system (the instrument we’ll be using to calculate the heart’s QRS axis) we need to address something even more fundamental.

What is the heart’s electrical axis?

To answer this question, I’m going to borrow an image from *Prehospital 12 Lead ECG – What You Should Know* © 1999 Medtronic Physio-Control. This is an outstanding educational resource. I encourage you to download the entire booklet to your hard drive and look at it later.

This diagram shows the sequence of ventricular depolarization. As you can see, the first area to depolarize (1) is the interventricular septum, which depolarizes in a left-to-right direction (responsible for the so-called septal Q waves in the lateral leads of a normal 12 lead ECG).

Next, the area around the left and right ventricular apex (2) depolarizes from an endocardial-to-epicardial direction (inside-out). You’ll notice that there are more arrows near the (2) on the left side of the heart. This is because the left
ventricle is more massive than the right ventricle. It has to be more massive because it’s responsible for circulating blood to the entire body and back. In contrast, the right ventricle is thinner, and attaches to the left ventricle like a pocket, because it only has to circulate blood to the lungs and back. In fact, while the septal wall is shared between the left and right ventricles, if you look at a cross-section of the heart, it’s really owned and operated by the left ventricle, which has the general appearance of a muscular tube.

Finally, the lateral walls of the left and right ventricle depolarize (3) and last the high lateral wall of the left ventricle (4). This is just to give you a general idea. Obviously we can’t look at the anterior and posterior walls from a cross section of the frontal plane.

Now notice the large block arrow superimposed over the top of the diagram. This is the heart’s mean electrical vector. That means if you averaged the millions of electrical vectors created as the ventricles depolarize in any given cardiac cycle, the average direction would be right-to-left, superior-to-inferior (for the normal heart). In the first place, that’s how the heart is oriented in the chest, but it’s also because the left side of the heart is more massive. More heart cells depolarizing means a a stronger signal that cancels out the signal coming from the right side of the heart, so the normal QRS axis runs from a right shoulder to left leg direction (very similar to lead II).

Clear as mud? Here’s the fun part.

When the heart’s mean electrical vector moves toward a positive electrode, you get an upright complex on the ECG in that lead.

When the heart’s mean electrical vector moves away from a positive electrode, you get a negative complex on the ECG in that lead.

When the heart’s mean electrical vector moves perpendicular to a positive electrode, you get a so-called equiphasic complex. It starts out positive (A) as the mean electrical vector approaches, but ends up negative (B) as the vector passes on by.

That is perhaps the most important theory of electrocardiography.

Now let’s go back to Einthoven’s (electrically) Equilateral Triangle. Imagine that the red arrow is the heart’s mean electrical vector. To help explain what happens next, I’m going to quote 12 Lead ECG – Art of Interpretation, by Tomas Garcia, MD and Neil Holtz, BS, NREMT-P. In my opinion, this is one of the best 12 lead ECG books you can buy (and no they don’t pay me to say that).

“In physics, two vectors (or in this case leads) are equal as long as they are parallel and of the same intensity and polarity. Therefore, we can move the leads [...] to a point passing through the center of the heart, and they will be the same.”

Since this is a critical point that is difficult to understand, I’m going to take this a step further. I interpret this to mean that lead I sees the mean electrical vector like the diagram to the left. In other words, it sees the heart’s mean electrical vector
relative to its own vector created by its negative and positive electrodes.

Likewise, leads II and III see the mean electrical vector relative to their own vectors.

Because this is true, we can take the three vectors (or sides) of Einthoven’s Triangle and make them intersect in the center.

We’ve just taken our most important theoretical step in the creation of the hexaxial reference system. If you can grasp this, it’s all downhill from here!

In Part III, we’ll introduce leads aVR, aVL, and aVF.

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**Part III**

In Part II, we discussed the heart’s mean electrical vector and how Einthoven’s Triangle (leads I, II, and III) can be redrawn to form the first 3 spokes of the hexaxial reference system. Essentially, we ended up with a shape like the one on the right.

When leads I, II, and III are drawn this way (as they often are) the arrows and Roman numerals are placed in the position of the positive electrodes.

(Perhaps this is why Einthoven reversed the polarity of lead II!)

Don’t worry, by the end of Part III, we’ll be done with all the theoretical stuff.

To complete the hexaxial reference system, we now need to discuss the augmented limb leads: aVR, aVL, and aVF.

aVR stands for augmented vector right, aVL stands for augmented vector left, and aVF stands for augmented vector foot. They are called the augmented limb leads because they are augmented (or amplified) through a modification of Wilson’s Central Terminal (WCT). The modification was necessary because otherwise the complexes would have been too small. A detailed explanation of Wilson’s Central Terminal will have to wait until we discuss the precordial leads.

In the meantime, just know that leads aVR, aVL, and aVF are derived from the same 3 electrodes as leads I, II, and III. They just examine different vectors by combining two electrodes together to form the negative pole of each lead.
For example, the negative for lead aVR is the combination of the black (left arm) and red (left leg) electrodes. The positive electrode for lead aVR is the white electrode (right arm). This has the effect of making the vector for lead aVR point toward the right shoulder.

For lead aVL, the negative is a combination of the white (right arm) and red (left leg) electrodes. The positive electrode for lead aVL is the black electrode (left arm). This has the effect of making the vector for lead aVL point toward the left shoulder.

The negative for lead aVF is a combination of the white (right shoulder) and black (left arm) electrodes. The positive for lead aVF is the red (left leg) electrode. This has the effect of making the vector for lead aVF point toward the left leg (or foot).

You will recall that in Part I we examined how Einthoven was able to refer to leads I, II, and III as Einthoven’s Equilateral Triangle even though anatomically speaking, leads I, II, and III form a scalene triangle on the human body.

For the exact same reasons, we can draw a mathematical representation of leads aVR, aVL, and aVF that looks symmetrical like the shape on the right.

We have just completed the final 3 spokes of the hexaxial reference system!

All we have to do is lay the diagram of leads aVR, aVL, and aVF on top of the diagram we created for leads I, II, and III. When you do, it will look like the diagram on the bottom.

This is the hexaxial reference system!
In Part IV, we’ll take a closer look at the hexaxial reference system and how it can be used to measure the heart’s electrical axis in the frontal plane.

**Part IV**

By now you should have a fairly good grasp of how the hexaxial reference system is derived from the first 6 leads of the 12 lead ECG.

Before we break down the finished diagram, let’s look at the hexaxial reference system laying on top of the patient’s anterior chest, with the arrows and leads in the position of the positive electrodes.

The first thing I would like you to notice is that lead I cuts the body in half horizontally and lead aVF cuts the body in half vertically.

The second thing I would like you to notice is that even though leads II, III, and aVF share the same positive electrode, they represent three separate vectors. This diagram should clearly demonstrate why we call them the “inferior” leads. It should also demonstrate why we call leads I and aVL the “high lateral” leads.

You will notice that leads III and aVL are on opposite sides of the hexaxial reference system. That’s why they are two of the most reciprocal leads on the 12 lead ECG. More on that later. Right now I’m just planting the seed.

You will notice that lead II cuts across the body in a “right shoulder-to-left leg” direction (white electrode to red electrode) which is the same direction as the heart’s normal axis. That’s probably why we were first taught to monitor lead II. It tends to show nice, upright P waves, QRS complexes, and T waves.

Now let’s look at the finished diagram.
If possible, click on the image above, and print it out for reference.

I’m going to do something a little bit unconventional here. Before I break down the various quadrants of the hexaxial reference system and discuss the normal ranges, we’re going to use it to calculate the heart’s QRS axis on an actual ECG.

After all, this is Part IV and we haven’t looked at a single 12 lead ECG!

For now, we’re only worried about the first 6 leads of the 12 lead ECG, because they are the leads that make up the frontal plane and the hexaxial reference system.

Do you remember the most important theory of ECG interpretation? If not, go back to Part II for a review. When the heart’s mean electrical vector (or QRS axis) moves toward a positive electrode, you get an upright complex in that lead. When it moves away from a positive electrode, you get a negative complex in that lead. When it moves perpendicular to a positive electrode, you get an equiphasic (and/or isoelectric) complex in that lead.

Now, let’s look at the first 6 leads in our sample. Can you spot the most equiphasic or isoelectric QRS complexes? If you said lead aVR, move to the head of the class!

We can deduce that this patient’s QRS axis (in the frontal plane) is moving perpendicular to the positive electrode in lead aVR. Now, look at your diagram of the hexaxial reference system and find lead aVR (-150 degrees to +30 degrees). We theorize that this patient’s QRS axis is moving perpendicular to lead aVR. So, which lead is perpendicular to lead aVR? Lead III!

Find lead III (-60 degrees to +120 degrees). The QRS axis is moving along the same vector as lead III. But is it moving toward -60 or toward +120? Go back to the sample ECG. Is the QRS complex positive or negative in lead III? It’s positive! You’ll also notice that lead III shows the tallest QRS complex in the frontal plane. Interesting!

Now look at the hexaxial reference system again. You’ll see little downward arrow in front of lead III at -60 degrees and a little upward arrow in front of lead III at +120 degrees. The positive electrode for lead III is at +120.

The QRS axis should be around 120 degrees.

Let’s take a look at our computer measurements and see how we did. Go to the top of the sample ECG and look for P-QRS-T Axis. To the right you will see three numbers. The middle number is the QRS axis in the frontal plane. What does it say? 121 degrees.
We’re only off by 1 degree, in a 360 degree circle! That’s pretty darned good. Does it always work out that perfect? No. But you can almost always get it within 10 or 15 degrees.

Now look at the previous diagram of the hexaxial reference system laying on top of the patient’s anterior chest and find the positive electrode for lead III. You’ll notice that the vector points downward toward the patient’s right leg. Guess what? This is a right axis deviation.

Now, you may be thinking, “This is way too much work!”

Yes and no.

This may be the first time you’ve ever used the hexaxial reference system, so of course it seems complicated, but it’s really not. In fact, I no longer require the diagram. Because I’ve done this so many times, some patterns have emerged that have simplified things for me dramatically.

In other words, there are some “tricks of the trade”.

In Part V, I’ll show you some startling relationships between the standard 12 lead ECG and the hexaxial reference system that may change the way you look at 12 lead ECGs forever!

**PART V**

In Part IV, I promised that I’d show you a fascinating relationship between the standard 12 lead ECG and the hexaxial reference system.

You will recall that to use the hexaxial reference system, you find the most equiphasic (or isoelectric) lead in the frontal plane (first 6 leads of the 12 lead ECG) and look for the perpendicular lead on the hexaxial reference system.

The example ECG we used was that of a 16 year old female with a congenital heart defect. The most equiphasic lead was lead aVR. We looked at the hexaxial reference system and noticed that the lead perpendicular to lead aVR was lead III. Since the ECG showed an upright QRS complex in lead III, we knew the frontal plane QRS axis was close to 120 degrees.

So what is the most difficult part of this seemingly cumbersome process? In my opinion, it’s squinting your eyes at the hexaxial reference system to figure out which lead is perpendicular to the equiphasic (or isoelectric) lead. Well, I have some good news! After performing this procedure dozens if not hundreds of times, I detected a very simple pattern.

To review, in Part IV we found out that lead III was perpendicular to lead aVR. Guess what? It works both ways. If lead III is perpendicular to lead aVR, then lead aVR is perpendicular to lead III. If you examine the hexaxial reference system, you will notice that leads I and aVF are perpendicular to each other. Likewise, leads II and aVL are perpendicular.

This diagram represents the layout of the first 6 leads of the 12 lead ECG in the standard format. You will notice that
when we draw a line between the perpendicular leads, they crisscross in the center.

If you commit this pattern to memory, there’s only one reason you’ll need the hexaxial reference system, and that’s to read the answer! In fact, once you get used to the numerical values that correspond to the various leads, you won’t even need that.

Let’s look at an example.

Which lead in the frontal plane shows the most equiphasic QRS complexes? Lead II. Which lead is perpendicular to lead II in the hexaxial reference system? The lead across from lead II (according to the cheat sheet diagram we just went over) is lead aVL. If you check the hexaxial reference system it will confirm that leads II and aVL are perpendicular to each other (electrically speaking).

Now look at the ECG. Is lead aVL positive or negative? It’s positive! Now look at the copy of the hexaxial reference system that you printed out in Part IV. Look for the aVL with the little “up” arrow in front of it. What is the numerical value? It’s -30 degrees! We estimate the QRS axis at -30 degrees.

Let’s check our work. Go to the top of this sample ECG and look for R-QRS-T Axes. The middle number will show you the QRS axis in the frontal plane. The computer measures it at -26 degrees. We’re only off by 4 degrees!

Is this making sense? If you attempt this on every 12 lead ECG, you will be amazed how simple it is. Not only that, patterns will emerge that will deepen your understanding of the 12 lead ECG.

My girlfriend is an emergency nurse in grad school to be a Clinical Nurse Specialist, and it annoys her to no end that I can glance at an ECG and predict the QRS axis in the frontal plane within 15 degrees.

To the uninitiated it seems like magic!

To re-enforce this lesson, click here. It’s one of the coolest ECG related things I’ve ever found on the Internet. Scroll down and click on Frontal Axis Demo. When it appears on your computer screen, click and drag the dial around the hexaxial reference system, and see what it does to the sample ECG on the screen. It’s quite fascinating! This is an incredible teaching aid and I only wish I’d thought of it!

In Part VI, we’ll go over the ranges for the QRS axis in the frontal plane.

**Part VI**

By now you can predict the QRS axis in the frontal plane within 15 degrees as long as you have an equiphasic (or isoelectric) lead in the frontal plane. So what constitutes a normal QRS axis? What is a left axis deviation? A right axis deviation?
If you don’t have a copy of the hexaxial reference system, go back to Part IV and print yourself out a copy.

As a review, lead I cuts the hexaxial reference system in half horizontally and lead aVF cuts the hexaxial reference system on half vertically. You can think of this as an x and y axis that divides the hexaxial reference system into quadrants. Hence, you can use leads I and aVF to place the heart’s electrical axis into one of the four quadrants. This is sometimes called the **Quadrant Method** for axis determination.

![Diagram of hexaxial reference system]

Remember that the **normal** QRS axis goes from a right shoulder-to-left leg direction in most patients. In other words, it tends to point down and to the left, or toward the **left inferior quadrant** of the hexaxial reference system, which ranges from **0 to +90 degrees**. When the QRS axis in the frontal plane is in the normal quadrant, you will have **positive QRS complexes in lead I** and **positive QRS complexes in lead aVF**.

![Diagram of left inferior quadrant]

When the QRS axis is **0 to -90 degrees**, we call it a **left axis deviation**. This is the **left superior quadrant** of the
hexaxial reference system. When the QRS axis is in the left superior quadrant, you will have positive QRS complexes in lead I and negative QRS complexes in lead aVF.

In reality, the QRS axis can be slightly into the left superior quadrant and still be considered normal.

When the axis is between 0 and -30 degrees, it is sometimes referred to as a physiological (as opposed to pathological) left axis deviation. With a physiological left axis deviation, lead II is usually equiphasic (remember that lead II is perpendicular to lead aVL and lead aVL points to -30 degrees on the hexaxial reference system). For a good example of this, see the ECG from Part V. Is this ECG normal? Absolutely not! But the axis is technically normal, even though it extends into the left superior quadrant at -26 degrees.

The most common causes of pathological left axis deviation are left anterior fascicular block or Q waves from inferior wall myocardial infarction. Some sources say that left ventricular hypertrophy pulls the axis to the left, and while this seems logical, in most cases patients with left ventricular hypertrophy have a normal QRS axis. Electrolyte derangements and ventricular rhythms may also present with a left axis deviation. Paced rhythms in particular should have a left axis deviation if the pacing lead is in the apex of the right ventricle.
If the QRS axis in the frontal plane is +90 to 180 degrees, it is a right axis deviation. This is the right inferior quadrant of the hexaxial reference system. With a right axis deviation, you will have negative QRS complexes in lead I and positive QRS complexes in lead aVF.

A right axis deviation is usually abnormal. It might indicate pulmonary disease, right ventricular hypertrophy, Q waves from lateral wall myocardial infarction, left posterior fascicular block, electrolyte derangement, or tricyclic antidepressant overdose, or a ventricular rhythm.

If the QRS axis is -90 to 180 degrees, something is very wrong (possibly your lead placement). This is the right superior quadrant of the hexaxial reference system, but in various publications it can be called an extreme right axis deviation, an indeterminate axis, or a right shoulder axis. It’s bad because it means the heart is depolarizing in the wrong direction. With an extreme right axis deviation, you will have negative QRS complexes in lead I and negative QRS complexes in lead aVF.
Finally, here’s a cheat sheet you can fall back on if all else fails. This one relies only on leads I, II, and III (although you can substitute lead aVF for lead III). This method works pretty good because, as we saw earlier, by looking for an equiphase QRS complex in lead II we can distinguish between physiological and pathological left axis deviation.

Remember, QRS complexes in lead III are allowed to be negative. However, negative QRS complexes in lead I or lead II are abnormal.

Do I expect you to remember all this right now? No, I do not. Experience is the best teacher, and there’s nothing like holding an ECG in your hand and associating it with a particular patient. My goal is simple. I want you to start seeing it.

When you capture a 12 lead ECG with good data quality, in most cases you’ll get a computerized interpretive statement at the top. You’ll also get the computer measurements of the heart rate, PR interval, QRS duration, QT/QTc interval, and P-QRS-T axes. When you see that the QRS axis is -66 degrees and the interpretive statement says “Left axis deviation” I want you to take a good look at the ECG. Do you notice that the QRS complexes are positive in lead I and negative in leads II, III, and aVF?

A deeper understanding of axis determination helps you really see the 12 lead ECG, not just lead II, and it ultimately helps you consider various possibilities that you hadn’t considered before.