It is easy to underestimate the importance of learning the skills of precise EEG localization compared with the bigger picture of EEG interpretation. On the face of it, the purpose of localization is to identify the location in the brain at which a recorded EEG event has occurred. Indeed, if this were the only benefit of learning accurate localization, it would still be a key skill in EEG interpretation. However, as we shall see in this chapter and elsewhere in this text, localization can help answer not only where an EEG event has occurred but also what an EEG event is. Understanding the topography and polarity of a discharge is the first step in deciding whether an EEG event is truly of cerebral origin or is instead an electrical artifact. Consider for a moment the potential negative impact on patient care of reporting an electrical artifact as an abnormal cerebral discharge. As we shall see, the shape or distribution of certain EEG discharges may not be consistent with cerebral activity because the localization does not make either topographical or biological sense. The skill of accurate EEG localization includes the skill of determine whether the shape or distribution of a discharge is or is not consistent with an event that originates from the brain. In addition, certain discharge topographies can suggest a specific type of discharge and the clinical syndrome to which the discharge might belong; in certain cases, the location of the discharge can reveal what it is.

Complete localization of an event includes pinning down both the event’s location and its polarity. For instance, an accurate localization would include not only the fact that an event occurs in the left anterior temporal electrode but also whether it is negative or positive at the scalp surface. Almost all types of EEG events can be localized, whether they be spikes, sharp waves, slow waves, or even voltage asymmetries. In the following discussion, the examples used are spike-like discharges, although the principles discussed here apply equally well to almost all types of EEG events (e.g., sharp waves, slow waves, etc.).

FOCAL EVENTS, ELECTRIC FIELDS, AND GENERALIZED EVENTS

Focal Events

A focal EEG event is one that occurs on a limited part of the brain surface rather than over the whole brain surface. Occasionally, an event may be so focal that it occurs in only one electrode. The large majority of discharges will also be detectable, though perhaps more weakly, in adjacent electrodes. The electrode position that picks up the highest voltage, be it positive or negative, is referred to as the discharge’s maximum. Although the discharge may be best seen at the maximum, adjacent electrodes often pick up varying amounts of the discharge. The hypothetical discharge shown in Figure 4-1 shows a discharge maximum in the right parietal electrode (P4) with a field that includes the right posterior temporal electrode (T6) and, to a lesser extent, the right occipital electrode (O2). A focal discharge having a broader field, such as the one shown in Figure 4-2, can have a maximum at one electrode (C4 in this example) but involve a substantial part of one hemisphere.

Rarely, an EEG event may occur so focally that its activity is only recorded in a single electrode, such as the example of the highly focal right parietal discharge shown in Figure 4-3. According to the schematic, the discharge would only be detected by the single electrode (P4), and adjacent electrodes would be electrically quiet. In practice, such highly focal discharges are uncommon and represent the exception rather than the rule (although this phenomenon of highly focal discharges is more commonly seen in newborns). The first two examples given above in which a discharge is detected by a group of electrodes is the more commonly encountered situation. The pattern of how strongly the discharge is picked up in various electrodes helps define the shape of the discharge’s electric field as discussed next.
Practical Approach to Electroencephalography

Figure 4-1  This focal discharge is clearly maximum in P4, but the electric field of the discharge extends to include T4 and O2. Rather than seeing a discharge occur at a single electrode position, this is the more common situation in which the maximum of a focal discharge is picked up in one location (P4 in this example) but the discharge can be detected to a lesser extent in adjacent electrodes (T6 and O2). In this case, the discharge can be said to be maximum in P4 with a field that extends to T6 and O2.

Figure 4-2  In the case of a lateralized discharge, the field of the discharge involves either a whole or nearly whole hemisphere. In this example, the discharge can be said to be lateralized to the right hemisphere.

Electric Fields

Several analogies have been used to describe the shape of the electric field of a typical discharge on the scalp surface and how its intensity drops off with distance from the maximum. The analogy of a pebble dropped into a quiet pool of water can be used to describe the way a simple field’s strength dissipates as it becomes more distant from the point of highest intensity (where the pebble hit the water). The wave that is formed is strongest at the point of impact but diminishes with increasing distance from the central maximum. This example is useful because many electric fields measured on the scalp do show this radially symmetric shape but, in practice, many electric fields dissipate with varying shapes.

Rather than showing a smooth and steady decrease in voltage in every direction from the central maximum point, it is possible for fields to dissipate gently in one direction and abruptly in another. A better analogy for the shape of electric fields is the visualization of mountain peaks. Mountain peaks give a more realistic picture of EEG fields because they need not be so perfectly symmetrical in shape as the circular waves caused by a pebble hitting water. Imagining the terrain around a 5,000-foot mountain peak, we might expect that the height of land surrounding the peak will fall off with varying steepness in each direction. Likewise, electric fields may manifest a steeper slope of voltage decrease in one direction and a more gentle slope in another direction. An abrupt and immediate falloff in voltage from a central point in all directions as shown...
in Figure 4-4 would correspond to a thin needle of land 5,000 feet high with nothing surrounding it, an uncommon finding both in geography and in electroencephalography but akin to the discharge in Figure 4-3.

The mountain peak analogy reminds us that an electric field can be visualized as a surface in three dimensions. Just as slope refers to the steepness of a curve imagined in two dimensions at a given point, the steepness of a surface imagined in three dimensions at a given point is referred to as the gradient at that point. (The slope of a curve at a given point is the slope of a line tangent to that curve at a given point. Similarly, the gradient of a surface at a given point is defined by the slope of an imaginary plane tangent to the surface at that given point.) The rate at which the terrain that surrounds the summit of a mountain falls off is the steepness of the terrain. The rate at which an electric field changes intensity at a particular point on a surface is called the electrical gradient; the two properties are analogous. The exercise of visualizing the shapes of electric fields is similar to visualizing the contours and steepness of a region of mountain terrain. Just as we would never confuse the area of maximum altitude of a mountain with the point of maximum steepness of a mountain (which may or may not be at the same point), so we will take care not to confuse the point of maximum voltage of an EEG event with the point of the maximum gradient of the field surrounding the maximum.

The illustration in Figure 4-4 depicts a highly focal discharge, similar to that shown in Figure 4-3. The plane of the rectangular grid is a representation of the voltages measured on the scalp surface. In this figure, areas close to the discharge’s peak are not involved, and relatively nearby electrodes would not “perceive” any change in voltage. Such highly restricted or “punched-out” discharges are relatively uncommon (just as 5,000-foot mountains in the shape of a needle are uncommon). The field shown in Figure 4-5 is somewhat more realistic, with a peak or maximum in the same position, but a more gradual falloff in voltage as distance increases from the maximum point. In this example, adjacent electrodes would pick up increasingly weaker voltages with increasing distance from the point of maximum. Figure 4-6 shows a discharge with a broad field, and, although the middle electrode would pick up the highest voltage, the adjacent electrodes would detect a voltage intensity of more than half that detected by the middle electrode. Figure 4-7 reminds us that, quite often, the electric field can slope off asymmetrically from its peak.

Generalized Events

In contrast to the focal events described earlier, some events occur in all brain areas at once and are said to occur in a generalized distribution. Figure 4-8 depicts a discharge with a perfectly even electric field. With cerebral discharges, even in the case of generalized discharges, there is almost always some unevenness to the field, and an area of maximum intensity can still be identified. In Figure 4-9, the discharge affects all brain areas and is, therefore, generalized, but the intensity is highest in the F3, Fz, and F4 electrodes.

The purpose of this chapter is to help the reader become adept at translating the patterns of pen deflections recorded on the EEG page into the particular localizations, polarities, and the shapes of the gradients that those patterns imply. In short, we examine the patterns that EEG pens will draw when they encounter
Any wave seen on the EEG is, therefore, a comparison of the electrical potential at two locations rather than an absolute measurement made at a single location. The waves that we are analyzing are, indeed, the outputs of constantly fluctuating voltmeters comparing two inputs (see Figure 4-10).

Inherent to the concept of the voltmeter is the idea of subtraction. If one probe of a voltmeter contacts a point at 105 mV and the second probe contacts a point that is at 100 mV, the voltmeter will read out 5 mV. Likewise, if the pair of points recorded is 2112 and 2117 or even 3 and 2, the voltmeter will read out the same result: the difference of 5 mV. The result of 5 mV that the voltmeter yields gives no clue as to which of these pairings generated it: 105 and 100, 2112 and 2117, or 3 and 2. The fact that an EEG channel only shows us the difference between two points rather than absolute values has both advantages and limitations. Because each wave displayed on the EEG is a continuous voltmeter output, the reader should always have in mind the following question: which two points are contributing to this channel's appearance?

The reader may be wondering which would be more logical, for the pen to go up or for the pen to go down, in the example in the preceding paragraph in which the difference is positive 5 μV. The answer to this question cannot be derived using mathematical or physical principles. Rather, it is an arbitrary convention that was decided by EEG machine manufacturers in the early days of EEG. The answer for the earlier example is that the pen goes down. The convention assumes that there are two input terminals to the amplifier, Grid 1 and Grid 2, which can also be called Input 1 and Input 2. The convention is: “First input more negative: pen goes down. First input more positive: pen goes up.” Some

EEG WAVES AND EEG POLARITY

Pen Up or Pen Down?

An understanding of what causes the EEG instrument’s pen to go up or down is the foundation concept of EEG localization and is one of the central skills to master in this chapter. Luckily, the convention is easy to understand. The challenge is to remember to apply it consistently when analyzing EEG patterns.

EEG Channels Are Fancy Voltmeters

A voltmeter measures the potential difference or “voltage drop” between two points. Because voltages are always differences, whenever a voltage measurement is made, the reader should be aware which two identifiable points are being compared. Even when it appears that the voltage at a single point is being described, it is implicit that the point is being compared with some standard (perhaps a ground or other “neutral” point). Likewise, even though there may be a temptation to think of the output of an EEG channel as representing the activity at some single point on the scalp, every channel deflection we see on the EEG is, in reality, a comparison of two different points on the body (or occasionally a combination of more than two points, as we shall see in later chapters).

Any wave seen on the EEG is, therefore, a comparison of the electrical potential at two locations rather than an absolute measurement made at a single location. The waves that we are analyzing are, indeed, the outputs of constantly fluctuating voltmeters comparing two inputs (see Figure 4-10).

Inherent to the concept of the voltmeter is the idea of subtraction. If one probe of a voltmeter contacts a point at 105 μV and the second probe contacts a point that is at 100 μV, the voltmeter will read out 5 μV. Likewise, if the pair of points recorded is −112 and −117 or even 3 and −2, the voltmeter will read out the same result: the difference of 5 μV. The result of 5 μV that the voltmeter yields gives no clue as to which of these pairings generated it: 105 and 100, −112 and −117, or 3 and −2. The fact that an EEG channel only shows us the difference between two points rather than absolute values has both advantages and limitations. Because each wave displayed on the EEG is a continuous voltmeter output, the reader should always have in mind the following question: which two points are contributing to this channel’s appearance?

The reader may be wondering which would be more logical, for the pen to go up or for the pen to go down, in the example in the preceding paragraph in which the difference is positive 5 μV. The answer to this question cannot be derived using mathematical or physical principles. Rather, it is an arbitrary convention that was decided by EEG machine manufacturers in the early days of EEG. The answer for the earlier example is that the pen goes down. The convention assumes that there are two input terminals to the amplifier, Grid 1 and Grid 2, which can also be called Input 1 and Input 2. The convention is: “First input more negative: pen goes down. First input more positive: pen goes up.” Some
convention is here to stay and can take some getting used to. It may be helpful to use the counterintuitive nature of the convention to help remember it.

Here is how the convention works in more detail: as noted, every EEG amplifier has two principle inputs, which we will refer to as INPUT 1 and INPUT 2. The EEG technologist decides which electrodes are plugged into INPUT 1 and INPUT 2 for any given channel according to which EEG montage is chosen. The situation of INPUT 1 being more negative than INPUT 2 can be stated in a number of ways, such as: “the difference between INPUT 1 and INPUT 2 is negative” or as the mathematical expression: “INPUT 1 - INPUT 2 < 0.” In such cases the amplifier’s pen deflects upward. Of course, the opposite holds true for the reverse situation: when INPUT 1 is more positive than INPUT 2, the pen deflects downward as in the example above (see Figure 4-11).

When INPUT 1 is more positive than INPUT 2, the pen goes down. When INPUT 1 is more negative than INPUT 2, the pen goes up.

Of all the ways to state this rule, the subtraction expression “if INPUT 1 - INPUT 2 > 0 . . . ” is most correct because it deals with all the possible combinations of each of the two inputs being positive, negative, or zero. One could quibble with the idea of saying that -3 is “more positive” than -5 because neither is positive. In this text, we use this simpler shorthand, stating that one electrode is “more positive” or “more negative” than another without regard to the sign of the electrodes' absolute voltages for simplicity's sake. Figure 4-12 shows another representation of this convention.

**EEG Amplifiers**

To understand the meaning of pen deflections, it is useful to consider the nature of the amplifiers used in the electroencephalograph. Perhaps the simplest conceivable amplifier design would be the single-end input amplifier. This type of amplifier would take a single signal as its input and furnish an amplified version of that signal as its output (see Figures 4-13 and 4-14). This is not, however, the type of amplifier used in EEG machines, and for good reason. A single-end amplifier is essentially using the building’s electrical ground as
the comparison input; however, such grounds are usually much too electrically contaminated or “dirty” to be useful for this purpose.

Actual EEG amplifiers, like the voltmeters described earlier, use two inputs (see Figure 4-15). The signal from INPUT 2 is subtracted from the INPUT 1 signal; the result is then amplified and serves as the output. This type of amplifier is also called a common mode rejection (CMR) amplifier. As we shall see, the strategy of subtracting one input signal from the other has several important advantages. Figure 4-16 shows how a CMR amplifier behaves with two sample electrical inputs. Note that the component of each signal that is common to both inputs is cancelled out, or “rejected.” Only the difference between the two signals appears in the output. Why is elimination of the part of the signal that is common to both electrodes an advantage? This technique of amplification is especially useful in the field of electroencephalography in which the signals of interest—brain waves—are of very low voltage compared with the ambient electrical noise from external sources that runs through the patient’s body. Because the pattern of this external noise signal tends to be similar in the various scalp electrodes, CMR amplifiers cancel out much or all of the external noise component of the signal, ideally leaving only the cerebral component for interpretation.

Event Localization Using a Bipolar Montage

The examples that follow consider a theoretical spike discharge on the scalp and how it would appear on the EEG record. The first example we examine is a hypothetical spike in the left central region of the brain (the area under the C3 electrode). A spike is, by definition, a quick event, and in this example, it will have a negative polarity (the scalp region where the spike
occurs will be momentarily negative compared with the surrounding scalp, which, for the purposes of this example, is neutral. The electrode set we use to record the spike is a single chain of standard electrodes that goes along the scalp from front to back just to the left of the midline: Fp1, F3, C3, P3, and O1 (the left fronto-polar, superior frontal, central, parietal, and occipital electrodes, respectively). The technique used for the following examples is the typical strategy of creating a bipolar chain with these electrodes by looking at a succession of pairings of adjacent electrodes from front to back: Fp1 to F3, F3 to C3, C3 to P3, and P3 to O1. The term bipolar is used because each EEG channel generated represents a comparison of two cerebral locations. Each of the two electrode locations can be said to be “of interest” because both reflect brain activity, and it is possible that a clinically important event could arise from under any of the five electrodes. (In the contrasting situation of referential montages described in more detail later, INPUT 1 is connected to an electrode over the brain, and INPUT 2 is connected to some other reference point that is presumably not “of interest” but is used for the purpose of subtracting noise.) Note that there are five electrodes in this chain but there are necessarily only four consecutive pairings. Thus, a chain of five consecutive electrodes will produce four channels of EEG in a bipolar chain.

“Negative Phase Reversal”

Figure 4-17 depicts the field of a 50-μV spike occurring at C3 with no activity at all in the surrounding electrodes. On the right, the four channels representing the output of the bipolar chain are depicted. It is worthwhile to go through each line of the output to understand exactly why voltage measurement shown on the left side of the figure is associated with the EEG trace on the right side of the figure.

The first channel, Fp1-F3, is measuring the difference between 0 μV at Fp1 and 0 μV at F3. Because there is no difference, the Fp1-F3 channel remains flat.

The second channel, F3-C3, is comparing 0 μV in INPUT 1 (F3) and −50 μV in INPUT 2 (C3). Because the convention is that if the first electrode is “more positive” than the second, the pen goes down, a downward pen deflection is produced.

Figure 4-17 A negative phase reversal showing a focal negatively charged spike occurring only in the C3 electrode—none of the negativity of the spike is picked up in adjacent electrodes. The numerical voltages that each electrode detects are shown. The dark shading denotes the region of the scalp that becomes negatively charged during the spike. The resultant EEG trace seen in a bipolar chain (Fp1-F3, F3-C3, C3-P3, and P3-O1) is shown to the right and the reasons for each specific pen deflection are described in the text.
The third channel, C3-P3, compares $-50 \mu V$ in INPUT 1 to $0 \mu V$ in INPUT 2. Now Electrode 1 is more negative than Electrode 2 (the opposite of what occurred in the second channel), so the convention tells us that the pen goes up.

Finally, in the fourth channel, there is no voltage difference measured between P3 and O1 (both $0 \mu V$), so the channel remains flat.

The resulting trace shows one of the classic patterns of EEG waves, the phase reversal, which is expanded on below. For the time being, note that, in this example, where the pen deflection reversed direction, or phase (in this case from down in the second channel to up in the third channel), the electrode in common to the channels where the phase reversed from down to up (C3 since the phase reversed between F3-C3 and C3-P3), points to the location of the discharge’s maximum.

As discussed earlier, focal EEG events on the brain surface rarely occur solely in an isolated pinpoint area of the scalp as in the example in Figure 4-17. Instead, there is typically a point of voltage maximum around which lower voltages can be detected. The example shown in Figure 4-18 is more similar to real-world events. Although the C3 electrode is the point of maximum intensity of this event, the adjacent areas measured by F3 and P3 are also affected, but not as strongly. This gradual drop-off in intensity of voltage shows that the event has a somewhat broader field, even though we are still dealing with a $-50 \mu V$ spike in C3. A good description of this spike would be that the spike has a maximum negativity at C3 but a field that also includes F3 and P3.

Now let’s return to Figure 4-18, which shows a more realistic gradient around a spike focus at C3. The resulting EEG trace is similar to the one we saw earlier but with some notable differences:

The first channel, Fp1-F3, is measuring the difference between 0 and $-30 \mu V$. Because Electrode 1 is “more positive” than Electrode 2, the pen deflects downward an amount corresponding to the difference of 30 $\mu V$.

The second channel, F3-C3, compares $-30 \mu V$ in Electrode 1 (F3) and $-50 \mu V$ in Electrode 2 (C3). Because the first electrode is again “more positive” than the second, a downward pen deflection is produced in this channel as well, corresponding to the smaller difference of 20 $\mu V$.

The third channel, C3-P3, compares $-50 \mu V$ in Electrode 1 to $-30 \mu V$ in Electrode 2. For the first time, Electrode 1 is more negative than Electrode 2 (the opposite of the case in the second channel), so the convention tells us that the pen now goes up.

Finally, in the fourth channel, Electrode 1 measures $-30 \mu V$, and Electrode 2 measures $0 \mu V$. The pen again deflects upward, corresponding to the fact that Electrode 1 is more negative than Electrode 2 by a 30-$\mu V$ difference.

Comparing the pattern of EEG waves in Figure 4-18 to the previous figure, we see that there are now deflections in all four channels. This reflects the fact that the field of this spike involves both adjacent electrodes, F3 and P3, and that the gradient of the field stretches out more broadly than in the first example. Stated another way, there is now an electrical gradient (difference) between all four channel pairs. The fact that there is a deflection in each channel reflects the fact that no two adjacent electrodes measure the exact same voltage and that there was an increase or decrease in voltage in every comparison. Because in channels 1 and 2 the pen goes down and in channels 3 and 4 the pen goes up, we say there is a phase reversal occurring between channels 2 and 3. A phase reversal is the point along a bipolar electrode chain at which the direction of the pen deflection changes (from down to up or from up to down). Because in this example C3 is the electrode common to channels 2 and 3, the two channels between which the phase “reversed,” this is the point of maximum of the discharge.

![Figure 4-18](image-url)
A second interesting observation can be made about this recording. Even though the biggest pen deflections can be seen in channels 1 and 4, the true maximum of the discharge lies between channels 2 and 3. This apparently paradoxical result occurs because, in this example, the electrical gradient was steeper at some distance from the maximum (nearer the forehead and occiput), similar to the example of a mountain peak in which the terrain could be steeper around the base of the mountain and less steep as it reaches its peak. Still, the “peak” is at C3, even though the deflections in Fp1-F3 and P3-O1 are larger. Clearly, in bipolar montages the maximum of a discharge cannot be located simply by finding the biggest waves—a pitfall to be avoided. This is because the measuring stick used to determine wave heights in bipolar montage tracings is the differences between pairs of points rather than the absolute value of the voltage at any given point. In bipolar montages, rather than using wave heights, the maximum is located by finding the phase reversal.

Each EEG channel in a bipolar chain passing from front to back along the head is, in reality, answering the question in its march along the brain: “is the next electrode getting more negative or more positive?” The following analogy illustrates this effect another way: a farmer has a large field and would like to build his house at the highest point in the field to have the best view of his farm from his house. The farmer does not have a standard instrument to measure height (an altimeter), and he does not trust himself to find the highest point using standard visual inspection. Rather, the only tool he can use to locate the highest point in the field is a crude instrument that only reports the difference in height of his current position compared with his last position as he takes steps across the field. It can inform him that the field has gotten higher compared with his last location (in which case its pen goes down) or that the field has gotten lower compared with his last location (in which case its pen goes up). He takes readings every time he walks 10 feet forward. Even without having the benefit of an altimeter that could report absolute numerical altitudes, as he walks forward through his field, it is easy to imagine a strategy he can use to locate the highest point along any track he walks.

Imagine that the farmer turns on the instrument (which senses its starting position) and then walks forward the first 10 feet. The instrument, comparing the starting position to his present position, reports “it’s getting higher” (the pen goes down). After the next 10 feet, it reports that it is getting higher again (the pen goes down again). After the next 10 feet, it reports “it’s getting lower” (the pen now goes up). This is the point of the “phase reversal” when the pen direction has changed. The farmer does not know the absolute altitude at the previous point, but he does know that the area between the points at which his instrument’s pen flipped from down to up must mark the highest point on the track he has walked so far. After the pen readings shift from downward to upward, he knows he has located a height maximum along the line he is exploring. This is the equivalent of a phase reversal in a bipolar chain on the EEG. Before making a final decision, he will probably want to get to the end of the field to make sure that he found the highest point on the whole path. If he wanted to make a topographic map of the whole field, he could perform the same top to bottom walk along the field in several parallel lines. To be even more complete, he might repeat the measurements walking on parallel tracks from right to left (at right angles to the original paths). Using this strategy and recording the amount his pen deflects on every measurement, he would eventually be able to draw a relative topographic map of the whole field, something like the grid shown in Figure 4-19.

In these examples, greater altitude in the farmer’s field is analogous to EEG voltage becoming more negative. The EEG reader can imagine “walking down” or scanning a bipolar chain along the scalp such as from Fp1 all the way to O1 and, like the farmer, feel as the pens go down that “it’s getting more negative” and then as the pens finally reverse direction that “it’s getting more positive.” When the pens switch direction, this implies that the point of maximum negativity was passed, identifying the position of the maximum voltage of the spike. Figure 4-19 shows the deflections that the farmer’s instrument might generate while walking along a single path, or likewise what an EEG machine might detect when exploring the parasagittal chain when there is a spike maximum at C3.

This example of measuring the altitude in a field with a device that only reports the change in altitude compared with the previous point is directly analogous to the process of examining successive electrodes (each channel representing a pairing of electrodes in an electric field) in a bipolar chain. Although the example assumes a field with a particular surface and predicted which type of pen deflections that surface would generate when explored with a chain of electrodes, practical EEG interpretation involves the reverse process: examining the channel outputs and ascertaining the shape of the underlying field.

Figure 4-19 The figure shows an imaginary “walk” down a bipolar chain extending from the frontopolar area (Fp1) to the occipital area (O1). (Note that the y-axis shows degree of negativity so that more negative voltages cause the curve to go up.) There is a maximum negativity at the C3 electrode. As the curve goes up, the successive measurements (Fp1 to F3, F3 to C3) show progressively increasing negativity causing downward pen deflections. After the comparisons pass over the “voltage hump” of the C3 electrode (C3 to P3 and P3 to O1), the first electrode in the comparison pair is now more negative than the second electrode, and the pen points up. When the maximum point (C3) is passed, the pen direction reverses phase (from down to up), and this phase reversal marks the maximum. (The pen deflections shown above the graph are similar to the readings that could have been obtained by the farmer in the farmer-in-the-field analogy described in the text.)
The “Positive Phase Reversal”

Next, consider the situation of a positive spike occurring on the scalp, again at C3, as shown in Figures 4-20 and 4-21:

The first channel, Fp1-F3, reflects the difference between 0 and 20 μV. Because Electrode 1 is “more negative” than Electrode 2, the pen deflects upward an amount corresponding to 20 μV.

The second channel, F3-C3, compares 20 μV in Electrode 1 (F3) and 50 μV in Electrode 2 (C3). Because the first electrode is again “more negative” than the second, another upward pen deflection is produced, this time corresponding to the difference of 30 μV.

The third channel, C3-P3, compares 50 μV in Electrode 1 to 20 μV in Electrode 2. Now Electrode 1 is more positive than Electrode 2 (the opposite of the case in the second channel), so the convention tells us that the pen goes down.

Finally, in the fourth channel, Electrode 1 measures 20 μV and Electrode 2 measures 0 μV. The pen again deflects downward, corresponding to the fact that Electrode 1 is more negative than Electrode 2 by 20 μV.

In contrast to the type of phase reversal illustrated in Figure 4-18, Figure 4-20 shows an example of a second type of phase reversal, the positive phase reversal. This type differs from the first in that the first represented a transition of pens going down to pens going up (as the eye proceeds down the page or pen deflections facing toward one another). In this second type of phase reversal, there is a transition of pens going up to pens going down, or pen deflections facing away from one another. The phase reversal with the pens-down-to-pens-up transition marks an area of maximum negativity, and the second type of phase reversal with the pens-up-to-pens-down transition marks an area of maximum positivity. As shorthand, the first type of phase reversal with the pens pointing toward each other can be called a negative phase reversal, and the second type with the pens pointing away from each other a positive phase reversal (see Figure 4-22). Working through these examples step by step as we did earlier, it becomes clear that in a bipolar montage:

When the phase-reversing waves point toward each other, the point of maximum intensity is negative. When the phase-reversing waves point away from each other, the point of maximum intensity is positive.

This generalization always holds true because of the basic convention of direction of pen deflection and polarity. In the case of the negative phase reversal, the transition from pens going down to pens going up is the same as passing from “getting more negative” to “getting more positive comparisons.” The opposite story holds true for the positive phase reversal with deflections that face away from each other. As you look downward through a chain with upgoing waves, the upgoing pens imply that the field is getting progressively more positive. After the waves flip to downward, the opposite is true: the field is now becoming progressively more negative, implying that a peak positivity has been passed.

Although it is possible to derive the fact that phase reversing waves that point toward each other represent negativities and phase reversing waves that point away from each other represent positivities from the basic convention of “negative-up,” this simple pair of facts (as depicted in Figure 4-22) is worth memorizing to speed the process of EEG interpretation once you have convinced yourself that it always holds true.

The “Isoelectric” Phase Reversal

So far, we have examined examples of a discharge’s maximum intensity when that maximum occurs at the very point at which an electrode has been placed.
Sometimes, however, a voltage maximum may occur between two electrode positions, and it is worthwhile to consider how this can change the appearance of a phase reversal. Figure 4-23 shows just such an example. The maximum negativity of $-50$ occurs between the F3 and C3 electrodes. At the F3 and C3 electrodes, voltages of $-40$ are measured. In the resulting bipolar recording, the expected negative phase reversal is seen, this time between the first and third channels, with the spikes pointing toward each other in the case of a negativity, as expected. This time, however, because F3 and C3 have the same voltage, the second, intervening channel is flat. This occurs because F3 and C3 are isoelectric to one another (they have the same voltage), and because a comparison of electrodes measuring the same voltage would generate no pen deflection, it is no surprise that this intervening channel is flat. This example illustrates the general concept that a phase reversal is still “valid” even with an intervening flat channel.

In such examples of a phase reversal with an intervening isoelectric (flat) channel, it is tempting to conclude that the maximum always lies in between the two electrodes of the isoelectric channel, as depicted in Figure 4-24. Although this is often the case, other field topographies are possible. For instance, given these pen deflections, it could be that $-40 \mu V$ is, indeed, the maximum and is shared by F3 and C3—the field may be “flat” between these two points as shown in Figure 4-25. In the case of this isoelectric type of phase reversal, as long as the two electrodes in question are fairly close to one another (such as F3 and C3), we generally assume that the true maximum is somewhere between F3 and C3, inclusive. In reality, we cannot know the true contour of the field between F3 and C3 based on the tracing at hand; if it were necessary to know more, we would have to place additional intervening electrodes. An example of an isoelectric phase reversal recorded from the brain in an actual EEG is shown in Figure 4-26.

**Event Localization Using a Referential Montage**

Referential montages compare an electrode placed over a brain area “of interest” to a reference point elsewhere on the head or body. The “electrode of interest” is almost always over a brain region and may also be referred to as the active electrode. The reference electrode, attached to INPUT 2 of the amplifier, is located at some other point (or points) on the body, sometimes near the brain but often at a distance from the brain. Examples of points chosen for the reference electrode include the earlobes, the skin over the mastoid processes (behind the ears), the nose, the chin, the Cz electrode, and the base of the neck. Another strategy for creating a reference electrode is to use the average of some or all of the brain or other electrodes as a virtual reference electrode. The comparative advantages and disadvantages of different reference electrode strategies is discussed in detail in the chapter on montages.

The active electrode is customarily attached to INPUT 1 of the amplifier, and the reference electrode is attached to INPUT 2. The strategy of this type of montage, in the best of all possible worlds, is to find an electrode pair in which INPUT 1 contains the brain activity of interest (plus, perhaps, some unavoidable amount of contaminating electrical noise), and INPUT 2 contains only the electrical noise that is contaminating INPUT 1 but none of its brain activity. With this type of pairing, the result of subtracting INPUT 2 from INPUT 1 is a cancellation of the electrical noise, leaving a pure trace...
Figure 4-23  An isoelectric phase reversal is shown. In this example, the point of the measured maximum negativity of $-40 \ \mu V$ is shared by the F3 and C3 electrodes. This diagram implies that the true maximum negativity of $-50 \ \mu V$ lies between the F3 and C3 electrodes and is not directly measured since there is no electrode between F3 and C3. The resulting trace on the right side of the figure shows an example of an “isolectric phase reversal.” Here, the location of the maximum is actually marked by a flat line in the second channel (F3-C3) because those two electrodes are measuring the same voltage ($-40 \ \mu V$) and are said to be isoelectric. The nature of the phase reversal can be appreciated by the phase change between the first and the third channels.

Figure 4-24  Two of the many possible shapes of a voltage gradient that could account for the type of isoelectric phase reversal shown on the right side of Figure 4-23. Panel A shows a gradient in which the true voltage maximum is actually located in between the isoelectric electrodes (F3 and C3). Panel B shows another possibility: that there is a plateau of maximum voltage between the two electrodes. If it were necessary to distinguish between these and other possibilities, additional electrodes would have to be placed between F3 and C3.

of the brain activity picked up by the active electrode that is attached to INPUT 1. This is an example of the ideal active electrode–reference electrode pair that is strived for in a good-quality referential recording. For the purposes of the idealized examples in this chapter, we assume ideal, noise-free active and reference electrodes that yield electrically noise-free recordings.

In some ways, the setup of referential montages makes them easier to interpret. Despite their many advantages, however, referential montages are often not the easiest montages to read. It is useful to compare the relative advantages and disadvantages of the referential technique to its cousin bipolar technique as we discuss them.

We now reconsider some of the same examples used earlier, starting with the simplest case of the highly focal negative spike in C3. Figure 4-27 shows the result of comparing each electrode in the parasagittal chain to a reference: Fp1-ref, F3-ref, C3-ref, P3-ref, and O1-ref. In these examples, the “ref” electrode is a hypothetical neutral reference electrode with a voltage of zero. Because in this example the spike’s field does not extend to the adjacent electrodes, there is no voltage difference between those electrodes surrounding C3 (Fp1, F3, P3, and O1) and the reference. C3, in contrast, is more negative than the reference, causing the pen to deflect upward (first electrode more negative—pen up!). This results in an EEG with four flat lines representing the four surrounding neutral electrodes and one visible spike generated by the C3-ref channel. There is a convenient simplicity to the result displayed in a referential montage: the pen only moves in a
channel that corresponds to an electrically active electrode. This is different from the same example we saw in the bipolar chain illustrated in Figure 4-17 in which a single electrode’s activity caused the pens to move in two channels.

Next we examine a $-50\mu$V spike in C3, the field of which spreads to the adjacent electrodes, F3 and P3. Figure 4-28 shows the output of a referential montage for a spike with the same field as was illustrated in Figure 4-18 in a bipolar montage. Once again, the output seems relatively simple, with a $-50\mu$V deflection seen in the C3-ref channel and lower amplitude deflections seen in the flanking channels, F3-ref and P3-ref, reflecting the fact that the spike’s field also involves those electrodes, although to a lesser extent. All of the deflections are upgoing because all of the active electrodes are relatively negative when compared with the neutral reference. The height of the deflection is proportional to the strength of the field in microvolts at each point.
Finally, we look at the example of a 50-μV “positive spike” in C3 with a field that includes F3 and P3. Figure 4-29 shows the EEG corresponding to such a spike using a referential montage. The main difference between this example and the previous one is that the pens go down, because the active electrodes are now more positive than the neutral reference electrode. Again, the relative heights of the spike in each channel correspond to the relative voltages at each electrode in the example. In a referential montage, knowing the height of a wave in millimeters and the sensitivity setting of the amplifier makes measurement of a wave’s absolute voltage a matter of simple multiplication (see Figure 4-30).

Comparison of the Bipolar and Referential Recording Techniques

According to the descriptions given earlier, the technique of the referential montage has multiple advantages over the bipolar montage technique: each channel includes only one “electrode of interest” or active electrode. Compare this to the more complex situation with bipolar montages in which a deflection in
the Fp1-F3 channel could indicate an event involving only Fp1, only F3, or both Fp1 and F3, but to different extents. The voltage of the event in a referential channel is directly proportional to the height of the wave. This is not necessarily true in bipolar montages, in which the point of maximum voltage can even be a flat channel, as we have seen in the example of the isoelectric phase reversal shown in Figure 4-23.

Why, then, does it often seem easier to read bipolar montages? The answer is related to the unpredictability of the assumption of the “clean” reference used in these examples. Ideally, we would like the reference to include only the exact same noise that is present in the active electrode. In practice, references often have noise of their own, sometimes to the point that they obliterate important signal information in the active electrode rendering the recording unreadable. This is not to say that, sometimes, a near-ideal reference cannot be found. With different patients during different parts of a given EEG study, depending on the patient’s behavior and other factors, the ability to make a clean referential recording varies greatly. Different reference electrode locations can yield large differences in the quality of the results. Each recording technique has its own advantages and disadvantages (Table 4-1).

![Image of EEG montage with Fp1, F3, C3, P3, and O1 labels](image)

**Figure 4-29** A 50-µV “positive spike” in C3 with field extending to F3 and P3. Because the active scalp electrodes are more positive than the neutral reference, the pens go down. The biggest pen deflection marks the maximum of the spike’s field at C3.

![Image of EEG sensitivity chart](image)

**Figure 4-30** The first step in ascertaining the voltage of a wave in an EEG trace is knowing the recording sensitivity used, stated in microvolts per millimeter. The sensitivity tells the reader how many microvolts of voltage each millimeter of pen deflection represents. In this example, the sensitivity is 5 µV/mm. In the top trace, the measured heights from the baseline of the spikes are 16 mm, 8 mm, and −8 mm, respectively. The relationship of millimeters to voltage is found by a simple multiplication 16 mm × (5 µV/mm) = 80 µV. Voltage measurements of sinusoidal waves as shown in the lower trace are made by measuring the peak-to-trough height of the waves, as shown.

Sensitivity = 5 microvolts/mm
Predicting the Appearance of the Bipolar Montage on the Basis of the Referential Montage

The following section consists of a set of exercises designed to aid the reader in visualizing how various EEG waves might appear differently depending on whether they are displayed in a bipolar or a referential montage. The ability to complete these exercises correctly implies a good understanding of the differences between the two montage types and how each type works. The reader may choose to solve the 14 montage problems, each shown on the following odd-numbered pages. The solutions are shown on the overleaf of each page.

We will start by looking at events in a referential montage and determine what their appearance would be in a bipolar montage. The examples used focus on a single chain of five electrodes, extending from the left frontopolar region to the left occipital region: Fp1, F3, C3, P3, and O1. This chain of electrodes is referred to as the left parasagittal chain. Again, to keep things simple, a single spike is used for these examples. In reality, the same line of reasoning applied to this spike can also be applied to any type of wave, such as sharp waves or slow waves. You may wish to look at the figures whose captions start with "Question" first (starting with figure 4-31) to attempt to solve the conversion problems before reading the narrative that follows which includes an explanation of the answers.

Figure 4-31 shows a simple event localized to a single electrode, C3. The appearance of this event in the bipolar montage can be predicted by imagining a series of subtractions. First, it should be noted that in a five-electrode chain, the referential montage displays five channels (Fp1-ref, F3-ref, C3-ref, P3-ref, O1-ref), but the bipolar montage solution will only include four channels, each channel representing a pairing of electrodes (Fp1-F3, F3-C3, C3-P3, P3-O1). For the purpose of solving these problems, the height of each wave can be measured in any unit (inches, millimeters, etc.)—the graphical answers are independent of the unit of measure used.

To determine what the appearance of the discharge in Figure 4-31 will look like in a bipolar montage, the value of the first bipolar channel is determined by finding the difference between the magnitudes of the discharge in Fp1 and F3. Because the value of each is zero, the difference between the two channels is also zero, and the resulting Fp1-F3 channel is flat (see Figure 4-34). The situation is different when determining the appearance of the F3-C3 channel. In this example, on the basis of an examination of the referential montage, F3 is zero, but C3 is upgoing by some amount (implying that C3 is negative by some amount). Because in the F3-C3 channel Electrode 1 is zero and Electrode 2 is negative, the pen goes down. Why is this? Because, as discussed earlier, according to the convention, when the first input (F3) is "more positive" than the second input in the pair (C3), the pen goes down. Another way to determine the pen direction is that when a subtraction of Electrode 1 − Electrode 2 is performed, the result will be a positive value, implying that the pen goes down. The most succinct way of stating this relationship is "F3 is 'more positive' than C3, so the pen goes down." The words "more positive" are in quotes because F3 is not, strictly speaking, positive.

Moving to the next electrode pair, C3-P3, now the pertinent comparison is a negative voltage in C3 minus a potential of zero in P3. C3 is more negative than P3, so the pen deflects upward. The final comparison is between P3 and O1, both of which have a zero value, so the comparison yields a flat line, reflecting a difference of zero. This succession of comparisons yields the appearance of Figure 4-34, the solution to the problem. This figure shows a typical-appearing phase reversal for a localized, negative surface event.

<table>
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<th>Table 4-1 The Comparative Advantages and Disadvantages of Bipolar and Referential Recording Techniques</th>
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The next example, shown in Figure 4-32 shows a discharge that resembles the previous example, a negative event with maximum in C3, but this time there is a field surrounding the C3 electrode. Examination of the figure reveals that the intensity of the field in C3 is exactly twice the intensity measured in the F3 and P3 electrodes. As a result, when going down through the electrode pairs, if F3 and P3 measure 5 “units” in height and C3 measures 10 “units” in height, the Fp1-F3 will reflect a 5-unit difference (and display a wave that is 5 units in height going downward, because Electrode 1 is more positive than Electrode 2). Likewise, F3-C3 will deflect the exact same amount in the same direction, because the difference between that electrode pair is the same, again with the first electrode being more positive than the second. For that reason, the first two channels of the bipolar solution are identical downward deflections, the height of which is exactly the same as

![Figure 4-31](image1)

**Question 1.** Predict how this discharge, displayed in a referential montage, will appear in a bipolar montage (answers to all questions appear on the subsequent page). The discharge consists of a simple, highly focal spike with a pure negativity in C3. The adjacent electrodes are inactive, implying that there is no gradient or gradual “falloff” in voltage in the surrounding electrodes.

![Figure 4-32](image2)

**Question 2.** Predict how this discharge, displayed in a referential montage, will appear in a bipolar montage. Like the previous example, this tracing shows a focal spike in C3, but this time with a larger field surrounding C3 as evidenced by the smaller upward deflections in F3 and P3. Note that the field dissipates in an even fashion with distance from C3. Absolute voltage measurements are given on the right side of the figure.

![Figure 4-33](image3)

**Question 3.** Predict how this discharge displayed in a referential montage will appear in a bipolar montage. This discharge is similar to the previous example except for the fact that voltage falls off more abruptly between C3 and its adjacent electrodes, F3 and P3. This steep gradient around C3 should be reflected in the appearance of the corresponding bipolar recording (shown on the next page).
Figure 4-34  Answer 1. The appearance of the same simple C3 spike shown on the previous page displayed in a bipolar montage. The flat lines in Fp1-F3 and P3-O1 reflect the fact that there is no electrical gradient between the outermost channels (Fp1 and F3, P3 and O1). Although such highly focal discharges involving only a single electrode may, indeed, be of cerebral origin, an electrode artifact may also produce this highly focal appearance.

Figure 4-35  Answer 2. In the referential montage shown in Figure 4-32 the height of the wave at C3 is evidence that the maximum negativity is located in that electrode. In the bipolar montage, C3's maximum negativity manifests as a phase reversal at C3 in this figure. The similar deflections seen in the outer channels, Fp1-F3 and P3-O1, reflect the fact that there is a gentle and steady gradient of decreasing negativity with increasing distance from the C3 electrode. This is one of the most common configurations seen for focal negative events arising from the brain. Deflections in all four channels in this figure confirm the presence of a field extending away from the discharge's maximum.

Figure 4-36  Answer 3. A representation of the discharge seen in Figure 4-33 is shown in a bipolar montage. The steep drop-off in voltage between C3 and its neighboring electrodes is manifested by higher deflections in F3-C3 and C3-P3 as compared to the previous example. The phase reversal seen in C3 still denotes this location as the point of maximum negativity.

the difference between the adjacent electrodes' voltage. The third bipolar channel, the C3-P3 comparison, has the same magnitude of difference as the previous comparison, but now because C3 is more negative than P3, the pen goes up the same number of units. This flipping of the pen direction (phase reversal) now that the voltage trend has changed (from successive electrodes becoming more negative to successive electrodes becoming more positive) defines the point of maximum negative voltage. This change in voltage trend causing the wave to flip its phase is the essence of the phase reversal. The phase “reverses” because, as the parasagittal chain is explored from front to back, the trend of successive voltage comparisons is no longer one of increasingly negative measurements but, instead, one of increasingly positive measurements. Finally, the last two channels, P3 and O1, have the same five unit difference with P3 more negative than O1, yielding the final 5-unit upgoing deflection. Figure 4-35 shows the expected phase reversal at C3.

The discharge shown in Figure 4-33 is similar to the preceding example, with a negative discharge seen in C3 and a diminishing field seen in F3 and P3. The example differs from the previous one in that the intensity of the
discharge drops off more abruptly from C3 to F3 and P3 (the gradient is steeper between C3 and F3 and between C3 and P3). When this type of field is shown in the bipolar montage, the location of the phase reversal at C3 has not changed (see Figure 4-36). The fact that the heights of the discharge in the second and third channels (F3-C3 and C3-P3) of Figure 4-36 are much higher than those in the outer channels (Fp1-F3 and P3-O1) reflects the fact that the gradient of the voltage drop-off immediately around C3 is steeper in this than in the previous example. This is analogous to the example of a mountain peak that is quite steep near its summit and less steep near its base.

Figure 4-37 shows what is, again, a very similar discharge with maximum negativity at C3. This time, the field is still strong in the adjacent electrodes, F3 and P3. The steep drop-off in voltage only occurs farther away from the C3 maximum of the discharge, between F3 and Fp1 and P3 and O1. When this discharge is displayed in a bipolar montage, the phase reversal again remains at C3, just as expected because this is still the point of maximum but second and third channels show low amplitudes, while the first and fourth channels show high amplitudes (see figure 4-40). This example provides an excellent demonstration of one of the relative weaknesses of the bipolar recording technique. A survey of the discharge in Figure 4-40 shows the highest (and most eye-catching) wave amplitudes near Fp1 and O1, the outer ends of the chain. The eye is not particularly drawn to the middle two channels with their lower amplitude deflections, yet these low-amplitude deflections mark the true maximum of the discharge. Why does this occur? As the reader well understands by now, the height of a wave in the bipolar montage does not represent the absolute voltage, but rather the rate of fall-off of the voltage or the voltage gradient between two electrodes. The point of maximum is marked by the position of the phase reversal, even if the deflections in the bipolar montage do not have particularly high amplitudes in that location. This observation helps emphasize the concept that, in bipolar montages, even when of very low voltage, phase reversals mark the point of maximum, whereas in referential montages, it is the greatest wave height that marks the point of maximum.

Figure 4-38 shows a discharge with a maximum shared between the F3 and C3 electrodes. Note that, on the basis of this configuration, it is possible that the discharge is “flat” in the region between the two electrodes, or, alternatively, there may be an even higher maximum point somewhere between the F3 and C3 electrodes (a schematic of these possibilities was shown in Figure 4-24). The two possibilities cannot necessarily be distinguished from the information provided by the tracing, and it is not necessary to know which of the two possibilities is the case to solve this problem. A discharge with equal maximum points appears as a particular type of phase reversal in a bipolar montage, as is shown in Figure 4-41. This pattern may be called an isoelectric phase reversal because the phases reverse around a flat, isoelectric channel (F3-C3). Here again, the interpreter must be aware that, despite the fact that this channel is flat, because the phase of the discharges reverses in the surrounding channels, this flat line marks the region of maximum voltage.

The wave pattern illustrated in Figure 4-39 represents a commonly encountered type of electrical event seen in referential montages. This example consists of a sharp wave with the exact same intensity across the whole parasagittal electrode chain (and perhaps across the whole scalp). Because there is no potential difference between any of the electrodes in this chain, the resulting bipolar tracing (see Figure 4-42) shows flat lines in each of its four channels—the apparent sharp wave cancels out completely in each of the four comparisons. Although it is not impossible for a discharge to be of similar voltage across a wide region of the head, a discharge that arises from the brain with exactly equal voltage across all scalp electrodes is rarely, if ever, encountered. The most common explanation for this type of pattern is electrical noise from an external source. Because of the noise’s external origin, it is possible for the noise signal to be of equal voltage all across the scalp. By contrast, discharges of cerebral origin almost always vary in voltage across the scalp, and therefore are almost always discernible on bipolar montages.

This tendency to cancel out common noisy activity is what gives bipolar montages their “cleaner” appearance and makes them appear to be easier to read. The efficiency with which bipolar montages can cancel out external noise is one of the major advantages of the bipolar recording technique. Less commonly, this type of cancellation of electrical events that are widely represented across the head can be a disadvantage. Occasionally, genuine cerebral activity (e.g., sharp waves or slow waves) can have a wide field across the scalp. Displaying such waves in a bipolar montage can result in a large amount of cancellation of such potentials, leading the reader to underestimate the voltage of the events. More often, however, the reader is happy that external noise sources are cancelled with the bipolar technique because this renders the underlying true electrocerebral activity easier to appreciate.

Figure 4-43 shows a downgoing spike, implying that the spike has positive rather than negative polarity. There is a surrounding field consisting of smaller positivities in F3 and C3. The appearance in the bipolar montage seen in Figure 4-46 is that of the classic “positive phase reversal” in which the phase-reversing waves point away from each other. Although epileptiform discharges more commonly show a negative charge at the scalp, occasionally they will show positive polarity, as in this example. Many nonepileptiform EEG waves may also manifest positive polarity, such as vertex waves of sleep, which can have both positive and negative components.

Figure 4-44 shows another frequently encountered waveform. In this example, there is a strong positivity in Fp1. The field of the positivity spills into F3, but with less intensity. The remaining three electrodes (C3, P3, and O1) do not detect the discharge. The same tracing in the bipolar montage shows one of the most commonly seen deflections in the EEG of awake individuals. The Fp1-F3 channel goes down, reflecting the fact that Fp1 is “more positive” than F3. Likewise, F3-C3 shows a
downgoing wave because F3 is more positive than C3, although the difference is not as great. The final two channels (C3-P3 and P3-O1) are flat because C3, P3, and O1 are all neutral.

The wave illustrated in this figure is consistent with an **eyeblink artifact**, which is common in the awake EEG (described in more detail in Chapter 6). Its appearance in the bipolar montage is illustrated in Figure 4-47. Because there is a net positive charge on the front of the globe of the eye, when the eyes are closed, the eyes bob upward (the so-called Bell’s phenomenon), causing a momentarily positive in the most anterior electrodes.

The pattern seen in Figure 4-45 suggests the familiar appearance of the posterior rhythm seen in the occipital lobes. The visual subtraction of sinusoidal curves such as those seen in this example is somewhat more challenging than subtracting the simple spikes we have been looking at so far, but the principles are the same. As we shall see, this example gives a surprising result based on the fact that, in this patient, the posterior rhythm is completely synchronized in the P3 and O1 electrodes.

**Figure 4-48** shows the expected flat channel in Fp1-F3 as both of these electrodes are inactive. A comparison of the flat F3 electrode to the lower voltage sinusoidal wave in C3 shows a mirror-image reflection of that wave, with the peaks and troughs flipped. The subtraction of P3 from C3 yields a similar result. As expected, at least mathematically, P3 and O1 cancel completely, and the P3-O1 channel is flat. This yields the paradoxical result of a posterior rhythm, strongest in the P3 and O1 channels, that is not seen at all in the most posterior channel (P3-O1) of the bipolar recording. In practice, this situation can occur in individuals in whom the posterior rhythm is highly synchronized and “in phase” in the posterior channels (the peaks and troughs of the waves in P3-ref and O1-ref line up perfectly with one another). In most patients, however, the posterior rhythm representations in P3 and O1 are somewhat out of phase with each other, and the subtraction of one from the other does yield a recognizable sinusoidal wave. Imagine that the wave in O1-ref were shifted one half wavelength to the right with respect to the wave in P3-ref. In that case, the rhythm seen in the P3-O1 channel of the bipolar montage would, indeed, have very high voltage.

Further, because C3 is more negative than F3 by the same amount that C3 is more negative than P3 (because the height of F3-C3 is the same as, but opposite in polarity to, the height of C3-P3), the voltage of Fp1, F3, P3, and O1 must all be the same. C3 must be more negative than those four electrodes by an amount equivalent to the heights seen in F3-C3 and C3-P3. Any solution that meets these constraints is potentially valid. Figure 4-50 shows three possible solutions to this problem.

Note that all three proposed solutions are equally correct from a “mathematical” point of view fitting the constraints implied by the bipolar montage: Fp1 = F3 = P3 = O1, and C3 has a “more negative” voltage than those four electrodes. However, certain of these solutions are more likely to be found in clinical EEG than others. Indeed, the top trace showing the pure negative discharge in C3 is the most likely to occur in actual EEG recordings. The middle trace, in which there is a negativity seen across all electrodes but strongest in C3, remains a possible solution. It is less attractive from the physiological point of view because it requires Fp1, F3, P3, and O1 all to be of the *exact same voltage*, but still within the field of the negative discharge—a relatively unlikely occurrence. The bottom trace of Figure 4-50 in which the surrounding electrodes are mildly positive but equipotential and C3 is mildly negative is also a mathematically sound solution, but even less biologically plausible for similar reasons. It would require a central negativity surrounded by a positivity of precisely constant intensity (no gradient).

Differences in solving the conversion problem in the bipolar to referential direction include the fact that the bipolar trace has four channels but the solution, the corresponding referential trace, needs to have five channels. More important, when converting referential traces to bipolar traces, there was only a single correct solution. As was seen with the previous example, any given trace in a bipolar montage can correspond to an infinite number of possible solutions in the referential montage. The reason for this is akin to the fact that there is only a single solution to the problem: “5 – 3 = ?” —the answer must be 2. If we ask the “reverse” version of this question, “subtraction of what two numbers gives 2 as a result?” the answer is an infinite number of pairs, such as 5 and 3, 101 and 99, –6 and –8, and so on. This analogy holds up well because bipolar traces are analogous to a display of differences and referential traces to a display of “absolute values.”

**Figure 4-51** shows a similar negative discharge maximum in C3, but this time with a more gradual gradient of decreasing voltage surrounding it, as evidenced by the deflections in the outer channels (Fp1-F3 and P3-O1). The possible solutions shown in **Figure 4-54** are all potentially correct because they all show the most negative voltage in C3 with voltages that are gradually decreasingly negative in the surrounding electrodes. The top and bottom traces, however, are the most biologically plausible with a negative event maximum in C3 and a gradient of decreasing negativity with increasing distance from C3. The middle trace is mathematically correct but biologically much less likely. Although in the middle trace the “maximum negativity” among

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**Predicting the Appearance of the Referential Montage Based on the Bipolar Montage**

The reverse of the problems we have been working thus far, predicting how a page will appear in the referential montage on the basis of its appearance in the bipolar montage, is associated with some unexpected challenges. The first such problem we will consider is shown in **Figure 4-49**, which shows a simple negative phase reversal in a bipolar montage. What will this look like in a referential montage? Going through each of the four channels, we develop a set of constraints: Analysis of the bipolar tracing tells us that because Fp1-F3 is flat, Fp1 and F3 must be of the same voltage. By the same line of reasoning, P3 and O1 must be of the same voltage.
Question 4. Predict how this discharge, displayed in a referential montage, will appear in a bipolar montage. Again, the highest voltage is seen at C3, but now there is only a small drop-off in voltage in the adjacent electrodes, F3 and C3, and then a more abrupt drop-off of voltage in the outermost electrodes, Fp1 and O1.

Figure 4-37

Question 5. Predict how this discharge, of equal voltage in F3 and C3 with surrounding electrodes quiet and displayed in a referential montage, will appear in a bipolar montage.

Figure 4-38

Question 6. Predict how this discharge, a negatively charged event that is spread evenly across the whole electrode chain, will appear in a bipolar montage.

Figure 4-39
the electrodes remains in C3, this solution implies two concomitant positive events at each pole of the brain (frontal pole and occipital pole) having the exact same magnitude and gradient and a completely neutral area in the C3 region, a relatively unlikely occurrence.

The discharge in Figure 4-52 again shows a spike with maximum negativity in C3. In this example, however, the higher amplitude deflections in the two center channels, F3-C3 and C3-P3, imply a steeper gradient of voltage change with increasing distance from the C3 electrode. Figure 4-55 shows results that are similar to the previous solutions seen in Figure 4-54. Again, the top and bottom traces are the most likely correct solutions for the same reasons given for the previous example—they are more biologically plausible. Note that the relative heights of the waves in F3 and P3 are much less than the height of C3, reflecting the more abrupt drop-off in voltage with distance from the point of maximum seen in this example. The top and bottom traces are commonly encountered patterns for EEG events recorded on the scalp.

Figure 4-53 shows an example of a particular type of phase reversal, the *isoelectric phase reversal*, that was discussed earlier. In this type of phase reversal, waves reverse phase (in this case, changing from downgoing to upgoing), but there is an intervening flat channel. Figure 4-56 shows three mathematically correct solutions, although the top and middle traces are the most plausible of the three. The bottom trace is a possible solution, but it requires a positive event to occur in C3, P3, and O1 at the exact same voltage across a relatively large area. The lack of a change in voltage or gradient...
**Figure 4-43** Question 7. Predict how this discharge, displayed in a referential montage, will appear in a bipolar montage. The figure shows a positive spike with maximum at C3 and with smoothly diminishing voltages at F3 and P3.

**Figure 4-44** Question 8. This pattern, displayed in a referential montage, suggests a strong positivity in Fp1 with diminishing strength in F3 and no field in C3, P3, and O1. Predict its appearance in the bipolar montage.

**Figure 4-45** Question 9. Predict how this discharge, displayed in a referential montage, will appear in a bipolar montage. Sinusoidal waves are present in this recording, most prominently in the posterior two electrodes and at half the voltage in the C3 electrode. This pattern is similar to what might be seen as the posterior (occipital) rhythm in some patients. In this example, the P3 and O1 signals are perfectly in phase, which is not always the case in actual patient recordings.
Figure 4-46  Answer 7. This figure shows the corresponding “positive phase reversal” with waves that point away from each other. Because the phases reverse at C3, this is the location of maximum positivity. The discharge should be compared to the discharge shown with the same field and the same intensity but opposite (negative) polarity in Figures 4-32 and 4-35.

Figure 4-47  Answer 8. The downward deflections in the first two channels reflect diminishing positivity across the first three electrodes in the chain (Fp1, F3, and C3). This pattern is consistent with eyeblink artifact, caused by a sudden positive charge near the frontopolar area related to upturning of the globe of the eye with eye closure.

Figure 4-48  Answer 9. The bipolar display of these sinusoidal waves shows a paradoxical effect in which the posterior rhythm is not evident in the most posterior electrode pairing (P3-O1) because of complete cancellation. This is a result of posterior rhythm waves in P3 and O1 being perfectly in phase, which is not always the case in actual clinical recordings (see text).
across C3, P3, and O1 make this a relatively unlikely explanation for the discharge shown in Figure 4-53.

The relatively simple tracing shown in Figure 4-57 initially appears straightforward but actually brings up particular difficulties in interpretation. A sole deflection is present in F3-C3, which implies that all the electrodes in the channel above it (Fp1 and F3) are at the exact same voltage, and all the electrodes in the channels below it (C3, P3, and O1) are also at their own exact same, but higher voltage (i.e., Fp1 = F3 < C3 = P3 = O1). The pattern suggests a plane of lower voltage anteriorly, a quick step-up between F3 and C3, and then a higher voltage plateau in the posterior electrodes. Though such escarpments may be seen in the world of geography, it is very unlikely that the brain would produce two such large perfectly equipotential zones immediately adjacent to one another. Figure 4-60 shows some of the possible mathematical solutions to this problem, but, in reality, none of the solutions is particularly attractive for the reasons described earlier. Indeed, when a lone deflection such as this one is encountered in the middle of a chain in a bipolar recording, it is probable that it represents an electrical artifact in the F3-C3 channel amplifier rather than a true cerebral event.

Note the distinction between a single channel/amplifier artifact and a single electrode artifact. If there is an artifact in a single electrode (perhaps because the electrode is touched, is loose, or “pops”), a deflection will be seen in all the channels that include that electrode. For instance, if the deflection in Figure 4-57 were due to electrode artifact in F3, why is it not also seen in the Fp1-F3 channel? Likewise, if it were due to an artifact in the C3 electrode, why is it not seen in the C3-P3 channel? Such single-channel artifacts are less common than single-electrode artifacts.

Figure 4-58 shows a pattern that can be interpreted either as increasing negativity going down the chain caused by a negative event in the posterior region, or increasing positivity going up the chain (through C3, F3, and Fp1) caused by a positive event anteriorly. If the former is the case with the tracing the result of a negative event in the posterior half of the brain, then there is again the problem that this negative event would have to be exactly equipotential in the bottom three electrodes: C3, P3, and O1. Because a negative event with the exact same voltage in C3, P3, and O1 does not seem plausible, this solution is much less likely. Indeed, note that all of the possible solutions suggested in Figure 4-61 must, and do, show the same voltage in those three electrodes. A simpler and more likely explanation is that this represents a positive event in the front of the head, as is seen in the top trace of Figure 4-61. The configuration of this discharge is again consistent with an eyeblink artifact as was described in Figures 4-44 and 4-47.

Figure 4-59 show the simplest possible bipolar tracing with four flat channels. This exercise serves as a reminder of what might be hiding behind any bipolar recording, whether or not it consists of flat channels. The top trace of Figure 4-62 reminds us that this bipolar tracing may truly reflect electrical silence. Because like activity cancels across bipolar chains, the middle trace shows a single spike present in all channels that has been “hidden” by the bipolar recording technique. Such cancellation is a frequent occurrence, especially if the spike represents noise from an external source. For instance, electrocardiographic (EKG) activity is almost always present throughout all head areas but is often not evident in bipolar displays. This is explained by the fact that the EKG potential may be of the same shape and amplitude across the regions in question and will cancel in the bipolar recording (it will also cancel in a referential recording if the chosen reference happens to contain the exact same representation of the EKG signal). Finally, the bottom trace of Figure 4-60 may be the most realistic of the group, because large amounts of electrical noise in the head can be cancelled out by the bipolar recording technique. It is always a good idea to keep in mind all the possibilities of what may be going on “behind the scenes” in a low-voltage bipolar tracing. Most often, the suppression of this common activity is seen as one of the principal advantages of the bipolar recording technique rather than as a loss of useful information.

Figure 4-49 Question 10. Predict how this discharge, displayed in a bipolar montage, might appear in a referential montage. The figure depicts a typical discharge with negative polarity and maximum in C3.
Figure 4-50  Answer 10. Three of many possible representations in the referential montage of the discharge shown on the previous page. All three of the solutions shown in this figure are mathematically possible, but the top solution is most likely (see text). They all have in common the fact that the outside four channels are of the same voltage and the middle channel is slightly more negative in comparison.
Figure 4-51  Question 11. Again, this discharge shows a maximum with negative polarity (phase reversal with waves pointing toward each other) in C3. There is a smooth gradient surrounding the maximum.

Figure 4-52  Question 12. Predict how this discharge, displayed in a bipolar montage, might appear in a referential montage. The figure shows another type of discharge with maximum negativity at C3; however, the second and third channels show a steeper drop-off of voltage than the outer channels.

Figure 4-53  Question 13. Predict how this discharge, displayed in a bipolar montage, might appear in a referential montage. This figure depicts a phase reversal with an intervening flat channel. This type of pattern is also referred to as an isoelectric phase reversal.
Figure 4-54  Answer 11. Possible representations in the referential montage of the discharge shown on the previous page. The top and bottom traces depict the discharge as having a net negative charge, with decreasingly negative voltage as distance from C3 increases. The middle trace shows an alternative solution. This is a mathematically correct solution that shows C3 as neutral, surrounded by electrodes that become increasingly positive with distance, however this solution is less plausible for reasons discussed in the text.
Figure 4-55  Answer 12. Possible representations in the referential montage of the discharge shown on the previous page. The solutions are similar to those shown for the previous figure; however, the field in the immediately surrounding electrodes, F3 and P3, is weaker. Again, the top and bottom traces are most biologically plausible.
Figure 4-56  Answer 13. Three possible representations of the discharge shown on the previous page are shown in the referential montage. The top tracing is the most plausible solution to this problem, showing a discharge with a shared negative maximum in C3 and P3. Although the middle and bottom tracings are mathematically correct, they are less biologically plausible (see text). All of the solutions have in common the fact that C3 and P3 are of the same voltage and more negative than the surrounding electrodes, which are, in turn, of an equal but more positive voltage.
Figure 4-57  Question 14. Predict how this pattern, a bipolar tracing showing a single channel with an upward deflection in the middle of a chain, might appear in a referential montage.

Figure 4-58  Question 15. Predict how this discharge, displayed in a bipolar montage, might appear in a referential montage. What type of commonly encountered EEG event does this pattern depict?

Figure 4-59  Question 16. Predict how this pattern, displayed in a bipolar montage, might appear in a referential montage. This example, showing four flat channels, is the simplest possible tracing but still has multiple possible solutions.
Figure 4-60 Answer 14. Possible representations of the discharge shown on the previous page are shown in the referential montage. The flat channels in the bipolar montage tell us that voltages at Fp1 = F3, and that C3 = P3 = O1, but at a more positive voltage. Although any solution that fits these constraints is mathematically valid, none is particularly plausible in terms of cerebral activity, and such patterns often represent an amplifier or channel artifact (see text).
Figure 4-61 Answer 15. Possible representations in the referential montage of the discharge shown in Figure 4-58. The top tracing is the most likely solution, representing a positive event that is strongest anteriorly. The bottom tracing suggests a negative event posteriorly but is less plausible because C3, P3, and O1 would have to be negative but of exactly equal non-zero voltage (see text). This pattern of a large anterior positivity is highly suggestive of eyeblink artifact.
Figure 4-62 Answer 16. Possible representations in the referential montage of the discharge shown on the previous page. The top tracing depicts electrocerebral silence. The middle and bottom traces are also valid, representing electrical noise in all electrodes that canceled in the original bipolar tracing.