Chapter 1
Arrays and Montages

1.1 Arrays

As the field of electroencephalography developed, the need for a standardized array of electrodes became increasingly apparent, resulting, in 1958, in the adoption of the International 10–20 System. Subsequently, the need for more closely spaced electrodes to allow for more precise localization led to an expansion of this system into what has come to be known as the Modified Combinatorial 10–10 System.

One, very important, failing of the International 10–20 System has been its inability to capture epileptiform discharges arising from seizure foci in the medial and anterior aspects of the temporal lobe. Of the multiple attempts to remedy this failing, two have found their way into clinical practice: first, utilizing a portion of the 10–10 System, namely, the inferior temporal chain; and, second, using one of the supplemental noninvasive electrodes, namely, the "true" anterior temporal electrode. Both of these are discussed at the end of this chapter.

1.1.1 International 10–20 System

The International 10–20 System was first described by Jasper in 1958 (Jasper 1958) and has become a worldwide standard. In developing this system, Jasper decided that "[p]ositions of electrodes should be determined by measurement from standard landmarks on the skull. . ." and that these "[m]easurements should be proportional to skull size and shape, insofar as

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possible." The standard landmarks Jasper chose were the nasion, the inion, and the preauricular points, and to maintain proportionality to the individual skull size, Jasper, rather than using predetermined distances in centimeters, decided on using percentages of the distances between these points on the individual patient's head.

The first line to be drawn lies in the midline and extends from the nasion to the inion. The first point on this line, according to Jasper (1958), is the Fp midline point, and this point "is 10 per cent of the nasion-inion distance above the nasion; the second point (F) is 20 per cent of this distance back from the point Fp, and so on in 20% steps back for the Central, Parietal, and Occipital points (hence the name 10-20 system)."

The next line to be drawn is "based upon the Central coronal plane. The distance is first measured from the left to right preauricular points . . ." and Jasper (1958) cautions that we "[b]e sure the tape is passing through the predetermined Central point at the vertex when making this measurement. Ten per cent of this distance is then taken for the Temporal point up from the pre-auricular point on either side. The Central points are then marked 20 per cent of the distance above the temporal points. . ."

The next line to be drawn is an "A-P line of electrodes over the temporal lobe, frontal to occipital, (and this) is determined by measuring the distance between the Fp mid line point . . . through the T position of the Central line, and back to the mid-occipital point. The Fp electrode position is then marked 10 per cent of this distance from the mid-line in front, and the Occipital electrode position 10 per cent of the distance from the mid-line in back. The inferior Frontal and posterior Temporal positions then fall 20 per cent of the distance from the Fp and O electrodes, respectively along this line" (Jasper 1958).

"The remaining mid-Frontal (F3 and F4) and mid-Parietal (P3 and P4) electrodes are then placed along the Frontal and Parietal coronal lines respectively, equidistant between the mid-line and temporal line of electrodes on either side" (Jasper 1958).

In explaining the rationale for the names of the various electrodes, Jasper (1958) commented that "[t]raditional anatomical terms have been employed to designate electrode positions over the various lobes of the brain, with the exception of the Central region which is, strictly speaking, partly frontal and partly parietal."

He goes on to note that "[i]n order to differentiate between homologous portions over left and right hemispheres it was decided to use even numbers as subscripts for the right hemisphere, and odd numbers for the left hemisphere . . . Electrodes at the mid-line in Frontal, Central and Parietal regions were originally designated F_0, C_0 and P_0 but this led to some confusion since P_0,

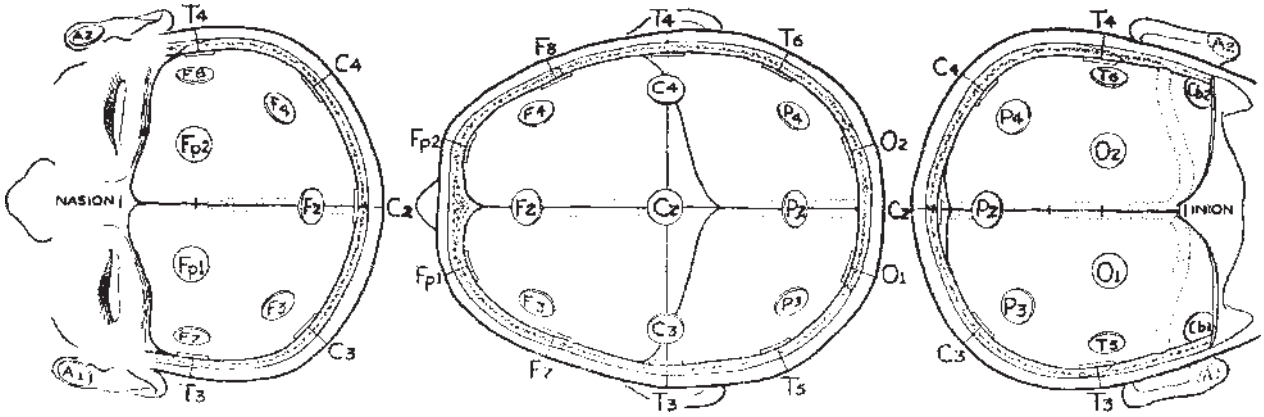

Figure 1.1 The complete International 10–20 System.
SOURCE: Jasper (1958)/with permission of Elsevier.

for example, might be interpreted as parieto-occipital. Consequently the midline positions have been changed to F_z, C_z and P_z ($_z$ for zero!)." The complete system of placements is shown in Figure 1.1 and schematically in Figure 1.2.

The full names of each of Jasper's 21 alphanumeric designations are given in Table 1.1. Subsequently, however, two alternative names have gained currency. The first alternative is trivial: "auricle" has been replaced by "ear." The second, however, is far more significant. In the same year that Jasper published his study, Abraham and Ajmone Marsan (1958) referred to F7 and F8 not as "inferior frontal," but as "anterior temporal," and this designation has stuck, despite the fact, as discussed below, that F7 and F8 do not overly the temporal lobe at all.

1.1.2 Anatomical Position of Electrodes of the International 10–20 System

Jasper (1958) stated that "[a]natomical studies should be carried out to determine the cortical areas most likely to be found beneath each of the standard electrode positions," and in his paper he briefly described two such studies.

"Two methods were employed: (1) metal clips placed along the Central and Sylvian fissures at operation were then used to identify these fissures in X-ray studies of the skull after the EEG electrodes had been applied, and (2) electrode positions were carefully marked on the heads of cadavers, drill holes placed through the skull, and the cortex marked with India ink in each position before removing the brain for examination. Brains with gross lesions or focal atrophy were excluded."

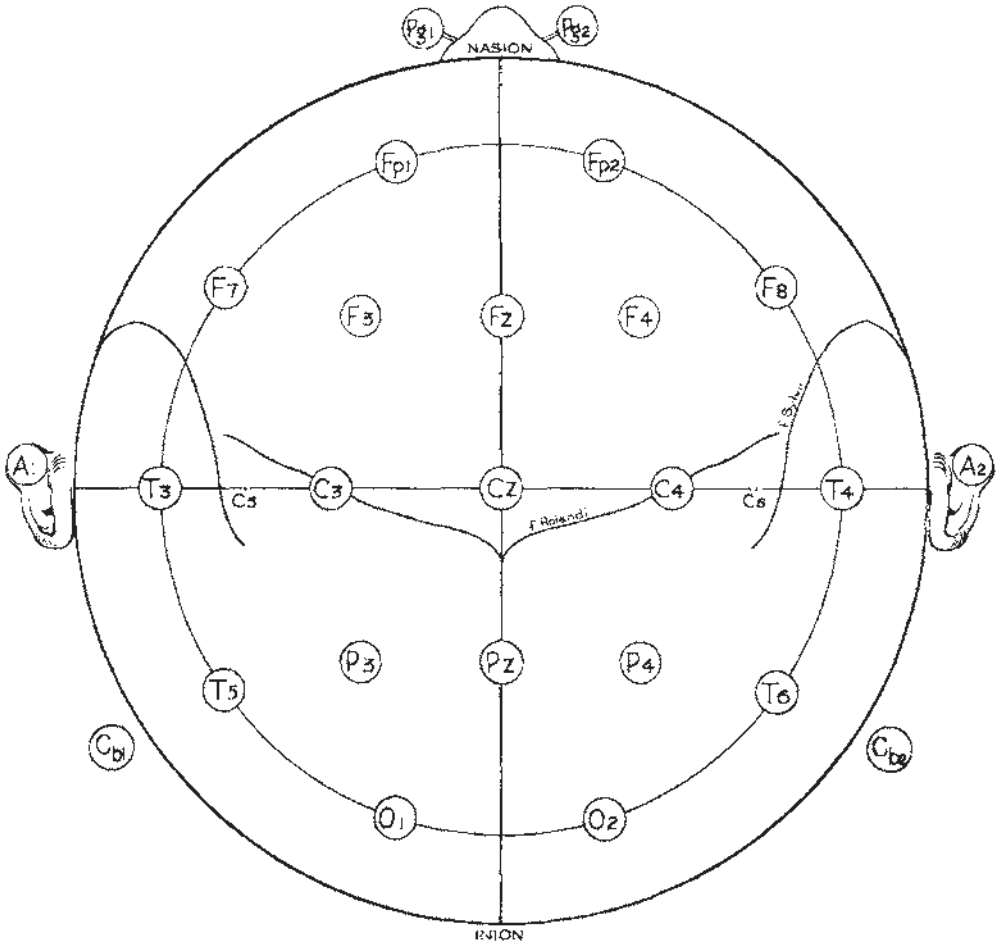

Figure 1.2 The complete International 10–20 System in schematic form.
SOURCE: Jasper (1958)/with permission of Elsevier.

Table 1.1 Electrode names in the International 10–20 System

		Fp1 left frontopolar		Fp2 right frontopolar		
	F7 Left inferior frontal[a]	F3 Left frontal	F_z Frontal midline	F4 Right frontal	F8 Right inferior frontal[a]	
A1 Left auricle	T3 Left mid-temporal	C3 Left central	C_z Central midline	C4 Right central	T4 Right mid-temporal	A2 Right auricle
	T5 Left posterior temporal	P3 Left parietal	P_z Parietal midline	P4 Right parietal	T6 Right posterior temporal	
		O1 Left occipital		O2 Right occipital		

[a] F7 and F8 are also known as "anterior temporal" electrodes.

"Although some variability was found, and is to be expected, the position of the two principle (sic) fissures should be within plus or minus about 1 cm. of that indicated on the drawings, provided the head measurements are carefully made and the brain is free of gross distortion due to expanding or contracting lesions. Due to the obliquity of the Central Fissure the upper central electrodes will usually lie pre-central while the lower ones will be post-central in most cases."

Jasper's original "anatomical studies" were followed up by Homan *et al.* (1987), who capitalized on the availability of computed tomography (CT) scanning to provide a more detailed correlation, and the results are summarized in Table 1.2.

The findings of Homan *et al.*'s study have significant implications for cases of suspected temporal lobe epilepsy. To begin with, although as noted earlier, F7 and F8 are often referred to as "anterior temporal," they do not, in fact, overly the temporal lobe at all. Consequently, if one wishes to adequately sample the anterior portion of the temporal lobe, it will be necessary to utilize a supplemental electrode, namely, as discussed further below, a "true" anterior temporal electrode, T1 or T2. Next, since none of the temporal electrodes (T3 and T4, T5 and T6) overly the inferior temporal gyrus, it will be necessary, if one wishes to sample this area, to place an "inferior temporal" chain, which is a fragment of the Modified Combinatorial 10–10 System, as discussed immediately below.

Table 1.2 Electrode positions as determined by CT scanning

Electrode position	Cortical location
F7,8	"Inferior frontal gyrus rostral portion of pars triangularis"
T3,4	"Overlapping middle and superior temporal gyri, rostro-caudal location – posterior to rolandic fissure"
T5,6	"Left-middle temporal gyrus caudal to termination of Sylvian fissure. Right overlapping superior temporal sulcus, with rostro-caudal location even with termination of sylvian fissure"
Fp1,2	"Rostral limit of superior frontal gyrus"
F3,4	"Middle frontal gyrus, near superior frontal sulcus; rostro-caudal location – even with temporal pole"
C3,4	"Precentral gyrus, shoulder to wrist area, caudal to middle frontal gyrus"
P3,4	"Superior parietal lobule near intraparietal sulcus, superior to posterior portion of supramarginal gyrus"
O1,2	"Occipital lobe, lateral and superior to occipital pole, overlapping calcarine fissure"

1.1.3 Modified Combinatorial 10–10 System

Jasper (1958) anticipated that electrode positions "intermediate" between those of the 10–20 System would be needed "for special localization studies," and in 1985, Chatrian *et al.* (1985, 1988) officially proposed "the '10%' electrode system." Some controversy ensued regarding the nomenclature of this system, and eventually, guidelines were proposed in 1991 (Sharbrough *et al.* 1991) by the American Electroencephalographic Society and in 2016 (Acharya *et al.* 2016a) by its successor, the American Clinical Neurophysiology Society (ACNS), for the "modified combinatorial system." In developing the nomenclature for this 10–10 System, three guiding principles were utilized, namely: (1) "[e]ach number should designate a sagittal line so the same postscripted number identifies all positions lying on that sagittal line"; (2) "[e]ach letter should appear on only one coronal line"; and (3) "[t]he letters should be derived from names of the underlying lobes of the brain or other anatomic landmarks."

Figure 1.3 illustrates the modified combinatorial nomenclature for the 10–10 System. As may be seen, the nomenclature of the original 10–20 System has undergone two significant changes, and these are highlighted in Figure 1.3 by white lettering on a black background.

The first change involves changing the T3 of the 10–20 System to T7 and the T4 of the 10–20 System to T8. This change represents a bow to the principle that each number should designate a sagittal line, and here the numbers in question are "7" and "8." The second principle, however, has not been followed, for, if it had, the names of these two electrodes would be C7 and C8. Doing so, however, would've been in conflict with the principle that the letter should reflect the underlying lobe, which, in this case, begins not with "C" but with "T."

The second change involves changing the T5 of the 10–20 System to P7 and the T6 of the 10–20 System to P8. This change represents a bow to two principles: that each number should designate a sagittal line, in this case, numbers "7" and "8," and that each letter should appear on only one coronal line, which here is "P." Changing "T" to "P," however, again brings us into conflict with the principle that the letter should reflect the underlying lobe, which is temporal, not parietal.

The ACNS concluded that "[a]lthough it would be desirable to switch to T7/T8 and P7/P8 for both clinical and education (including publication) purposes, it would be an acceptable alternative to continue to use T3/T4 and T5/6" (Acharya *et al.* 2016a).

In this text, when referring to the 10–20 System, this acceptable alternative is utilized. The nomenclature proposed by Jasper in 1958 has stood the

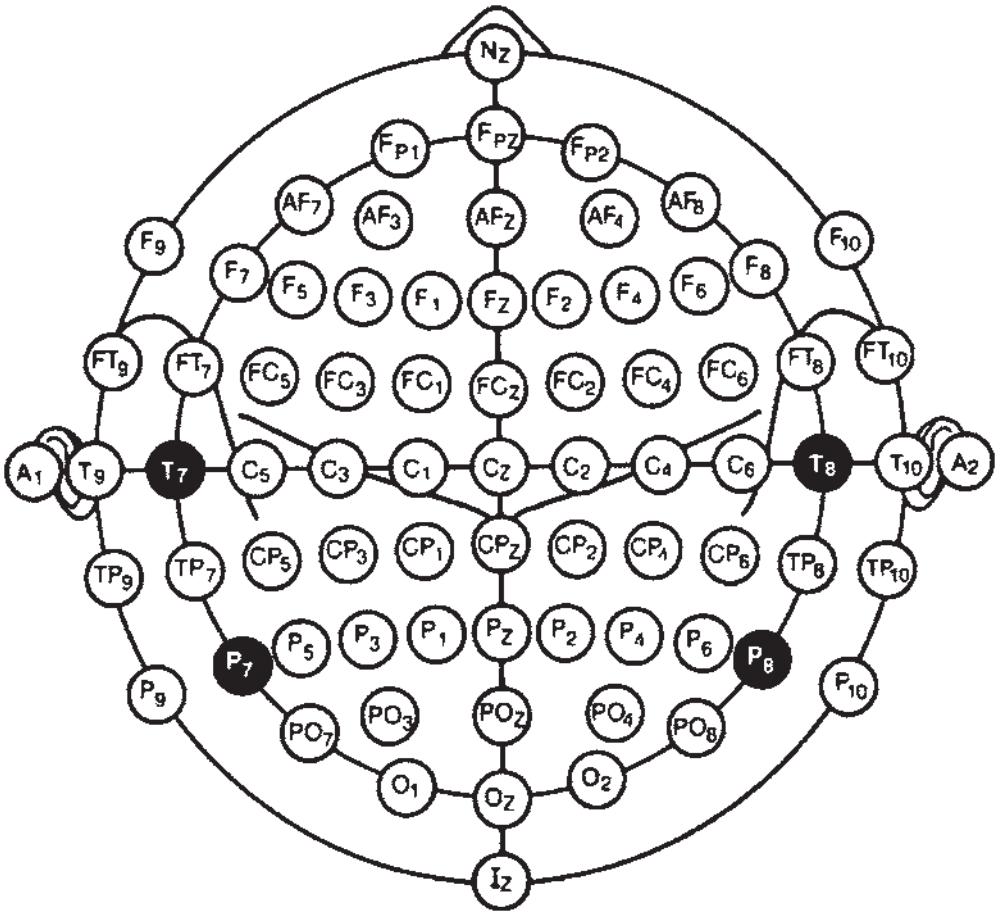

Figure 1.3 The modified combinatorial system for the 10–10 System. See the text for a discussion of T7, P7, T8, and P8.
SOURCE: Acharya et al. (2016a)/with permission of Wolters Kluwer Health, Inc.

test of time, both in clinical and research applications, and until the proposed changes have been shown to have greater utility for both these purposes, the case for their universal adoption remains unproven.

The full 10–10 System is generally reserved for situations, such as planning for epilepsy surgery, where precise localization is required. Fragments of the 10–10 System, however, may be utilized on an ad hoc basis. For example, when it is suspected that seizure foci are present in the middle or inferior temporal gyri, utilizing the "inferior temporal" chain of F9/10-T9/T10-P9/P10 results in a greater detection rate than does reliance on the 10–20 System (Bach Justesen *et al*. 2018).

1.1.4 Supplemental Noninvasive Electrodes

Two, very different, noninvasive electrodes have been utilized in order to better sample medial temporal interictal epileptiform activity or ictal activity, namely nasopharyngeal, and "true" anterior temporal leads.

Nasopharyngeal leads were developed in the late 1940s (Roubicek and Hill 1948; McLean 1949). These leads consist of a 10–15 cm insulated wire with a 2-mm uninsulated tip; they are inserted into each nostril and then rotated outward such that the tip is directed toward the medial aspect of the temporal lobe. These, however, have fallen out of use as they are uncomfortable, prone to artifact, and, most importantly, are less sensitive than "true" anterior temporal leads (Goodin *et al*. 1990; Sadler and Goodwin 1989; Sperling and Engel 1985).

"True" anterior temporal leads, customarily designated T1 and T2, were developed by Silverman (1960a) and are placed on the scalp "at a point 1 cm. above one-third of the distance from the external auditory meatus to the external canthus." Homan *et al*. (1988), using CT scans, found that these electrodes overlay the "[t]emporal pole overlapping superior temporal sulcus, more in middle than superior temporal gyrus." These "true" anterior temporal leads have been found superior to both F7 and F8 for the detection of interictal epileptiform discharges (Gambardella *et al*. 1998; Goodin *et al*. 1990; Nowack *et al*. 1988; Sadler and Goodwin 1989; Silverman 1960a; Sperling and Engel 1985) and for electrographic seizure activity, when either of these originate in the medial aspect of the temporal lobe (Homan *et al*. 1988).

1.2 Montages

As was the case with arrays, the need for a standard set of montages became apparent as the field of electroencephalography developed, but with montages, the need became particularly pressing. Eventually, this need was met with the elaboration of a set of standard montages as recommended by the American Clinical Neurophysiology Society (Acharya *et al*. 2016b).

1.2.1 Bipolar Montages

In bipolar montages, each derivation consists of two adjacent electrodes, and these derivations are linked together to form chains. These chains, in turn, may be oriented longitudinally or transversely. Longitudinal chains begin anteriorly and extend posteriorly, and an example of a longitudinal

chain would be the left temporal chain, which is composed of the derivations Fp1-F7, F7-T3, T3-T5, and T5-01. Transverse chains begin on the left and cross over into the right hemisphere, and an example of a transverse chain would be the frontal chain, composed of derivations F7-F3, F3-Fz, Fz-F4, and F4-F8. Bipolar montages composed only of longitudinal chains are called, as might be expected, longitudinal bipolar, while, and again as might be expected, montages composed of transverse chains are called transverse bipolar.

1.2.1.1 Longitudinal Bipolar Montages

Longitudinal bipolar montages may be displayed in one of the two different fashions: "anatomic" or paired. The first of these fashions is termed "anatomic" because the various chains are displayed in accordance with their actual position on the scalp, beginning with the left temporal chain, followed by the left parasagittal chain, then to the midline chain, followed by the right parasagittal chain, and finally ending with the right temporal chain, as seen in the first column of Table 1.3. The second of these fashions is termed paired because the various chains are displayed as homologous pairs, with the parasagittal pair formed by the left parasagittal chain, followed by the right parasagittal chain, and the temporal pair formed by the left temporal chain, followed by the right temporal chain. This paired fashion becomes a little more complicated depending on whether one places the parasagittal pair over the temporal pair, or vice versa, and on where one places the midline chain, as seen in the second and third columns of Table 1.3.

1.2.1.2 Transverse Bipolar Montages

Transverse bipolar montages are composed of five different transverse chains, displayed in an anterior-to-posterior fashion, with some minor differences yielding two different fashions. The first of these fashions is illustrated in the first column of Table 1.4. As may be seen there, the nomenclature for the most anterior chain, "frontopolar," is a little strained; although this chain does indeed contain the Fp_1-Fp_2 derivation, it also includes the two adjacent derivations, giving it a semicircular aspect. Similarly, although the occipital chain does include the O_1-O_2 derivation, it also includes adjacent derivations, again yielding a semicircular shape.

Turning now to the second of these two fashions, as seen in the second column of Table 1.4, there are two changes relative to the fashion just described. First, a midline chain has been included. Second, the ears have been included at the beginning and end of the central chain.

Table 1.3 Longitudinal bipolar montages. For the anatomic montage and each of the two paired montages, each of the chains is accompanied, immediately to its right, by the derivations making up that particular chain

Anatomic		**Paired**		**Paired**	
Chain	*Derivations*	*Chain*	*Derivations*	*Chain*	*Derivations*
Left temporal	Fp1-F7	Midline	F_z-C_z	Left temporal	Fp1-F7
	F7-T3		C_z-P_z		F7-T3
	T3-T5	Left parasagittal	Fp1-F3		T3-T5
	T5-01		F3-C3		T5-O1
Left parasagittal	Fp1-F3		C3-P3	Right temporal	Fp2-F8
	F3-C3		P3-O1		F8-T4
	C3-P3	Right parasagittal	Fp2-F4		T4-T6
	P3-O1		F4-C4		T6-O2
Midline	F_z-C_z		C4-P4	Left parasagittal	Fp1-F3
	C_z-P_z		P4-O2		F3-C3
Right parasagittal	Fp2-F4	Left temporal	Fp1-F7		C3-P3
	F4-C4		F7-T3		P3-O1
	C4-P4		T3-T5	Right parasagittal	Fp2-F4
	P4-O2		T5-O1		F4-C4
Right temporal	Fp2-F8	Right temporal	Fp2-F8		C4-P4
	F8-T4		F8-T4		P4-O2
	T4-T6		T4-T6	Midline	F_z-C_z
	T6-O2		T6-O2		C_z-P_z

Table 1.4 Transverse bipolar montages. The main difference between these two transverse bipolar montages is the expansion of the central chain in the second montage by the addition of the ears

Chain	**Derivations**	**Chain**	**Derivations**
Frontopolar	F7-Fp1	Frontopolar	Fp1-Fp2
	Fp1-Fp2	Frontal	F7-F3
	Fp2-F8		F3-F_z
Frontal	F7-F3		F_z-F4
	F3-F_z		F4-F8
	F_z-F4	Central	A1-T3
	F4-F8		T3-C3
Central	T3-C3		C3-C_z
	C3-C_z		C_z-C4
	C_z-C4		C4-T4
	C4-T4		T4-A2
Parietal	T5-P3	Parietal	T5-P3
	P3-P_z		P3-P_z
	P_z-P4		P_z-P4
	P4-T6		P4-T6
Occipital	T5-O1	Occipital	O1-O2
	O1-O2	Midline	F_z-C_z
	O2-T6		C_z-P_z

1.2.2 Ipsilateral Ear Referential Montages

In an ipsilateral ear referential montage, each derivation is composed of a scalp electrode and the ipsilateral ear electrode. These derivations may then be displayed in either an unpaired or paired fashion.

In the unpaired ipsilateral ear referential montage, as seen in the first column of Table 1.5, the various derivations are grouped in anatomic regions (e.g., the left temporal region consisting of the derivations F7-A1, T3-A1, and T5-A1), and these regions are displayed from left to right, beginning with the left temporal region, then to the left parasagittal region, then to the midline, followed by the right parasagittal region, and ending with the right temporal region.

The paired ipsilateral ear referential montages are so named because they are composed of pairs of derivations, with each pair containing homologous electrodes, for example, the frontopolar pair, which is composed of the derivations Fp1-A1 and Fp2-A2. Depending on how these pairs are grouped, one arrives at two different paired ipsilateral ear referential montages, as seen in Table 1.5. In the first of these montages, seen in the second column of Table 1.5, a midline pair is seen; this is followed by pairs of parasagittal derivations (frontopolar, frontal, central, parietal, and occipital) and then pairs of temporal derivations (anterior-, mid-, and posterior temporal).

Table 1.5 Ipsilateral ear-referential montages

Unpaired		**Paired**		**Paired**	
Region	*Derivations*	*Region*	*Derivations*	*Region*	*Derivations*
Left temporal	F7-A1	Midline	F_z-A1	Anterior temporal	F7-A1
	T3-A1		P_z-A2		F8-A2
	T5-A1	Frontopolar	Fp1-A1	Mid-temporal	T3-A1
Left parasagittal	Fp1-A1		Fp2-A2		T4-A2
	F3-A1	Frontal	F3-A1	Posterior temporal	T5-A1
	C3-A1		F4-A2		T6-A2
	P3-A1	Central	C3-A1	Frontopolar	Fp1-A1
	O1-A1		C4-A2		Fp2-A2
Midline	F_z-A1	Parietal	P3-A1	Frontal	F3-A1
	P_z-A2		P4-A2		F4-A2
Right parasagittal	Fp2-A2	Occipital	O1-A1	Central	C3-A1
	F4-A2		O2-A2		C4-A2
	C4-A2	Anterior temporal	F7-A1	Parietal	P3-A1
	P4-A2		F8-A2		P4-A2
	O2-A2	Mid-temporal	T3-A1	Occipital	O1-A1
Right temporal	F8-A2		T4-A2		O2-A2
	T4-A2	Posterior temporal	T5-A1	Midline	F_z-A1
	T6-O2		T6-A2		P_z-A2

In the second of these montages, seen in the third column of Table 1.5, pairs of temporal derivations appear first, followed by parasagittal pairs, and ending with the midline pair.

1.2.3 Choosing Among Montages

Most electroencephalographers find one montage more congenial than others and, in practice, tend to preferentially utilize it to review the recording, and for most electroencephalographers, this is the anatomic longitudinal bipolar, or "double banana" montage. This practice enables the reader to become quite familiar with how a normal background appears, and this may be quite advantageous, as it allows abnormalities to appear in stark relief (Klass 1977). There are, however, disadvantages to using only one montage to view a recording, and because of these disadvantages, it is recommended (Acharya *et al*. 2016b) that at least three montages be used for each reading: one longitudinal bipolar, one transverse bipolar, and one ipsilateral ear referential.

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