1 EEG basics

1.1 Electrode nomenclature, polarity and referential vs. bipolar montages

Electroencephalography (EEG) is a technique that measures the spatial distribution of voltage fields on the scalp and their variation over time. The origin of this activity is thought to be due to the fluctuating sum of excitatory and inhibitory postsynaptic potentials. These potentials arise primarily from apical dendrites of pyramidal cells in the outer (superficial) layer of the cerebral cortex and are modified by input from subcortical structures, particularly the thalamus and ascending projections of the ascending reticular activating system. Structures in the thalamus serve as a 'pacemaker'. This produces widespread synchronization and rhythmicity of cortical activity over cerebral hemispheres.

The dendritic generators are vertically oriented and have two poles, one relatively negative and the other relatively positive. This is termed a dipole. Dipoles are sources of electrical current consisting of two charges of opposite polarity separated by relatively small distances. Since cerebral potentials are produced by dendritic generators radially oriented to the surface, a scalp electrode usually detects only one end of the generator at one point in time. In general, approximately 10 cm^2 of cortex needs to be discharging synchronously for the signal to be appreciated on scalp EEG.

The hardware necessary to record the EEG employs differential amplifiers. Each amplifier records the potential difference between two scalp electrodes (the electrode pair is referred to as a derivation or channel). Each amplifier has two inputs connected to scalp electrodes. By convention, when input 1 (historically referred to as grid 1 or G1) is relatively negative compared to input 2 (grid 2 or G2), there is an upward deflection; when input 1 is relatively more positive than input 2, there is a downward deflection. It is the relationship between the two inputs that determines the direction and amplitude, and not the absolute values. Simply put, the tracing at each channel (derivation) displays G1 minus G2, with negative values causing upward deflections. Table 1.1 shows some examples to help further demonstrate these principles.

In the following four examples the inputs are switched (Table 1.2).

As can be seen from both tables, there are no 'positive' or 'negative' deflections, there are only upward or downward deflections. When there is no deflection, inputs are equipotential and are either equally active or inactive.

When looking at only a single derivation (a one-channel recording of the potential difference between an electrode pair), one can only state the relationship of input 1 to input 2, i.e. it is either more or less negative or positive. However, it is not possible to localize cerebral activity or determine its polarity without further derivations/channels. Understanding polarity, as well as accurately assessing other factors such as the frequency of the activity being evaluated (cycles/second), its morphology, location, voltage, reactivity and symmetry in conjunction with the age and state of the patient are necessary for proper interpretation

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TABLE 1.1 Polarity

Input 1	Input 2	Difference	Deflection direction
+50	+20	+30	Down
+50	+50	0	—
+50	+70	−20	Up
+50	−50	+100	Down

of the EEG. In order to adequately represent the topography of the voltage, additional amplifiers and channels are needed for the sequential display of the EEG data, and this display of multiple channels is termed a montage. A montage refers to a collection of derivations for multiple channels recorded simultaneously and arranged in a specific order. Montages enable the technologist and electroencephalographer to systematically visualize the field of electrical activity of the brain.

Electrodes are applied to the scalp in accordance with the International 10-20 System (Figure 1.0). Different regions of the brain are identified as Fp (frontopolar), F (frontal), C (central), P (parietal), O (occipital) and T (temporal). Odd numbers refer to the left side, even to the right, and Z to midline placements. 'A' signifies an ear channel (A1 for left ear, A2 for right). Electrode placement has been standardized with this system, with electrode sites determined by anatomical skull landmarks. Technologists measure the distance from the nasion to the inion and the head circumference, marking precise electrode locations based on 10% or 20% intervals of those distances, hence the name '10-20'.

Montages may be viewed as software that enhances the use of the EEG machine (hardware) to function as a form of brain imaging. There are two basic types of montages: bipolar and referential. These two recording methods can be compared to techniques used to determine altitude at different points on a mountain. The referential type of recording (formerly incorrectly termed 'monopolar') is comparable to measuring the elevation with reference to a particular point, either on land or at sea level. Bipolar sequential recording is similar to measuring the difference of elevation between nearby points, going serially in a particular direction. Another analogy that has been used to describe the electrical potential field on the scalp is that of the surface of the sea. In this example, a number of buoys (the electrodes) float on the sea's surface with varying vertical displacements representing fluctuations of electrical potential.

TABLE 1.2 Polarity with inputs switched

Input 1	Input 2	Difference	Deflection direction
+20	+50	−30	Up
+50	+50	0	—
+70	+50	+20	Down
−50	+50	−100	Up

With a bipolar sequential recording, scalp electrodes are linked in straight lines (either anterior–posterior or transverse) and each channel records the difference in potential between electrode pairs. In a referential montage, any electrode may be used as the reference point with respect to which the potentials of the other electrodes can be measured. In this type of recording, scalp electrodes are combined to one or two common reference sites, often ear(s), the vertex (Cz) or an average of all electrodes (termed a 'common average reference'). Again, an amplifier records the difference between electrode pairs in separate channels; in a referential recording, the second input (G2) is always the reference.

Some advantages and disadvantages of each type of recording are described below.

Short distance bipolar recording

Advantages

(1) Value of phase reversal in localization, particularly when this occurs at the same electrode in two montages run at right angles to each other. Phase reversal in a sequential bipolar montage refers to the opposite simultaneous deflection of pens in channels that contain a common electrode. It is important to realize that a phase reversal does not imply normality or abnormality. This instrumental phase reversal usually, but not always, indicates that the potential field is maximal at or near the common electrode. To be certain that one has accurately defined the site of maximal involvement,

it is necessary to use an additional bipolar montage at right angles to the first, or a referential recording.

(2) Bipolar montages usually display local abnormalities well, since a phase reversal is often present. The exception occurs when the discharge is maximal at either the beginning or the end of the sequential chain.

(3) Can help resolve ambiguous findings on referential montages due to an active reference.

Disadvantages

(1) Amplitudes can be misleading; in any given channel higher amplitude indicates a greater potential difference, not necessarily the most active site, while low amplitude could be due to two electrodes being equally active and canceling or both electrodes being inactive.

(2) Diffuse potentials with relatively flat gradients are not detected well.

(3) Waveforms might be distorted and sham frequencies can be introduced.

Referential recording

Advantages

(1) Amplitude can be used to localize the site of maximal involvement if the reference is inactive. In referential recordings, when the reference is inactive (or is the least active electrode), the site of maximal involvement is identified as the one having the greatest voltage (i.e. the greatest amplitude of deflection).

(2) Little distortion of frequency or waveforms.

(3) Diffuse patterns with flat gradients can be detected. In contrast to focal abnormalities, diffuse discharges are frequently better appreciated on referential montages, particularly when there is a flat gradient.

(4) Can help resolve difficulties in bipolar recordings due to equipotential areas, horizontal dipoles or unevenly sloping gradients.

Disadvantages

(1) The reference electrode may not be inactive or be the least active electrode – it may be very active. When the reference electrode is active, because it is located near the peak of the potential being studied, interpretation can be more difficult. A major problem with the use of referential montages is that it is often difficult to use an inactive reference or to realize that the reference is active.

A reference may be active because of artifact or it may be within the cerebral field under study. With an active reference there often appears to be a 'phase reversal' on a referential montage, i.e. some electrodes are more negative than the reference, while others are more positive. One has to look at relative polarity, as well as amplitude, to decide which is the most active site. For those electrodes that are more active than the reference, the greatest amplitude indicates the site of maximal involvement. In contrast, for sites less active than the reference, the largest amplitude indicates the least active area. The deflection of the maximal and minimal sites will be in opposite directions. When the reference is the most active site, deflections in all channels are in the same direction, i.e. there is no phase reversal. Furthermore, the largest amplitudes occur at those sites that are the least active. This type of situation can be confusing, since one cannot be sure if the reference is uninvolved or is the most active of all scalp electrodes.

(2) Greater problem with artifact – depends on the reference employed. No single reference electrode is ideal for all situations. The ear electrodes frequently are contaminated by temporal lobe spikes as well as electrocardiogram (EKG) and/or muscle artifact. The Cz electrode, which is often a very good choice in helping to display focal temporal abnormalities, is very active during sleep.

P1: OTA/XYZ P2: ABC
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Other midline reference electrodes, such as Fz or Pz, also have limitations: during wakefulness Fz is in the field of vertical eye movements, while Pz is usually in the field of the posterior dominant 'alpha' rhythm field (see section below on alpha rhythm); thus these references are often active.

It should be realized that if the same electrodes are used on a bipolar and referential montage then the montages will contain equivalent information, i.e. although the arrangement may differ, the pieces are the same. The two types of montages, bipolar and referential, should be employed in recording the EEG, as each has its own advantages and disadvantages. *Often, utilizing a different reference or a bipolar montage helps clarify localization problems.*

The American EEG Society has published suggestions for standard montages to be used in clinical EEG. The montages listed below are not intended for some purposes, such as neonatal EEG, all-night sleep recordings or for verification of electrocerebral inactivity. Three types of montages were suggested:

(1) longitudinal bipolar (LB) montage

(2) referential (R) montage (such as ipsilateral ear)

(3) transverse bipolar (TB) montage.

1.2 Normal EEG: awake and asleep

EEGs can be performed on patients of all ages, including neonates. There are marked maturational changes that occur in infancy and early childhood, while in adults between the ages of 20 and 60 years, the EEG is relatively stable. Further fairly subtle changes occur in the elderly. Thus in different age groups different patterns characterize wakefulness, drowsiness and sleep.

The normal adult EEG contains a number of different background rhythms and frequencies. These include alpha, beta, delta, mu, theta and normal sleep activity (such as V-waves, spindles, K complexes and positive occipital sharp transients of sleep (POSTS)). EEG activity is conventionally divided into the following frequencies (number of waveforms/s or hertz (Hz)):

Delta – refers to frequencies below 4 Hz. Delta activity, which is the slowest waveform, is normal when present in adults during sleep. In normal elderly subjects, delta activity is sometimes seen in the temporal regions during wakefulness, and in a generalized distribution, maximal anteriorly, during drowsiness. It is usually abnormal under other circumstances.

Theta – ranges from 4 Hz to less than 8 Hz. It is often present diffusely in children and young adults during wakefulness, whereas in adults it occurs predominantly during drowsiness. Like delta activity, theta activity may occur in the temporal regions in normal elderly adults during wakefulness.

Alpha – ranges from 8 to 13 Hz.

Beta – above 13 Hz. This activity is usually most prominent anteriorly and is often increased during drowsiness and in patients receiving sedating medication, particularly barbiturates or benzodiazepines.

In the analysis of the EEG the following need to be evaluated:

(1) frequency

(2) voltage

(3) location

(4) morphology

(5) polarity

(6) state

(7) reactivity

(8) symmetry

(9) artifact.

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An important feature of the EEG is the frequency of the *alpha rhythm*, also known as the posterior dominant rhythm. During wakefulness, the alpha rhythm is present over posterior regions of the head, maximal with the subject relaxed and eyes closed. It attenuates with eye opening. Its frequency ranges from 8 to 13 Hz in adults and is typically sinusoidal. Some normal individuals do not have an alpha rhythm during wakefulness. By itself, this is not abnormal. There is often an asymmetry of the alpha rhythm with the right side being of higher voltage. A consistent asymmetry of the alpha rhythm of 50% or more (expressed as a percentage of the higher side) is considered abnormal. Since the right is often slightly higher in voltage, an asymmetry of 35–50% may be significant and considered abnormal when the right is the lower amplitude side. Focal slowing of the alpha rhythm unilaterally is rare and a difference of 1 Hz or greater is significant. An asymmetry of reactivity or frequency is a better indicator of a focal abnormality than is a voltage asymmetry.

The *mu rhythm* (7–11 Hz) is present in some normal individuals in wakefulness and drowsiness; it arises from the Rolandic cortex (primary sensorimotor cortex) at rest. It is often asynchronous and asymmetric, and can be unilateral. The mu rhythm attenuates with voluntary movement of the opposite side, such as clenching a fist, or even thinking about moving the opposite side.

A *breach rhythm* is a sharply contoured central or midtemporal pattern, often resembling a mu rhythm, that is seen with a skull defect, including a craniotomy or a burr hole. It can persist following bone replacement. It is composed of normal patterns that appear accentuated in sharpness and often in amplitude; faster frequencies are more 'enhanced' (higher amplitude and sharper appearing) than slower frequencies. It is sometimes misinterpreted as epileptiform.

Low-voltage beta activity is usually present in the normal EEG. Beta activity can show a mild (35%) asymmetry; however, a consistent asymmetry, particularly when associated with other findings, is a sensitive indicator of a cortical abnormality on the lower amplitude side, assuming that there is not an extra-axial collection on that side or a skull defect on the opposite side.

Theta and delta activity are classified as rhythmic (also known as monomorphic) or arrhythmic (polymorphic), intermittent or continuous, and regional (or focal) or generalized. Focal slowing (theta or delta), particularly when persistent and of delta frequency, is often associated with a structural lesion. Arrhythmic slowing is classically seen with lesions affecting white matter, whereas rhythmic slowing is more suggestive of subcortical (gray) dysfunction. Attenuation or loss of faster frequencies suggests cortical dysfunction or a collection between the cortex and the recording electrodes (including extracranial fluid).

Drowsiness: During drowsiness there is a decrease in frequency or persistence of the alpha rhythm, appearance of slow lateral eye movements, decrease in myogenic artifact and increase in beta frequencies.

Sleep is divided into non-REM and REM sleep. Non-REM sleep includes stages I and II and slow wave sleep (delta sleep, formerly stages III and IV).

Activities present during non-REM sleep include:

POSTS: Positive occipital sharp transients of sleep. These occur in light stages (I and II) of non-REM sleep.

Vertex (V) waves: Sharp potential, maximal at the vertex but with a field extending to bilateral fronto-central regions, surface negative, appears at the end of stage I non-REM sleep and persists in deeper sleep.

Sleep spindles: Usually paroxysmal, sinusoidal, low-medium amplitude 12–14 Hz activity lasting about a second and maximal in the vertex and fronto-central regions. Spindles (and K-complexes) mark the beginning of stage II non-REM sleep.

K complexes: High voltage, diphasic slow wave (duration at least 0.5 s) frequently associated with a sleep spindle. They are related to the arousal process, usually maximal at the vertex and can occur spontaneously or in response to sudden sensory stimuli.

Slow wave sleep: This is characterized by delta activity $\leq$2 Hz and $>$75 uV occupying at least 20% of the recording.

REM (rapid eye movement) sleep: The EEG is low voltage and there are rapid eye movements. Saw-toothed waves also occur in central regions.

Sleep spindles and V-waves can be affected by cerebral lesions. A persistent asymmetry in sleep usually indicates an abnormality on the side of the lower voltage. Focal delta activity during sleep may also be present.

Figure list

Figure 1.1 Alpha rhythm and blinks.

Figure 1.2 Alpha rhythm reactivity.

Figure 1.3 Mu rhythm and eye movements.

Figure 1.4 Mu rhythm.

Figure 1.5 Excess beta and active reference.

Figure 1.6 Lambda waves.

Figure 1.7 Slow lateral eye movements of drowsiness.

Figure 1.8 Positive occipital sharp transients of sleep (POSTS).

Figure 1.9 Vertex waves and sleep spindles.

Figure 1.10 K-complexes and POSTS.

Figure 1.11 Rapid eye movement (REM) sleep.

Figure 1.12 Focal slowing.

Suggested reading

American Electroencephalographic Society (1994) Guidelines in EEG, Number 7. *Journal of Clinical Neurophysiology* **11**, 30–36.

Burgess, R.C., Iwasaki, M. and Nair, D. (2006) Localization and field determination in electroencephalography and magnetoencehalography. In: Wyllie, E., Gupta, A. and Lachhwani, D.K. (eds), *The Treatment of Epilepsy. Principles and Practice*, pp. 141–168. Lippincott, Williams and Wilkins, Philadelphia.

Connolly, M.B., Sharbrough, F.W. and Wong, P.K.H. (2003) Electrical fields and recording techniques. In: Ebersole, J.S. and Pedley, T.A. (eds), *Current Practice of Clinical Electroencephalography*, pp. 72–99. Lippincott, Williams and Wilkins, Philadelphia.

Erwin, C.W., Sommerville, E.R. and Radtke, R.A. (1984) A review of electroencephalographic features of normal sleep. *Journal of Clinical Neurophysiology* **1**, 253–274.

Gloor, P. (1971) Recording principles. Volume conductor theory. *Spike and Wave*. **2**, 1–48.

Klem, G.H. (2003) *Artifacts*. In: Ebersole, J.S. and Pedley, T.A. (eds), *Current Practice of Clinical Electroencephalography*, pp. 271–287. Lippincott, Williams and Wilkins, Philadelphia.

Knott, J.R. (1969) Electrode montages revisited: How to tell up from down. *American Journal of EEG Technology* **9**, 33–45.

Kozelka, J.W. and Pedley, T.A. (1990) Beta and mu rhythms. *Journal of Clinical Neurophysiology* **7**, 191–208.

Lesser, R.P., Luders, H., Dinner, D.S. *et al.* (1985) An introduction to the basic concepts of polarity and localization. *Journal of Clinical Neurophysiology* **2**, 45–61.

Markand, O.N. (1990) Alpha rhythms. *Journal of Clinical Neurophysiology* **7**, 163–189.

Niedemeyer, E. (2005) *The normal EEG of the waking adult*. In: Niedermeyer, E. and Lopes de Silva, F. (eds), *Electroencephalography: Basic principles, clinical applications and related fields*, pp. 161–166. Lippincott, Williams and Wilkins, Philadelphia.

Niedemeyer, E. (2005) *Sleep and EEG*. In: Niedermeyer, E. and Lopes de Silva, F. (eds), *Electroencephalography: Basic principles, clinical applications and related fields*, pp. 193–207. Lippincott, Williams and Wilkins, Philadelphia.

Tao, J.X., Baldwin, M., Hawes-Ebersole, S. *et al.* (2007) Cortical substrates of scalp EEG epileptiform discharges. *Journal of Clinical Neurophysiology* **24**, 96–100.

Tatum, W.O. 4th, Husain, A.M., Benbadis, S.R. *et al.* (2006) Normal adult EEG and patterns of uncertain significance. *Journal of Clinical Neurophysiology* **23**, 194–207.

Tyner, F.S., Knott, J.R. and Mayer, W.B. Jr. (1983) *Artifacts*. In: *Fundamentals of EEG Technology*, Volume **1**, pp. 280–311. Raven Press, New York.

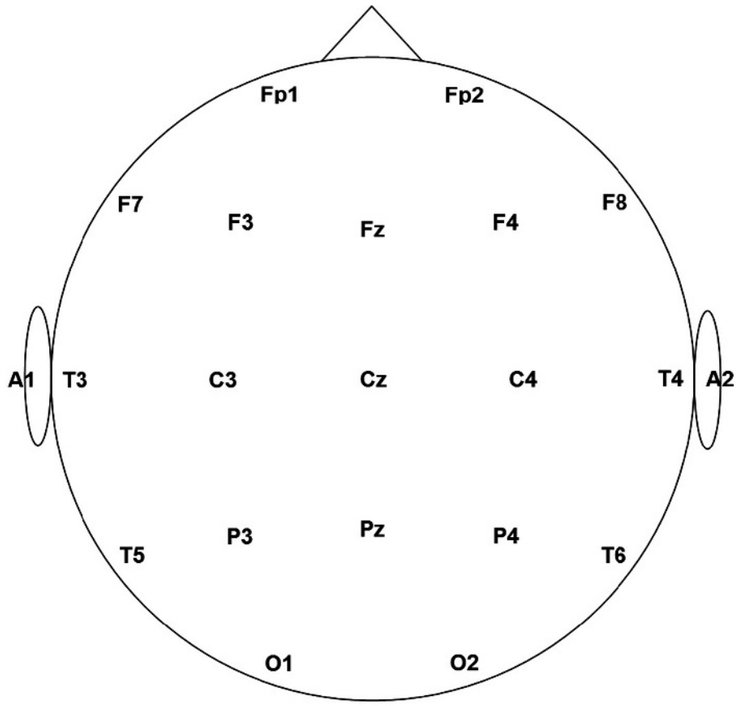

Figure 1.0 International 10–20 system.

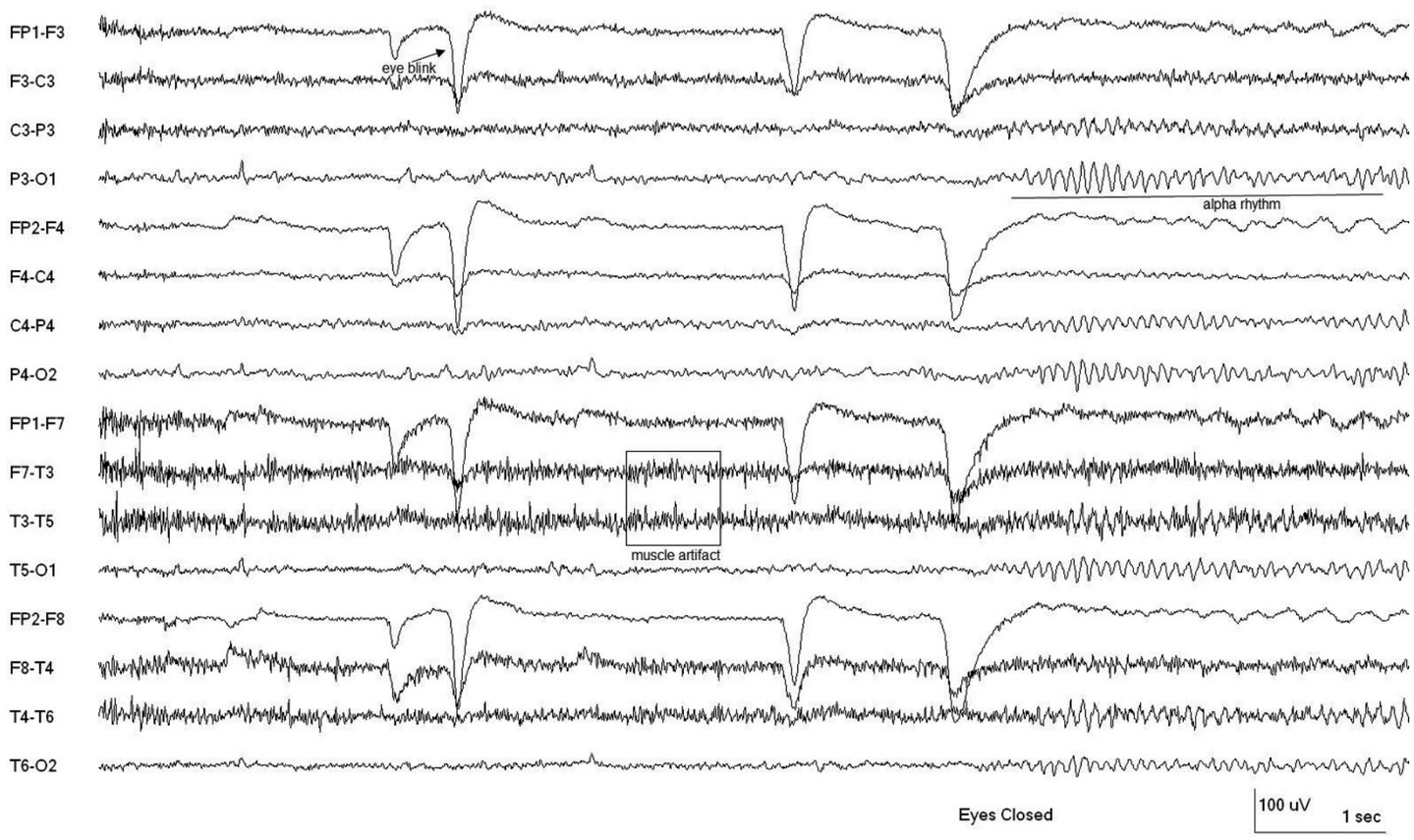

Figure 1.1 Alpha rhythm and blinks. (a) Following eye closure, rhythmic activity of 10 Hz is present posteriorly. This represents a normal alpha rhythm (sometimes referred to as the posterior dominant rhythm). The activity is maximal in O1 and O2 electrodes and seen to a lesser extent in parietal (P3/P4) and posterior temporal (T5/T6) regions.

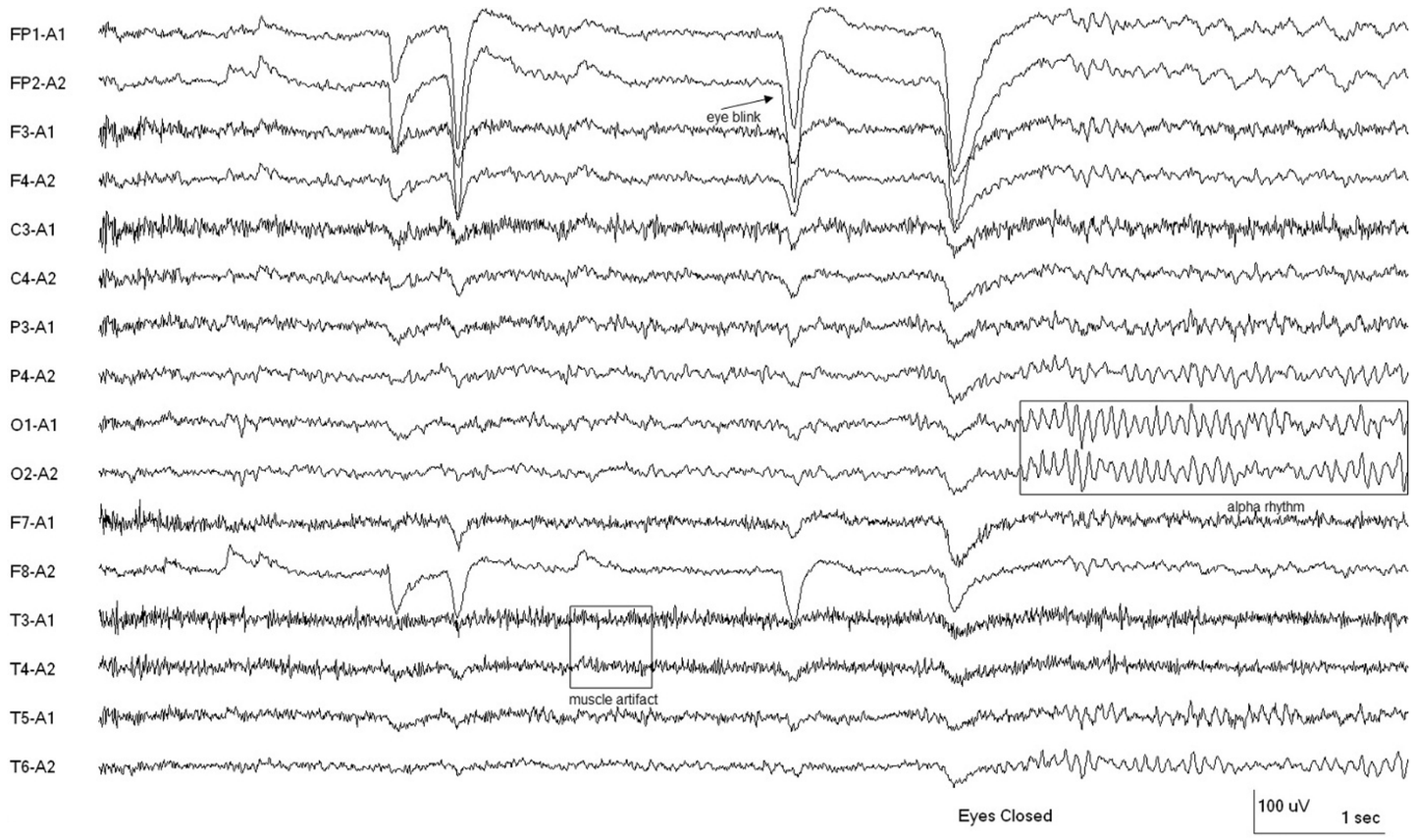

Figure 1.1 (*Continued*) (b) The same epoch in a referential montage, with ipsilateral ear reference. Blinks appear as prominent deflections on the EEG because the eye is a dipole, with the cornea being surface positive and the retina surface negative. During blinks the eyes go upward (Bell's phenomenon). This causes Fp1 and Fp2 electrodes to become relatively positive and there is a downgoing deflection in Fp1 and Fp2 channels. The opposite occurs if there is a downward movement of the eyes. Further monitoring of eye movements, utilizing electrodes inferior to orbits, is demonstrated in Figure 2.5c.

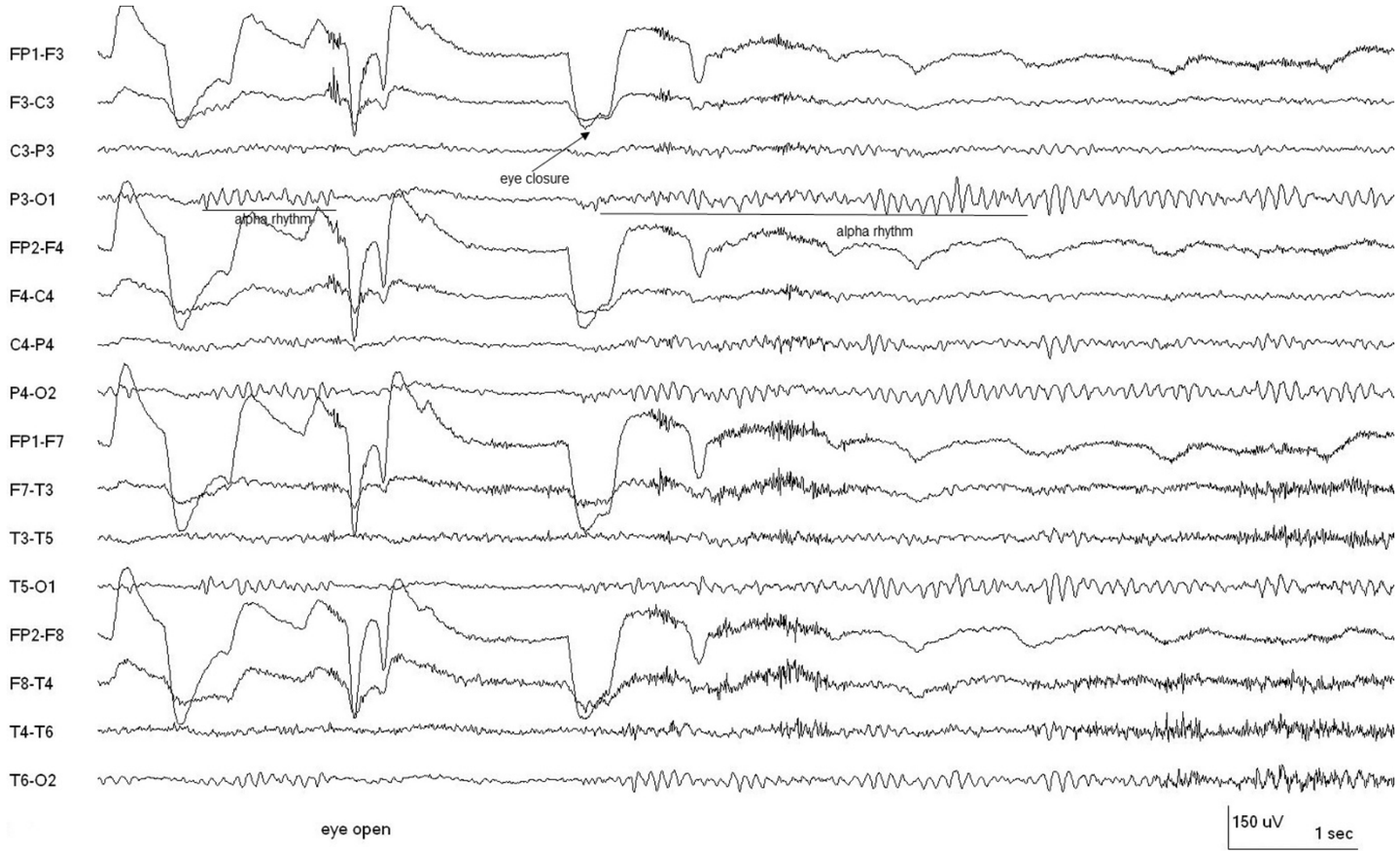

Figure 1.2 Alpha rhythm reactivity. Attenuation of the alpha rhythm following eye opening in a 72-year-old man. The alpha rhythm returns following eye closure, best seen in channels containing O1 and O2.

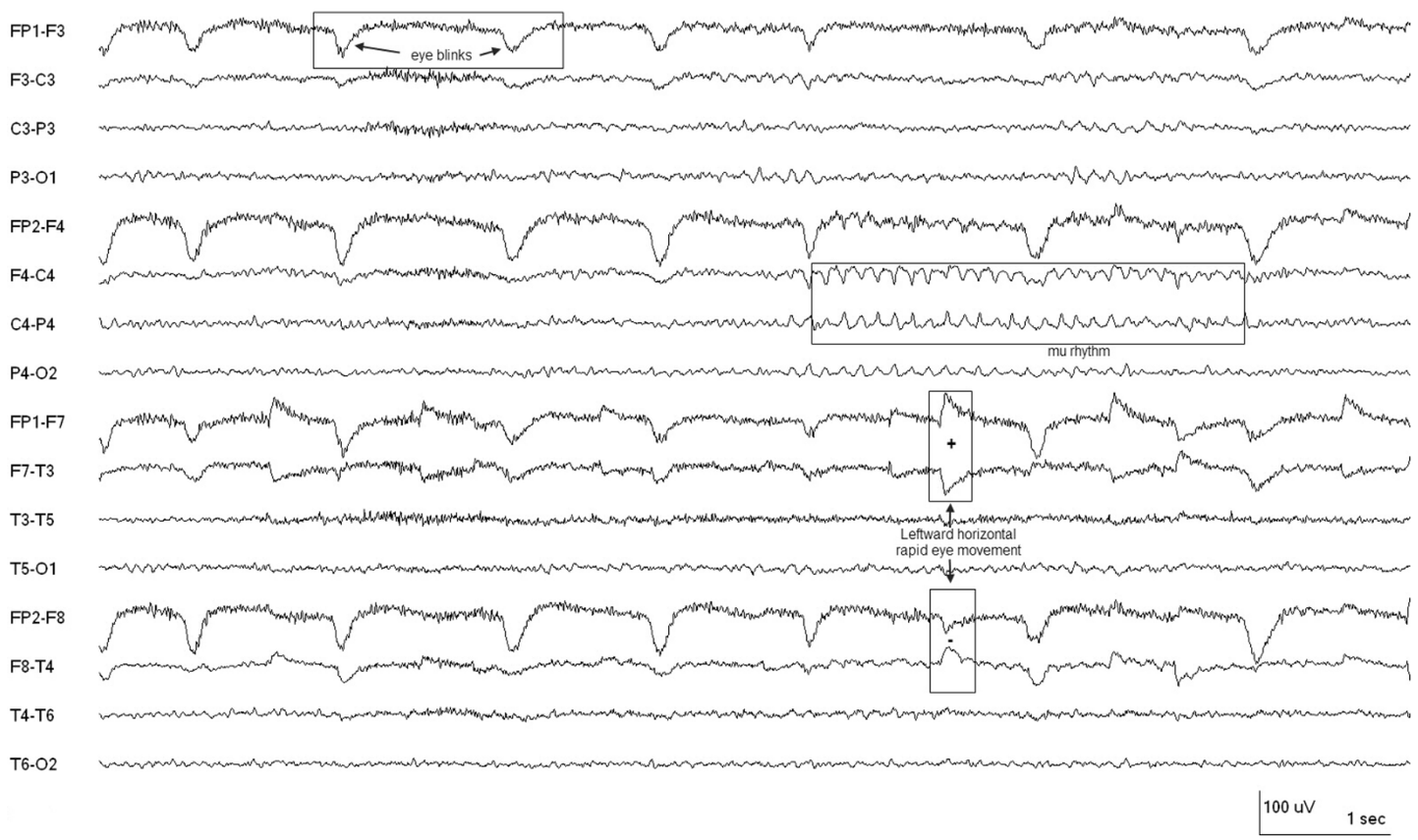

Figure 1.3 Mu rhythm and eye movements. (a) A mu rhythm prominent in the right parasagittal region in a 45-year-old man. The spike-like component is surface negative and maximal at electrode C4, as demonstrated by the phase reversal on this bipolar montage. This morphology, containing a sharp negative component alternating with a blunt positive component, as seen in F4-C4 and C4-P4, resembles the Greek letter mu giving this rhythm its name. There is also a typical leftward horizontal eye movement shown with a positivity at F7 (due to the cornea moving towards F7; deflections moving away from each other on bipolar) and negativity at F8 (deflections moving towards each other on bipolar).

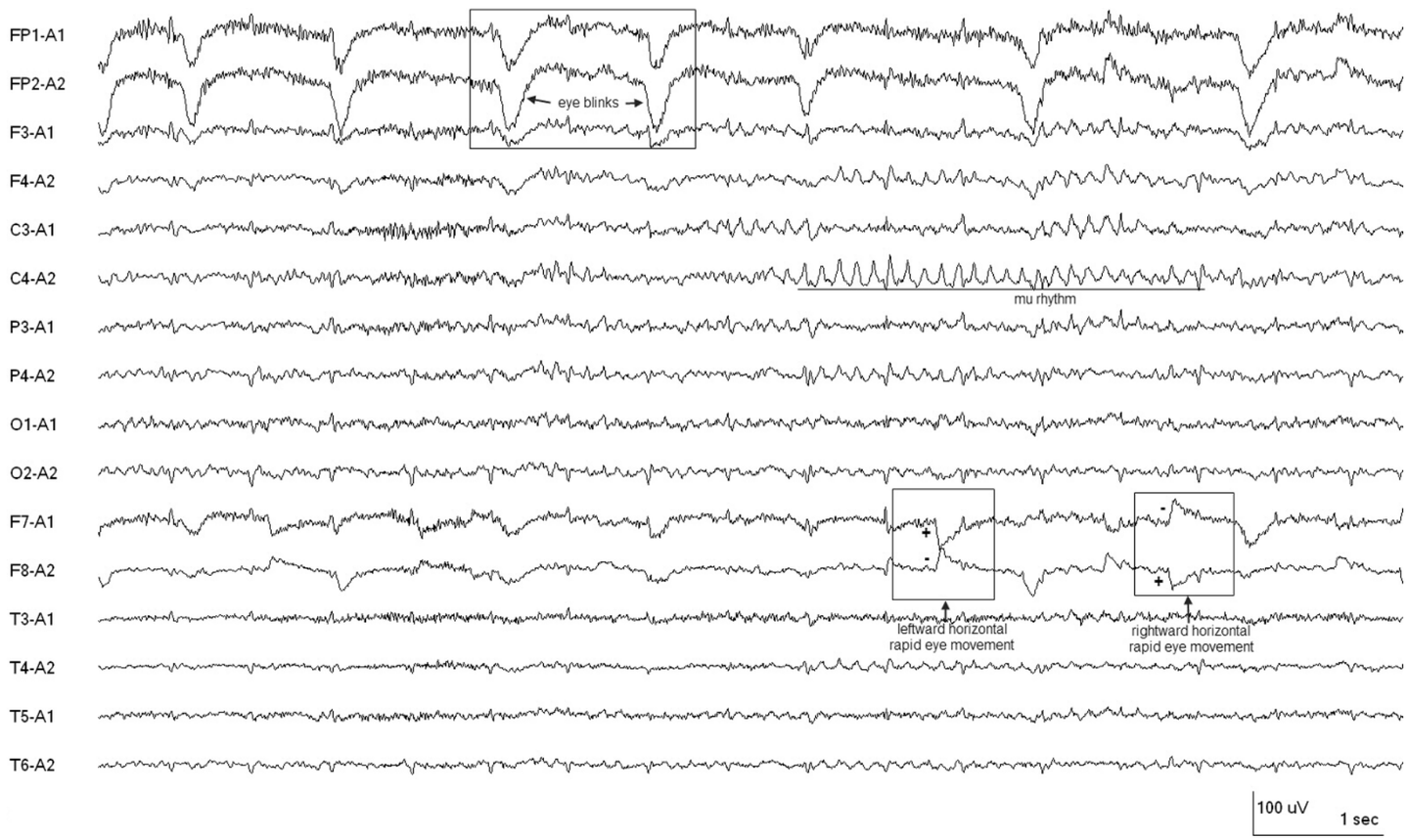

Figure 1.3 (*Continued*) (b) In this reformatted referential montage to ipsilateral ears, the same mu rhythm as seen in Figure 1.4 is best seen in the C4-A2 derivation, confirming that the maximum discharge is at C4 (electrode with the greatest amplitude on a referential recording, assuming an inactive reference). The spike-like component is upgoing indicating that C4 (input 1) is more negative than A2. Leftward (positivity at F7) and rightward (positivity at F8) rapid eye movements are shown as well.