Part I   **Basics**

Chapter

1

Introduction

Electroencephalograms (EEGs) are ubiquitous in clinical neurology. They are used to evaluate transient neurological symptoms such as impaired awareness, altered sensations, or abnormal movements. They form a part of the evaluation of common neurological illness such as epilepsy, stroke, tumors, dementia, encephalopathy, and encephalitis. Their role in critical care medicine is increasingly being recognized. Neuroscience trainees can be sure to encounter them in the office, emergency room, at the bedside, and during various certification examinations. However, the level of comfort among trainees to confidently interpret EEGs is variable. At first, most trainees will be intimidated by their appearance and instinctively limit themselves to reading their reports. Misinterpretations of electrographic waveforms are also common resulting in needless suffering from misdiagnoses and medication misuse [1]. The best way to avoid these situations is to interpret the EEG yourself and understand its implications. Simply put, this book empowers you to do just that!

The aim of this chapter is to introduce the reader to the EEG through the following sections:

1. Basics
2. Indications
3. Limitations
4. Electrodes
5. Placing Electrodes (10–20 System)
6. Instrument
7. Display
8. Parameters
9. Calibration
10. Safety

Basics

History

In 1875, a British physiologist, Richard Caton first recorded "feeble currents of varying direction" through electrodes placed on the cortical surfaces. His work laid the ground work for electroencephalography. Later in 1929, Hans Berger, a German psychiatrist, recorded the first alpha rhythm (Berger waves) inventing the modern electroencephalogram. He was also the first to use it to study neurological disease [2]. In 1935, Gibbs, Davis, and Lennox first demonstrated the 3 Hz spike and wave of idiopathic generalized epilepsy (IGE), the subsequent year Gibbs and Jasper first reported interictal discharges in focal epilepsy [3,4]. The first EEG laboratory opened at Boston's Massachusetts General Hospital in 1936 [5]. Since then, the test has gained widespread use.

Biology

The main generators of electrographic activity are summations of excitatory and inhibitory postsynaptic potentials of pyramidal cells in the superficial layers of the cortex. Synaptic activity, unlike action potentials occurs constantly and is not an all or none response. Therefore, normal cerebral activity is continuous. Neurons are radially oriented in the cortex and generate radially oriented dipoles (opposing or polar charges). The superficial (outer) ends of these dipoles leads to tiny voltage fields on the scalp (potentials). The EEG records and displays the spatial distribution of these potentials and their variations with time [6]. Additional inputs from subcortical structures such as the thalamus and reticular activating system (RAS) synchronize neuronal activity and generate electrographic rhythms [7]. It is believed that at least 6–10 square centimeters of cortex (sizable area) is required to produce a waveform over the scalp. Therefore, smaller potentials or foci may be missed on scalp recordings [8].

Physics

Cortical neuronal activity generates scalp potentials. These potentials may be imagined to resemble mountain peaks. They are maximum at their focus and loose strength as distance from the source increases. Voltage is the difference in strength between two potentials (measured in microvolts or uV) and current is the flow of charge (electrons) between them (measured in milliamperes or mA). Like a river, current will flow from a region of higher potential (taller peak) to a region of lower potential (smaller peak). Resistance (measured in ohms) is the impediment encountered by the current during its flow. The relationship between voltage (V), current (I), and resistance (R) is governed by the equation $V = IR$ (Ohm's law) and forms the basic physical principle of recording EEGs.

The EEG machine measures and amplifies the strength and direction of the current between two electrodes (over two different potentials) and displays this as a waveform. The reader can interpret these waveforms to determine their location and significance when the recordings from pairs of electrodes (channels) are viewed on a display in standardized formations (montages) [9].

Indications

The EEG is inexpensive, readily available, painless, and noninvasive. Hence it is used in a wide variety of clinical settings. Furthermore, it has incredible temporal resolution. This means it changes almost instantly (milliseconds) with changes in cerebral activity. This is far superior than the very best scans which may take (at least) several minutes to show physiological changes.

For the reader's benefit, a few common indications are listed below.

Clinic

- Evaluate transient neurological spells or symptoms for potential seizures.
- Identify the risk of recurrence (epilepsy) after a first-time seizure.
- Define the type of epilepsy or syndrome.
- Investigate cognitive decline.

Wards (or Epilepsy Monitoring Unit)

- Capture and characterize neurological events.
- Potentially rule in or rule out epilepsy.
- Quantify and localize seizures.
- Guide epilepsy treatments including medication adjustments and surgery.
- Characterize sleep–wake states (sleep studies).

Emergency Room and Intensive Care Unit

- Diagnose and manage status epilepticus.
- Diagnose and differentiate encephalopathic states.
- Guide the titration of anesthesia and sedation.

Operating Room

- Intraoperative guidance in several neurosurgical and vascular procedures (such as carotid endarterectomy) [10].

Limitations

Despite all its advantages, the EEG has important technical and practical limitations.

Technical

Despite the best techniques (and intentions), recording cerebral activity from the scalp has limited spatial resolution. Each electrode samples a vast area of cortex, therefore it is not possible to precisely pinpoint the origin of cerebral waveforms but only estimate the general region. Furthermore, the dampening effect of thick skull bones makes scalp potentials very small (microvolts). They need to be amplified many hundreds of times over for display. Large amplifications may also result in heavy contamination from ambient electrical noise (60 Hz) and other types of artifact. Another issue is that the EEG in principle assumes the cortical surface as a smooth sphere but, the cortex is deeply in folded. Only about a third of the cortex (superficial gyri) is accessible for scalp recordings. Cortical potentials that are deep (sulcal), inferior (basal), or hidden (insular or mesial) have poor scalp signals [11].

Practical

The reader must understand that the EEG is a snap shot in time. Like a photograph of the ocean, it reflects the surf only at that point in time. It cannot predict future storms or calm seas. When seen, epileptiform abnormalities (discharges) may be associated with epilepsy, but they are not diagnostic of it. However, epileptiform abnormalities are more specific (about 95%) than sensitive (about 30%) for epilepsy. A small percentage of healthy adults (less than 1%) and a slightly higher percentage of healthy children (less than 4%) will have epileptiform abnormalities [12]. Less than a third of those with focal brain lesions will also have epileptiform abnormalities in the absence of clinical seizures [13]. Conversely, less than half of those with epilepsy have epileptiform abnormalities on a single scalp EEG. This yield is maximal within the first 24 hours or so after a seizure and decreases thereafter. The yield also improves with repeat studies, but it is never absolute. Also, the number of discharges correlates weakly with severity of the epilepsy or seizure focus [14]. Then there is the experience and skill of the reader themselves for which there is no substitute. Most readers will have some neuroscience background, but this is variable. Sleep – whether natural or after sleep deprivation increases an EEGs yield and every effort should be made to include it. So do activation procedures such as photic stimulation and hyperventilation. Increasing the duration of the recording with ambulatory EEG or long-term monitoring will further improve the sensitivity and specificity of the EEG. Recording a patient's seizures on long-term video EEG is considered the gold standard for confirmation of epilepsy [15,16].

Electrodes

Scalp electrodes are small cup shaped disks made of silver, gold or plastic coated with silver chloride. They have a flat rim with a 1 cm diameter and small hole in the central dome for electroconductive gel. This design allows the electrodes to fix on
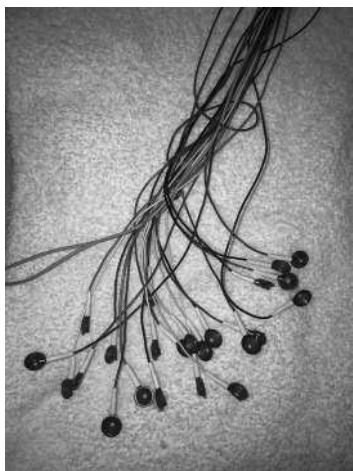
Figure 1.1 Scalp electrodes.

the scalp and effortlessly conduct electrical signals to the EEG machine. The electrode impedance (resistance to the flow of alternating current) must be less than 5 kohms. Higher impedances result in bad recordings. After carefully cleaning the scalp, electrodes are affixed with the help of small strips of gauze soaked in collodion or using electroconductive paste. If used, collodion is air-dried to form secure connections. Unprepared oily scalps result in higher impedance that distort the cerebral waveforms while sweat or gel bridges between electrodes result in lower impedances (short circuits) leading to artifact [17]. Figure 1.1 shows scalp electrodes.

Placing Electrodes (10–20 System)

Scalp electrodes must be placed on the scalp in a standardized fashion so that EEG recordings do not differ between laboratories. To achieve this, the "International 10–20 System of Electrode Placement" was developed by Dr. Herbert Jasper at the Montreal Neurological Institute in the 1950s and is accepted the world over with a few modifications [18].

According to this system, electrodes are placed on the scalp based on 10% or 20% increments of circumference measurements using easily identifiable skull landmarks. These are the nasion (top of the nose), inion (occiput), tragus, pinna, and mastoids. Each electrode position is described with a letter and a number. The letter indicates the underlying region the electrode records from (not exactly the lobe) such as prefrontal (Fp), frontal (F), temporal (T), parietal (P), occipital (O), and central (C). The number assigns its distance and position (right or left) of the midline (Z). Odd numbers overlie the left hemisphere and even numbers overlie the right hemisphere. A1 and A2 denote the left and right ear lobes (or mastoids). Figure 1.2 shows the typical 10–20 system arrangement.

1. The technician will first measure the longitudinal circumference of the head in the sagittal plane from nasion through the vertex (uppermost point of the head) to inion and this distance is considered 100%. Five points are marked along this line as follows – **Fpz** (10% from nasion), **Fz** (20% from Fp), **Cz** (20% from Fz), **Pz** (20% from Cz), and **Oz** (20% from Pz and 10% from inion) as shown in Figure 1.3.
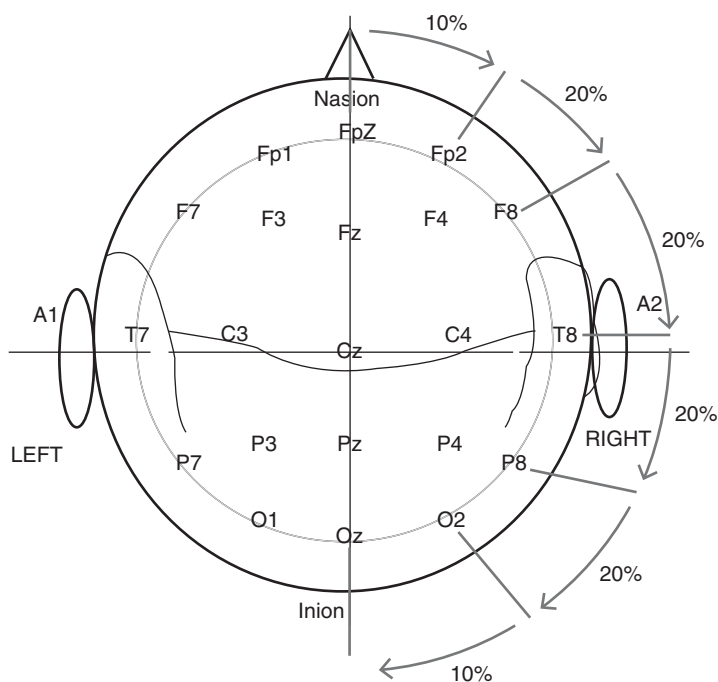
Figure 1.2 Electrode positions per the modified 10–20 system when viewed from the top of the head (not to scale).

2. Next, the transverse circumference is measured in the coronal plane from left to right preauricular points (root of the zygoma) through the vertex and this distance is considered a 100%. Seven points are marked along this line as follows – **A1** (Left preauricular point), **T7** (10% from left preauricular point), **C3** (20% from T7), **Cz** (20% from C3), **C4** (20% from Cz), **T8** (20% from C4), and **A2** (10% from T8 and at right preauricular point).

3. Then, a lateral circumference is measured from Fpz (anteriorly) to Oz (posteriorly), this passes through T7 on the left and T8 on the right. Points are marked (left/right) starting **Fp1/2** (10% from Fpz), **F7/8** (20% from Fp1/2), **T7/8** (20% from F7/8), **P7/8** (20% from T7/8), and **O1/2** (20% from P7/8 and 10% from Oz).

4. Finally, another parasagittal circumference is marked from Fp1 to O1 (through C3, left) and Fp2 to O2 (through C4, right) and considered 80% of the distance from Fpz to Oz. Three points are marked at 25% along this line as follows: **F3/4**, **C3/4**, and **P3/4**.
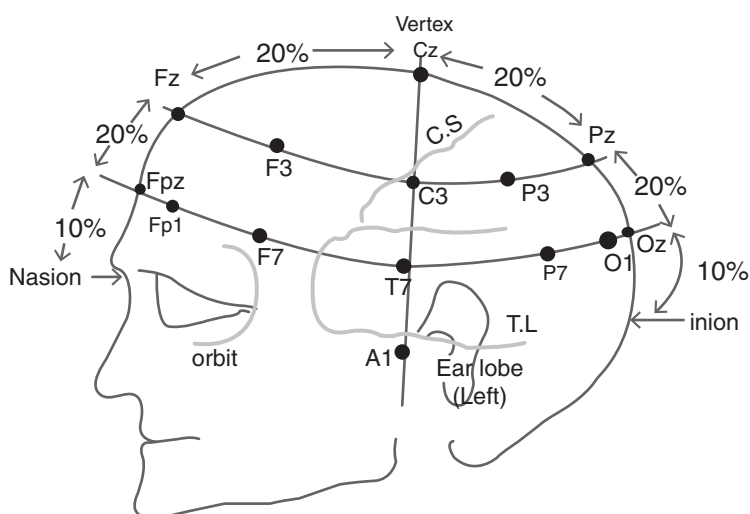
Figure 1.3 Electrode positions per the modified 10–20 system when viewed from the left side of the head (not to scale).

The system described here (modified combinatorial nomenclature) is an adaptation of the original 10–20 system as it renames four electrodes (T3 is T7, T4 is T8, T5 is P7, and T6 is P8) [19]. This conforms with the American Clinical Neurophysiology Society (ACNS) guidelines and is used in most EEGs in this book [20]. Some less commonly used placements include sphenoidal and nasopharyngeal electrodes. Sphenoidal electrodes are thin wires inserted through a needle placed between the zygoma and mandibular notch. They penetrate to a depth of 3 cm and may provide better resolution of anterior and mesial temporal structures [21]. Nasopharyngeal electrodes are placed through the nares into the posterior pharynx [22]. These placements are not routinely used as they are invasive and uncomfortable with debatable benefits.

Instrument

The EEG system amplifies and processes electrical signals recorded by pairs of scalp electrodes and displays these as waveforms on a digital screen. At its core are combinations of amplifiers called differential amplifiers. These additionally serve to reduce noise artifact between electrode pairs through common mode rejection by which the same

artifact potential at both electrodes in each electrode pair will get cancelled out. However, for common mode rejection to work both electrodes in each electrode pair should be equally matched. If one of them is poorly fixed (high impedance) there is artifact in that channel. Scalp electrode impedances should be low for onward flow of current into the EEG system. Scalp electrode impedances should not exceed 5 kohms and impedance checks should be performed before each recording. Gain refers to the factor by which the signal is amplified and is measured in decibels (dB). Typically, a scalp signal needs to be amplified 1,000–100,000 times over (60–100 dB of voltage gain). Digital display systems will sample the amplified signal for storage and display. The sampling frequency refers to the number and density of data points sampled in time. Cerebral waveforms typically occur within 0.5 to 30 Hz frequency range so most digital displays will use a sampling frequency of 100 to 500 Hz to display representative waveforms [23]. A typical EEG set up consists of electrodes which must be applied to the patient's scalp. Each electrode has a wire connecting it to a headbox. The headbox is attached to a computer with a digital display screen using a thick cable. Figure 1.4 shows the parts of a typical EEG set up.
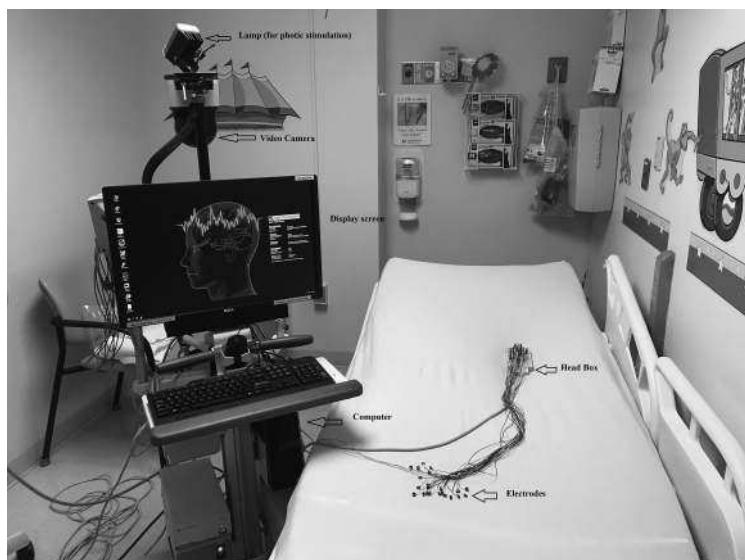

Figure 1.4 Typical EEG setup with electrodes, head box, computer, and digital display.

Display

There are a number of commercially available EEG systems. Readers must familiarize themselves with the individual nuances of the system used in their laboratory. For most displays, the top bar contains the recording parameters, montage, and other settings that can be easily changed per the reader's preference. A technologist's log may be pulled up to the right of the display. Most systems will show 10–15 s per page. Each major division (thicker lines) is 1 s within which there are five subdivisions (thinner lines) of 200 ms each. The EEG records in this book run at 15 s per page unless otherwise specified.

The appearance of the EEG will depend on its "montage." Most readers will default to the longitudinal bipolar montage (double banana) to begin their review. Most EEGs in this book are also shown in this montage. Figure 1.5 shows a typical display in the longitudinal bipolar montage.

The top four channels (each a pair of electrodes) are Fp1-F7, F7-T7, T7-P7, P7-O1. These record the patient's left temporal region in anterior to posterior direction (i.e., Fp1 is the anterior most electrode, and O1 is the posterior most in this chain).

The next four channels are Fp2-F8, F8-T8, T8-P8, P8-O2. These record the right temporal region in anterior to posterior direction. Placing these two sets in a staggered fashion allows the reader to easily compare both temporal activities.

Similarly, the following two sets compare the left paracentral Fp1-F3, F3-C3, C3-P3, P3-O1 and right paracentral Fp2-F4, F4-C4, C4-P4, P4-O2 regions. The bottom last two channels – Fz-Cz and Cz-Pz record over the midline. The final channel represents the electrocardiogram [EKG]. Other montages are described later in Chapter 3.
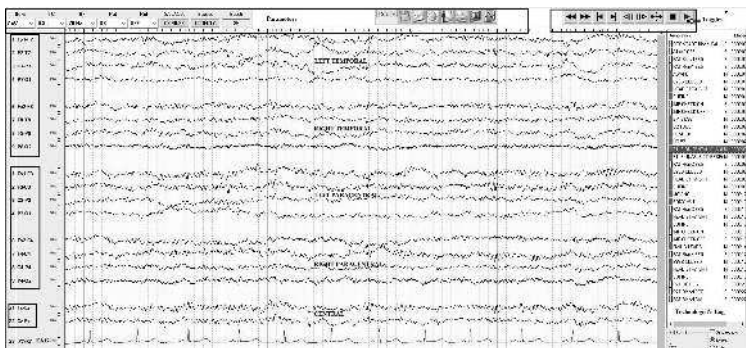

Figure 1.5 Typical appearance of an EEG display in longitudinal bipolar or double banana (DB) montage. Our laboratory uses a version of the Nihon Koden Workbench. Displays will vary depending on commercially available software in use.

Parameters

Sensitivity

The sensitivity (uV/mm) determines the magnification or size of the waveforms displayed. The reader can determine the strength of the potential (uV) as the product of its height (mm) and sensitivity (uV/mm). Readers will prefer a sensitivity of 7 uV/mm for most records. Low-voltage records may require a higher sensitivity. A maximum sensitivity of 2 uV/mm may be used to detect very low-voltage cerebral activity during brain death determinations. Lower sensitivities (such as 15 uV/mm) may be useful when reviewing higher amplitude waveforms such as spike waves to better appreciate their morphology.

Filters

The display allows filters to be applied to the signal. Clinically relevant cerebral activity lies between 0.5 to 50 Hz. Activity outside of this range (below or above) are potentially noise and may need to be filtered out to appreciate the underlying waveforms. At a filter cutoff frequency, at least 30% of that frequency is attenuated by filtration and the amount of attenuation exponentially increases above or below that frequency depending on the filter type. The time constant (t) is reciprocally related to the filter cutoff frequency. The reader should be familiar with three commonly used filters.

Low-Frequency Filter, LFF (High Pass): This filters out frequencies lower than the cutoff frequency allowing higher frequencies to pass. Standard LFF setting is 1 Hz (t 0.16 s). Low-frequency filters are useful in removing low-frequency contaminants such as pulsations, movements, and temperature related artifacts while preserving low-frequency detail such as slowing.

High-Frequency Filter, HFF (Low Pass): This filters out frequencies higher than the cutoff frequency allowing lower frequencies to pass. Standard HFF setting is 70 Hz. High-frequency filters are useful in removing high-frequency contaminants such as myogenic artifact while preserving high-frequency detail such as sharpness.

Notch filter is designed to specifically remove 60 Hz electrical noise.

Paper Speed

Most displays have their paper speed at 30 mm/s. Fast speeds (such as 60 mm/s) are useful to review high-frequency waveforms as they space out the closely packed activity while slower speeds (15 mm/s) may be useful for slow frequencies [24].