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The Normal EEG in an Adult

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Summary

When an experienced electroencephalographer sits down to review an EEG, whether obtained on a pen/ink-based analog machine or from the cathode ray tube screen of a digital device, a number of mental integrations take place seamlessly. This chapter addresses the "normal" EEG observed in people older than 18 yr of age. Topics to be covered include the normal waking background rhythm (alpha rhythm); beta activity; mu, theta, and lambda waves; activation effects on the EEG; and features of normal sleep.

Key Words: Awake and sleep EEG; normal EEG; routine EEG.

1. INTRODUCTION

When an experienced electroencephalographer sits down to review an EEG, whether obtained on a pen/ink-based analog machine or off of a cathode ray tube screen from a digital device, a number of mental integrations take place seamlessly. This chapter examines the "normal" EEG observed in people older than 18 yr of age.

2. RECORDING PRINCIPALS

EEG recording electrodes are glued onto the scalp in an orderly fashion according to an agreed on measured placement, referred to as either the International 10-20 or 10-10 system *(1)*. The electrodes are plugged into a head-box, which allows the technician to record in either a bipolar or a referential fashion. The former is a system in which adjacent electrodes are connected to a differential amplifier. The latter is a system in which each electrode is connected to a differential amplifier and compared with a common electrode. The differential amplifier has two inputs (G1 and G2), and amplifies the difference in voltage at the two input sites. The output is then charted onto a graph in the case of an analog-based EEG machine, so that the difference in voltage is graphed against time. In the case of a computer-based system, the inputs are digitized and the amplifier registers the voltage differences and stores it as a digital signal for display on a cathode ray tube. In either case, the viewed information is essentially the same.

There are certain basic rules that are followed by the technician to ensure high quality and reproducible results. There are strict guidelines related to the placement of the electrodes so that the same electrodes end up in the same spots, regardless of which technician applies them. The electrodes need to be tested for impedance and maintained below 5000 Ω. The electrodes, when recording in a bipolar montage, are connected in straight lines going from

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front to back and from left to right. Displays of the output tend to follow similar rules, and the left side of the head is usually displayed above the right side.

There is also a polarity convention that all manufacturers of EEG equipment follow. Originally, when all of the device outputs were graphic pens, the convention was that if the G1 input was more negative than the G2 input, the pen deflection was upward. It follows that either a negative event at G1 or a positive event at G2 would have led to an upward deflection. A positive event at G1 or a negative event at G2 leads to a downward deflection. These rules still apply to digital recording devices, but there are obviously no pen deflections, simply movement of the signal off of the baseline. By connecting electrodes in linear arrays, one can graph fields and electrical polarity of given potentials over time *(2)*.

3. THE AWAKE AND RESTING STATE

After the electrodes are attached, the montage selected and the machine calibrated, the technician is ready to record. Recordings are done for between 20 min (minimum) and several hours in selected circumstances. The patient is recorded initially in the awake resting state, with eyes open, and recorded again with eyes closed. Unless there is a specific reason to the contrary, part of the recording session should be performed with the patient hyperventilating and receiving intermittent photic stimulation. The patient may also be allowed to fall asleep and, therefore, EEG can be recorded during sleep induction and sequencing into the various stages of sleep.

4. THE ALPHA RHYTHM

When electroencephalographers sit down to review a normal study, they are usually drawn first to the prominent background alpha rhythm. As with all repeating rhythms, it is most important to note the frequency and the location of the activity, its amplitude, and its reactivity. The alpha rhythm oscillation is between 8 and 13 Hz and is most prominent over the more posterior aspects of the head. Its amplitude or voltage in a bipolar (P4–O2) derivation is anywhere from 15 to 65 µV. This is reactive or responsive to mental activity and to eye opening or closure. The rhythm is partially or completely blocked by mental activity or by eye opening *(3)*. Likewise, it is enhanced by relaxation and by eye closure (Fig. 1).

For healthy adults, there is a bell-shaped distribution curve for the alpha frequency, centering around 10.0 Hz. The frequency is significantly affected by cerebral blood flow and may vary by up to 2 Hz in any individual, based on flow changes. It normally does not vary by more than 1 Hz during the course of the record and shows very little change during long time spans. Although it has been reported that the alpha rhythm may slow by 1 Hz every 10 yr after the age of 50 yr, in more recent studies that controlled for subtle disease states, such changes did not appear. In a few healthy subjects (<2%), no apparent alpha rhythm can be seen. In a few more subjects (<7%), a very low-voltage alpha rhythm is observed. Because recordings are bipolar, one can improve on alpha detections by increasing the inter-electrode distances. When this is done, the finding of an absent alpha rhythm is actually quite low. The frequency may also vary slightly in relationship to the menstrual cycle, where it is faster by up to 0.3 Hz during the follicular phase. This variation is probably below the level that can be visually recognized.

The alpha rhythm is most prominent over the posterior aspects of the head. In some individuals, it is overwhelmingly occipital in its distribution. In approximately one-third of healthy adults, the alpha rhythm is widely distributed and incorporates parietal and posterior temporal regions.

Fig. 1. This recording shows the presence of a normal alpha rhythm present over the posterior head regions. Note how the alpha rhythm attenuates just before a spontaneous eye opening marked by the eye movement artifact noted over the frontal electrodes, approximately midway through the recording.

There may be a side-to-side amplitude asymmetry, noted in approx 60% of people, in which the right side tends to be of slightly higher amplitude. The left side may be more predominant in left handed individuals. The difference in amplitude between the two hemispheres is not more than 50%. If it is more than that, it is almost always related to an identifiable abnormality. The skull can act as an amplitude attenuator and, therefore, as one ages and as one's skull thickens, the amplitude of the alpha rhythm tends to diminish.

The state of the eyes is important to the alpha rhythm. The alpha rhythm is the rhythm of the awake, resting, eyes-closed individual. In most people, the alpha rhythm will be blocked or significantly attenuated when the eyes are open (Fig. 1). Similarly, mental effort, such as doing simple math, likewise blocks alpha rhythm in approximately three-fourths of healthy subjects.

5. BETA ACTIVITY

Beta activity (>13 Hz) is defined by three relatively distinct frequency bands: 18 to 25 Hz activity, which is the most frequently encountered; 14 to 17 Hz activity, which is less common; and the still rarer, greater than 25 Hz activity. The first two frequencies are seen commonly over the frontal regions and become more prominent as the subject gets drowsy. These two beta rhythms are usually of low voltage (<25 μV). It can be markedly increased by the use of some drugs, most notably the benzodiazepines and barbiturates. However, in those circumstances, it is felt that the rhythm is a provoked cortical rhythm and not a normal one. A good review of beta activity is in the textbook on EEG by Niedermeyer *(4)*.

6. MU RHYTHM

The mu rhythm is a centrally located rhythm with a frequency of 8 to 10 Hz. It is thought to be the resting rhythm of the pre- and post-Rolandic cortex. It is more commonly noted in the younger adult population, in whom it is detected in up to 20% of people younger than 30 yr of age. The likelihood of finding it decreases with increasing age. It is reactive to motor programming. It is seen during times of relaxation and can be affected by the state of the eyes. When seen, the technician often asks the patient to make a fist contralateral to the side in which the rhythm has been observed. This movement or even the thought of this movement blocks the rhythm. The mu rhythm may appear quite asymmetrically, although that is not of any pathological significance, except for the possibility that there may a skull defect on the side of this rhythm (breach effect) (Fig. 2).

7. THETA RHYTHM

Theta activity is defined as activity between 4 and 7 Hz. Although theta activity is often a sign of disease or of sleep onset, it may also be seen as part of a normal awake EEG. Although some intermittent low-voltage theta activity is seen over the frontal–central regions in healthy people while resting and awake, this is usually not a well-developed nor regular rhythm. Under a circumstance in which the subject is performing some moderately difficult mental task, such as spelling or mathematics, one can occasionally see a well-developed theta rhythm in the frontal midline region *(3)*. A small amount of left temporal theta activity during wakefulness is also expected as a normal factor in aging, starting around the age of 50 yr *(3)*.

8. LAMBDA WAVE

Occasionally, ones sees occipital positive sharp slow waves in the record of a patient who is lying quietly in bed awake. These waves may be quite asymmetric and raise the possibility

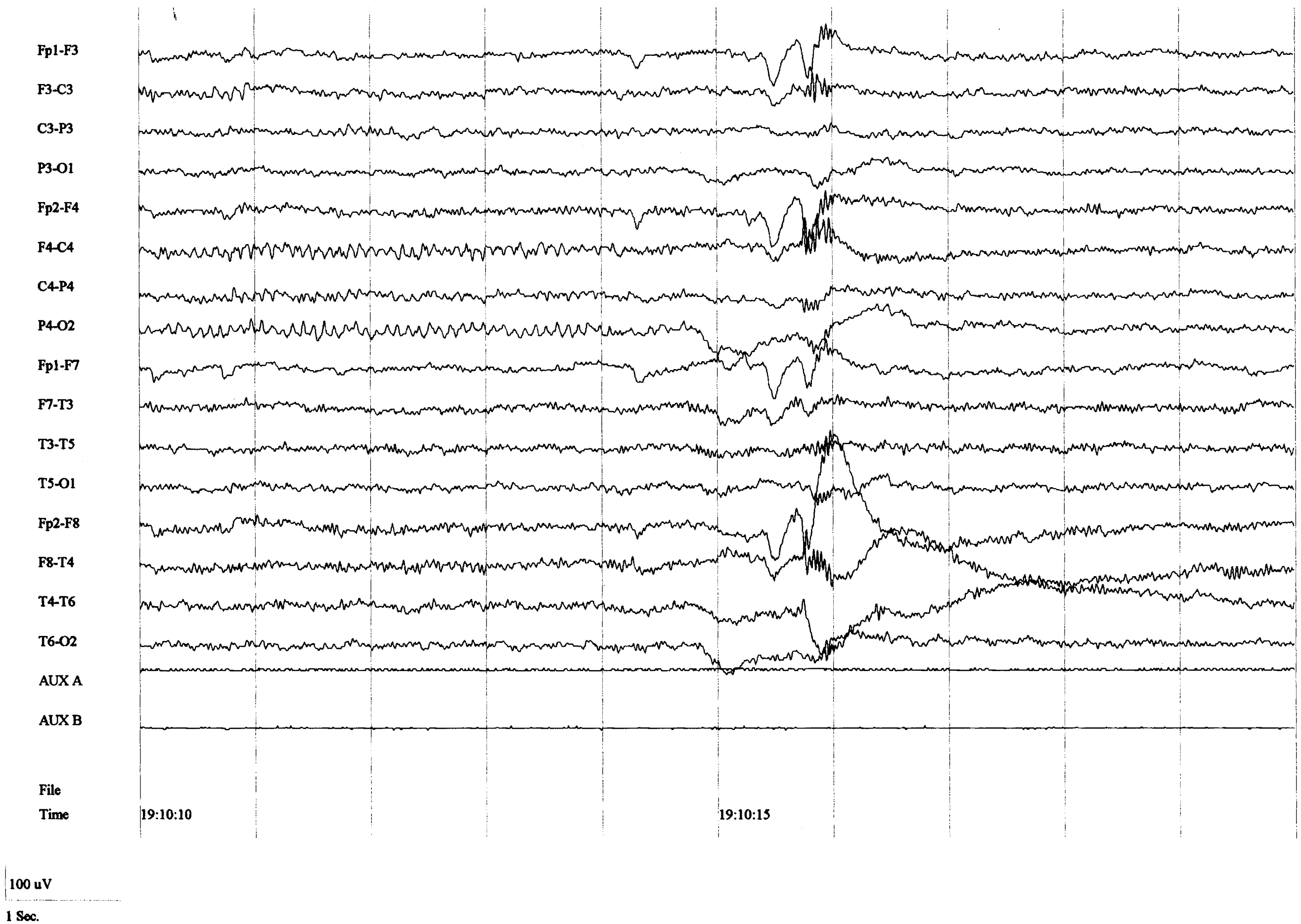

Fig. 2. This tracing shows the presence of a sharp-appearing 11-Hz rhythm present over the right central region that abruptly stops associated with an eye movement. This rhythm also blocks with movement of the right hand and is classic for the mu rhythm.

of a focal abnormality. The normal lambda wave is identified by doing a few simple maneuvers. The wave is felt to represent occipital lobe activity in a person who is actively reading or scanning the room. Often the subjects have their eyes open and are looking carefully at the ceiling tiles. The technician will have the patient reproduce the maneuver that they felt caused the waves to appear in the first place. They will then have the patient close their eyes, which will block the normal lambda wave but usually not have an effect on the abnormal activity. They will then have them open their eyes and look at a plain piece of paper, which also blocks the normal lambda wave but will not effect the epileptiform discharges, which are most often mistaken for a lambda wave *(3)*.

9. RESPONSE TO HYPERVENTILATION

Hyperventilation is a method of "activating" the EEG. It may bring out focal or generalized slowing in cases of structural disease or of more diffuse encephalopathic disorders. It also can bring out interictal epileptic discharges or trigger more overt symptomatic seizures. It should not be performed in the very elderly patient or in someone suspected of having any intracranial mass lesions or a recent transient ischemic event/stroke. In the adult population, it is normal to hyperventilate the patient for 3 to 5 min. The technician usually tries to, at minimum, double the base breathing rate, and to have the subject exhale more deeply than usual. This act causes the subject to exhale excessive amounts of CO_2 and become hypocapnic. The hypocapnia causes mild cerebral vessel vasoconstriction and, hence, mild cerebral hypoxia. The hypoxia and the hypocapnia together potentially can produce changes that may signal a disorder. One additional variable that must be considered is the blood glucose level at the time of this test. If the response is one of significant generalized slow wave activity, the technician often will give the patient a glass of orange juice and wait 10 to 15 min and repeat the exercise. If the slowing is still present, it takes on significance as a potential abnormality. The normal response in a healthy adult is to have no slow wave or epileptiform activity brought out by this maneuver. It is normal to sometimes see a patient exhibit greater alpha activity as a result of hyperventilating than they had otherwise shown.

10. RESPONSE TO INTERMITTENT PHOTIC STIMULATION

Similar to hyperventilation, intermittent photic stimulation is performed to "activate" the EEG. Photic stimulation is performed by using a commercial stroboscopic stimulator placed approx 1 m from the patient's eyes. They are asked to keep their eyes closed and look straight ahead while the ambient room lighting is turned down. The test is performed by alternating flashes varying from 1 to 35 Hz and lasting for 10 s and interrupted by 10 to 30 s with no stimulation. The variables that need to be controlled for are the distance from the subject to the strobe, the luminance of the strobe, direction of gaze, and level of consciousness. The most common abnormal activation is to produce epileptic activity in relationship to the photic stimulation. In healthy people, one may see any level of "driving." This phenomena appears in the occipital leads and is the result of a "flash" visual evoked response. Therefore, the background rhythm gets linked to the timing of the photic stimulator (Fig. 3). The first response appears shortly after the stimulator goes on (<100 ms) and stops when the stimulator shuts off. It is more likely to occur around the baseline background frequency (±2–4 Hz). One may also *see* what is referred to as a photomyogenic response as a normal variant. In this condition, widespread muscle twitching appears, which is timed to the stimulator. This reaction is felt to

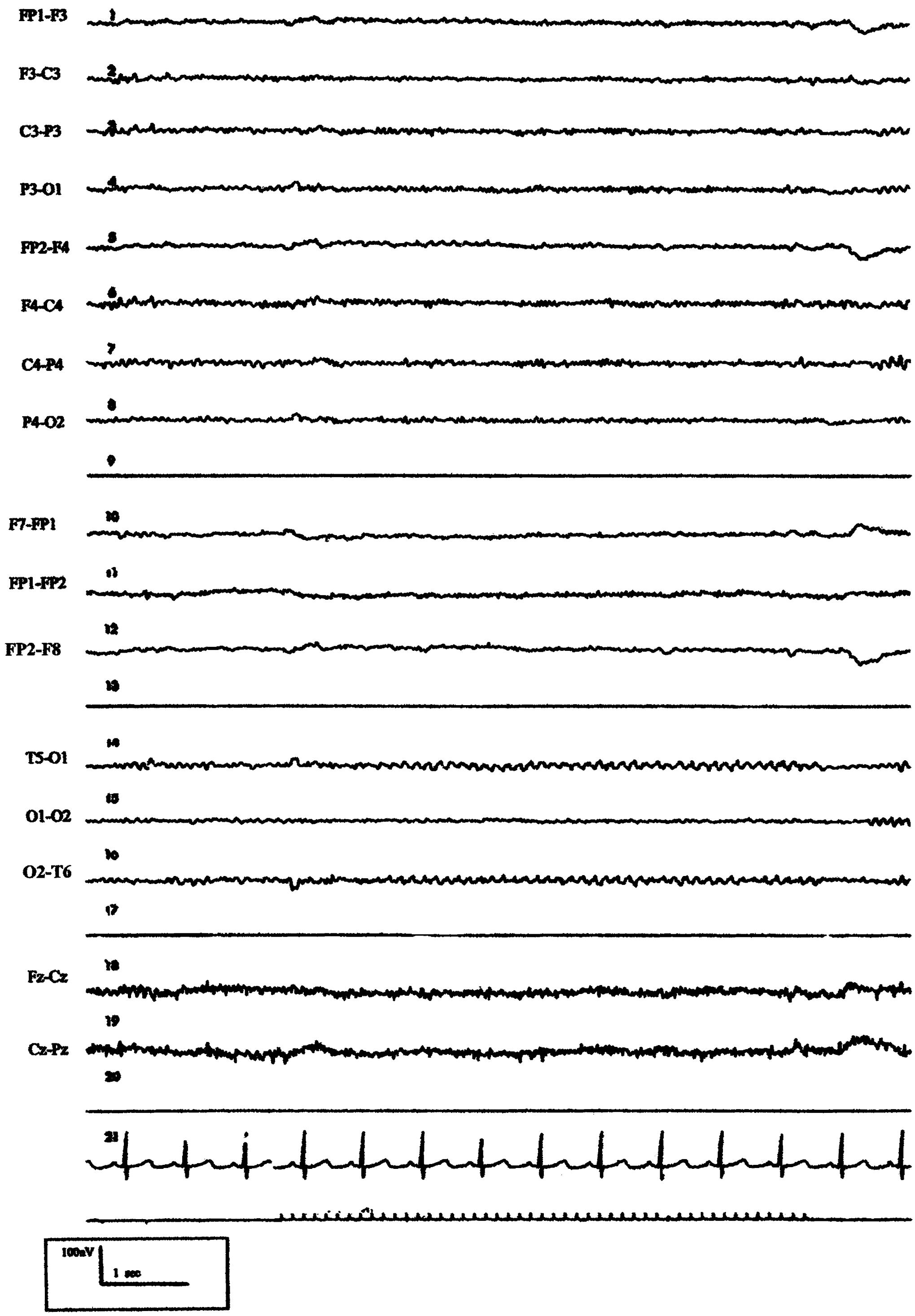

Fig. 3. Midway through this 20-s portion of a routine EEG is the 10-s period of intermittent photic stimulation noted by the artifact on the last channel. The frequency of the photic stimulator is eight flashes per second. There is a prominent evoked response noted over the occipital leads at the same frequency. This is a normal reaction.

represent a heightened brainstem-mediated reflex reaction to the photic stimulator. Additional enhanced levels of photic driving reactions are recognized and defined in a review by Waltz et al. *(5)*.

11. SLEEP

Many patients will come to an EEG lab and immediately fall asleep. Others may come with that in mind and never attain even a minimum level of drowsiness. For an electroencephalographer, sleep is useful to observe for several reasons. Similar to hyperventilation and photic stimulation, it may bring out latent abnormalities. There are some disorders, such as juvenile myoclonic epilepsy, in which waking up from sleep may be the only time one sees the markers for this disorder. In many EEG laboratories, the technician tries to get at least some sleep on every study. In other labs, the staff are asked to have the subject stay awake for significant portions of the night before the test to try to assure that the patient will fall asleep easily.

Four stages of non-rapid eye movement sleep are described next. Seldom does a subject get beyond Stage III during routine testing, but all stages are noted as they happen in a healthy person. Chiappa and Santamaria's book on drowsiness is an excellent dissertation on the subject *(6)*.

12. DROWSINESS OR STAGE I

The first suggestion that a patient is going to sleep is that there is a sudden drop in the voltage of their background alpha rhythm, followed by intermittent theta activity noted over the more posterior head regions (Fig. 4). This presleep or twilight state is usually followed by early Stage II. However, patients may alternate back and forth from awake resting to drowsiness for extended periods of time. In the healthy elderly patient, they may skip this state completely and go into Stage III or IV. Other healthy elderly patients may spend most of their sleep time in drowsiness and Stage II of sleep and have very little of the later stages noted.

Vertex sharp waves may begin to be seen in deeper stages of drowsiness, Stage Ib sleep. Vertex sharp waves are centered around the CZ electrode, with maximum voltage noted in the adjacent electrodes (C3 and C4). The wave may have complex morphology and consist of several phases. The initial phase is usually a surface negative biphasic sharp wave followed by a high-voltage surface negative slow wave, lasting up to 400 ms in duration.

13. STAGE II

This stage's onset is identified by the appearance of spindles. They are frontal–centrally predominant waves that occur as a cluster lasting for one to several seconds in duration. The spindle frequency is between 11 and 15 Hz and, in healthy adults, they are bilateral and synchronous in their appearance, with an amplitude up to 30 μV. Spindles may appear by themselves or following a vertex wave. In that latter situation, the wave is called a "K complex" (Fig. 5). Vertex waves are increasingly prevalent in Stage II sleep, and often persist in deeper stages as well. During the progression into deeper aspects of Stage II, the background rhythm continues to slow into the slower theta ranges, and high voltage generalized and frontally predominant delta slow waves are noted (<4 Hz).

During Stage II of sleep, occipital predominant high-voltage sharp slow waves are occasionally noted. These waves look like the lambda waves described in Section 8. These are referred to as either lambdoid waves or posterior occipital sharp transients of sleep. The physiological basis for posterior occipital sharp transients of sleep is probably very similar to

Fig. 4. Approximately half-way through this record, the alpha rhythm gradually fades and is replaced by slower theta frequency activity. There are no eye movement artifacts and this pattern evolved into Stage II sleep. Therefore, this tracing shows the transition from wakefulness to sleep, i.e., drowsiness.

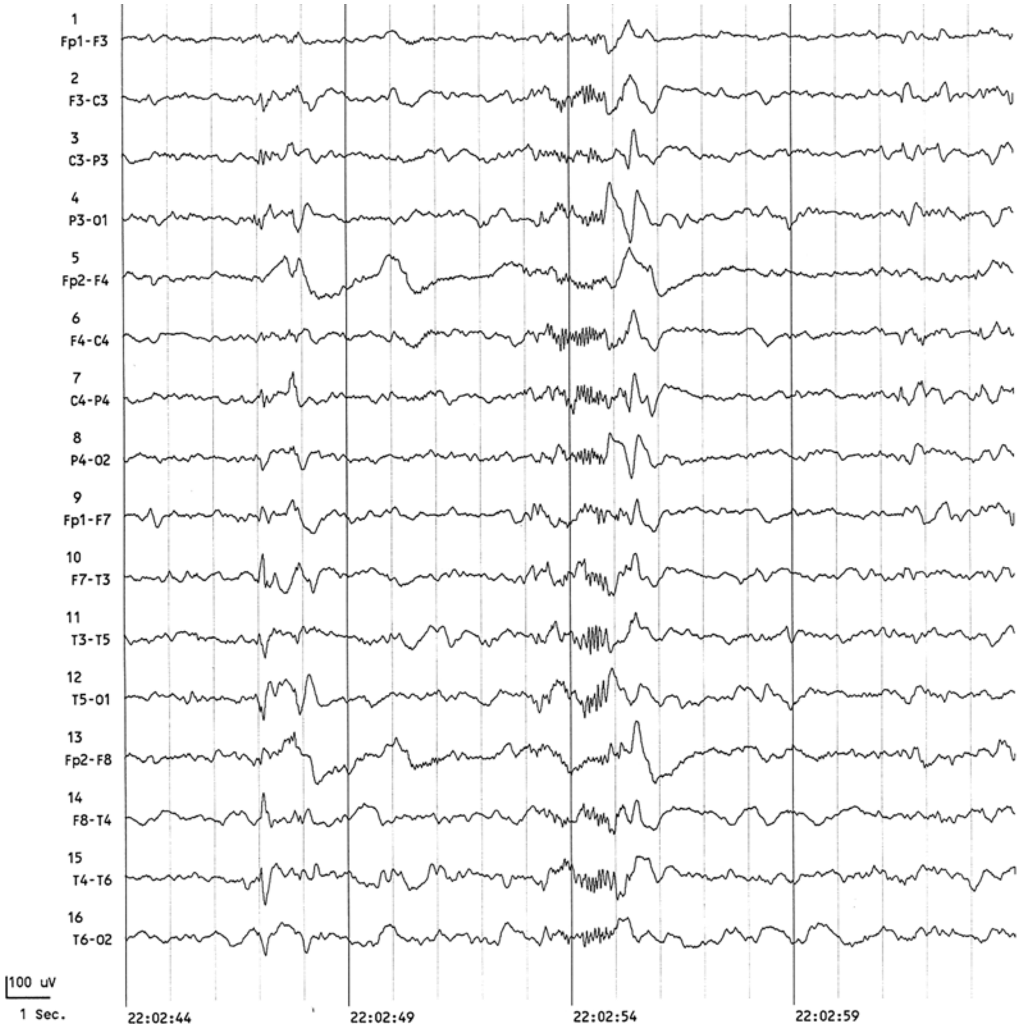

Fig. 5. This record, approximately half-way through, shows classic frontal–centrally predominant fast bursts of "spindle" activity followed by a centrally predominant high-voltage slow sharp wave, vertex wave. This complex is also referred to as a "K-complex," and is one of the hallmarks of Stage II sleep.

lambda waves. Their relation to visual dreams remains contested. Occasionally, these waves may extend into Stage III of sleep.

14. STAGE III

Occasionally a patient may go on to Stage III sleep. In this phase, there are still vertex waves, spindles, and K-complexes, but they occur less frequently and seem to be overwhelmed by the more prominent delta wave activity (<4 Hz). This slow wave activity is widespread but has a frontal and central predominance. It should be the most frequently noted rhythm and should be present for 20 to 50% of the record (Fig. 6). Stage III and the later Stage IV of sleep are most often associated with increases in the interictal discharges of temporal lobe epilepsy.

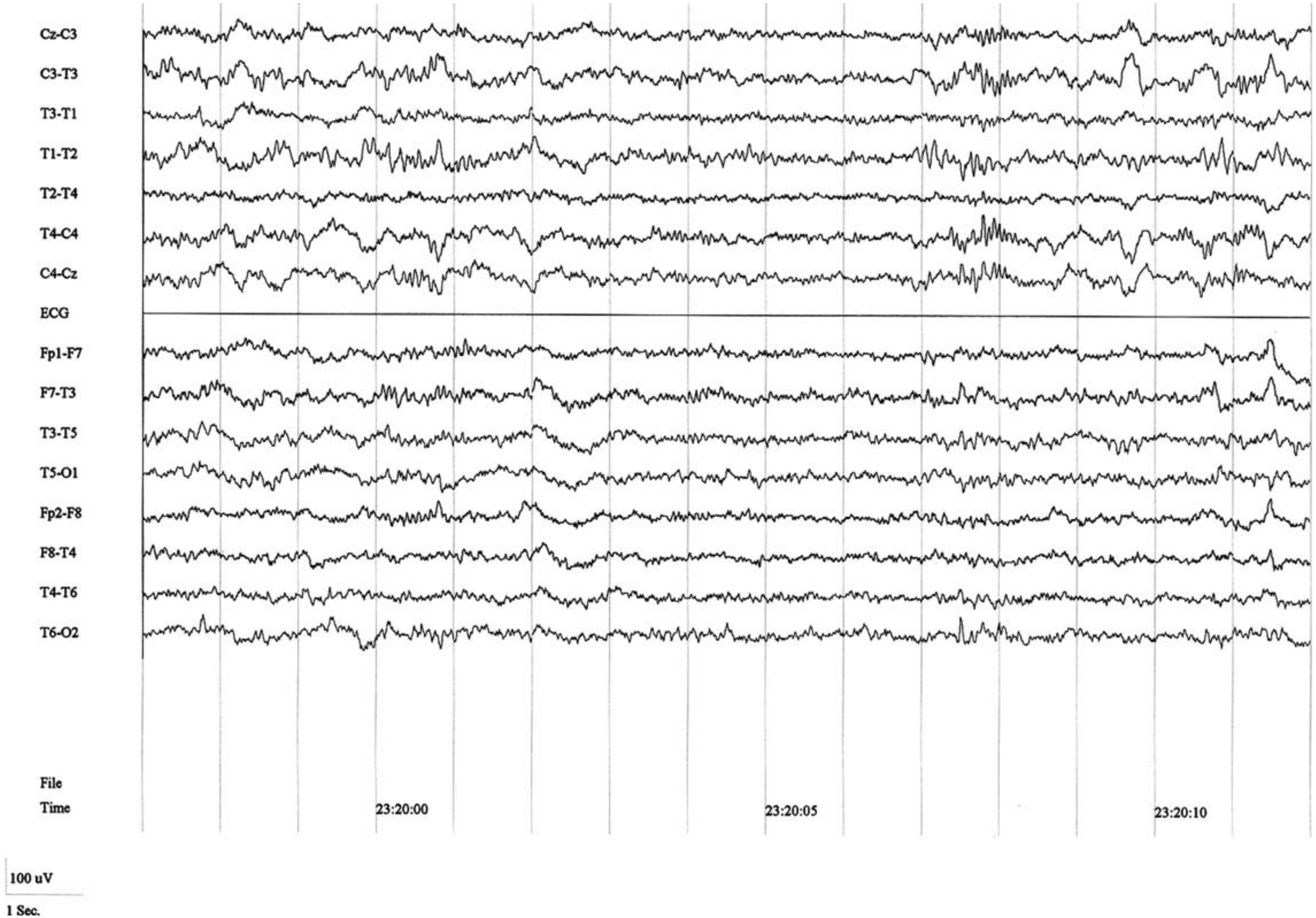

Fig. 6. As a subject progresses into Stage III sleep, as shown here, the background slows into the delta frequency range and is present approx 40% of the time.

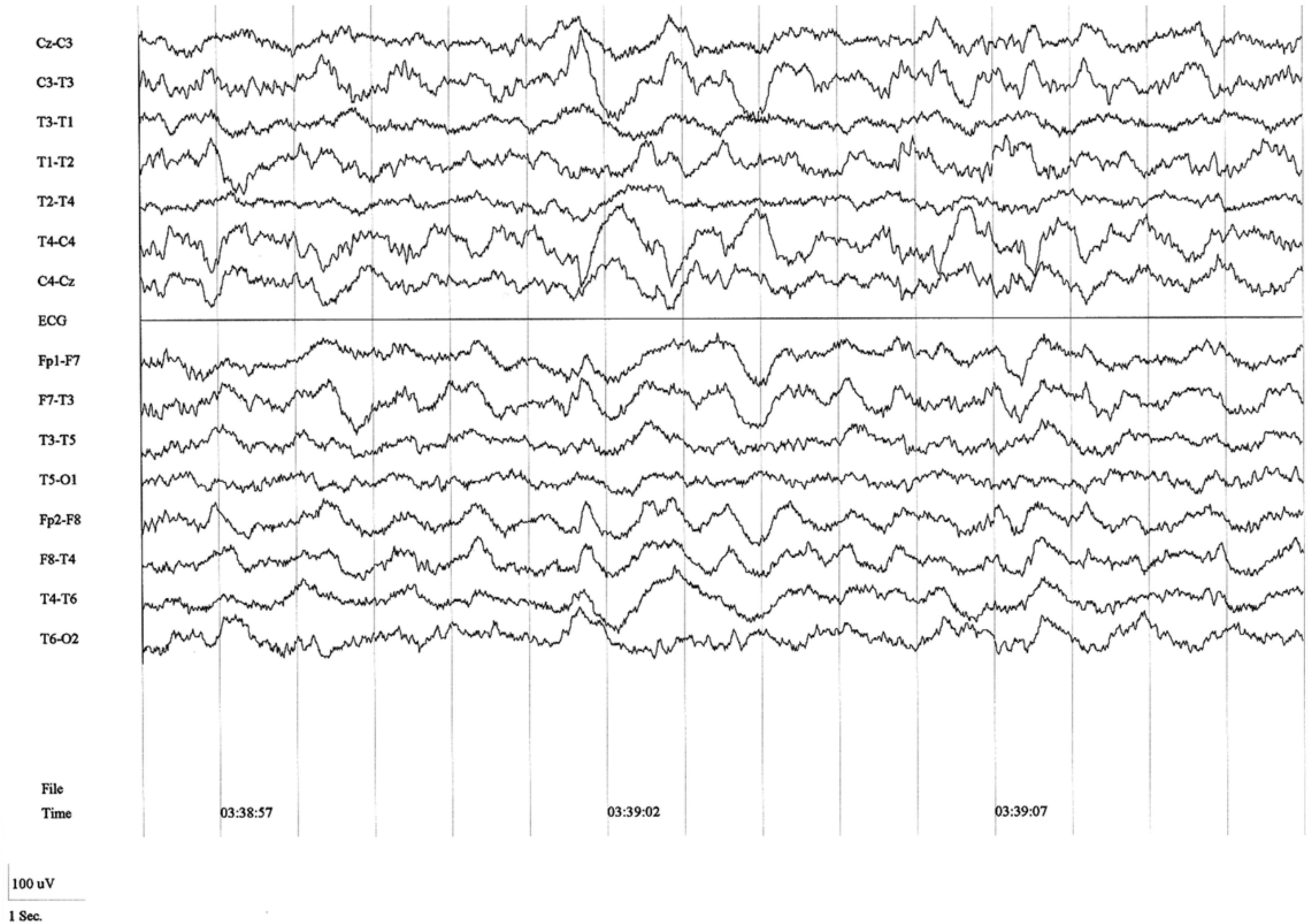

Fig. 7. When the background is more than 50% delta activity, the subject is considered to be in Stage IV of sleep, as noted on this portion of the record.

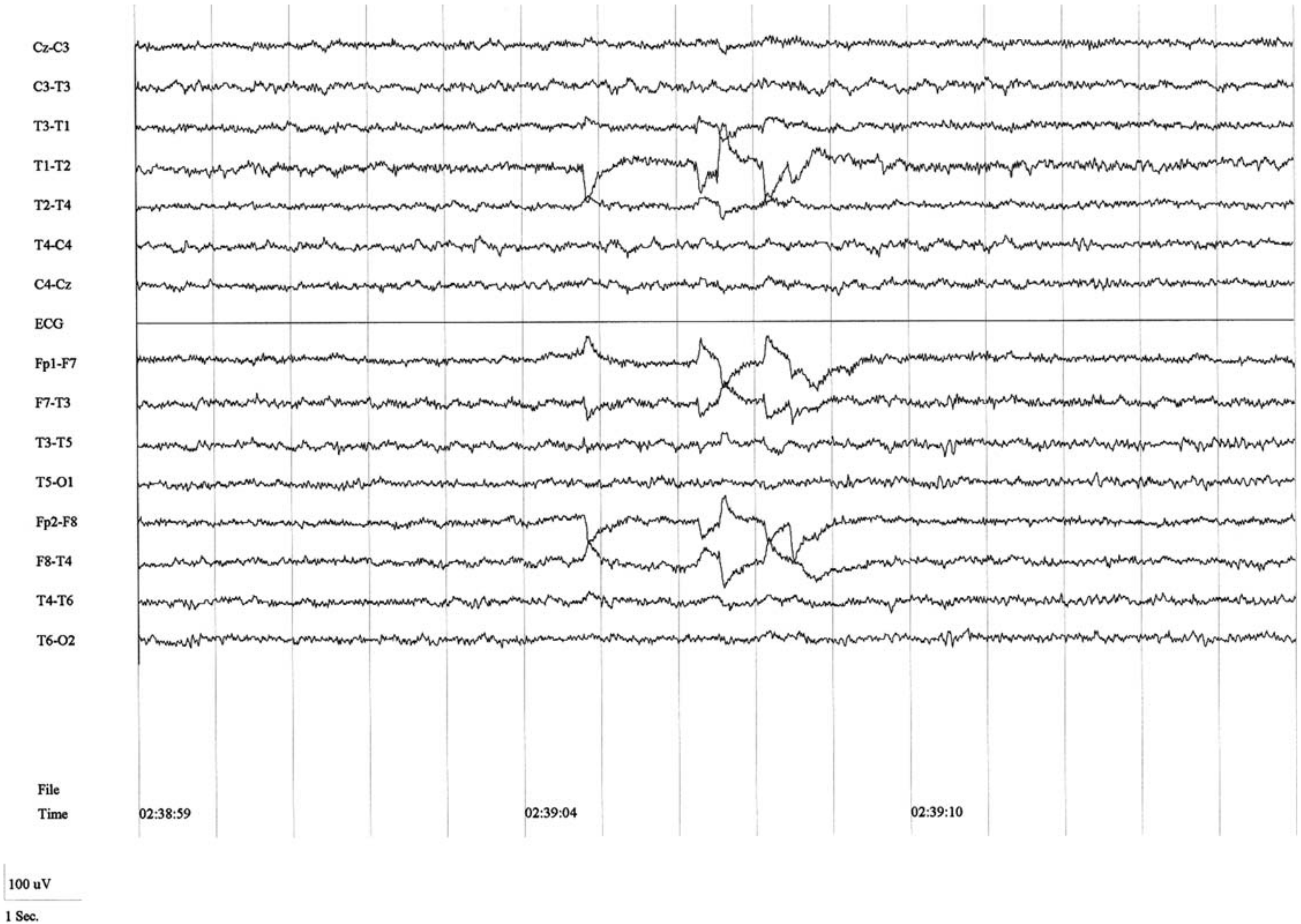

Fig. 8. Rapid eye movement sleep follows Stage IV in the sequencing of sleep. As noted here, the background is a low-voltage fast rhythm, as is seen in the wakeful state, but is also associated with lateral eye movements with a frequency of approx 1 Hz. These eye movements are seen over the lateral temporal leads, where they are out of phase with each other from side to side.

15. STAGE IV

Stage IV also has rudimentary vertex waves, spindles, and K-complexes, but shows further slowing and a more persistent delta-frequency background. In this stage, most (>50%) of the time of the recording is associated with continuously appearing delta activity (Fig. 7). This stage is only rarely achieved in the routine EEG recording.

16. REM

In sleep laboratories, the REM stage is divided into tonic and phasic components based on the simultaneous recording of other physiological parameters not routinely monitored during EEG acquisitions *(7)*. The other recordings include respiration effort and pulse oximetry, and chin and leg EMG activity. From a strictly EEG perspective, the background rhythm returns to what seems to be a drowsy or wakeful state, with low-voltage theta and alpha frequency activity, and with large, slow lateral eye movements (Fig. 8). This stage of sleep is also rarely encountered in routine EEG. When it is, perhaps ideally, the time from onset of drowsiness to the time of onset of REM should be measured. If it is short (<10 min), then the subject might consider a formal sleep lab referral to rule out narcolepsy.

REVIEW QUESTIONS

1. What system ensures consistent EEG recording technique? What is the upper limit of electrode impedance that is tolerated in EEG acquisition?
2. An upward deflection on an EEG conventionally indicates a negative or positive event?
3. What is the lower limit of normal for the waking posterior background rhythm in an adult patient? What are its characteristics?
4. What defines an abnormal degree of asymmetry in alpha amplitude?
5. What medications lead to excess beta activity? Can beta activity be a normal finding?
6. What maneuver may demonstrate reactivity of the mu rhythm?
7. What patients should not be asked to perform hyperventilation?
8. Are photic driving responses normal? What is the most characteristic frequency of photic driving?
9. What is the defining EEG feature of Stage II sleep?
10. What differentiates Stage III from Stage IV sleep?

REVIEW ANSWERS

1. The International 10-20 system ensures that electrodes are applied in a systematic fashion by the technologist to each patient. Electrode impedances are kept at 5000 Ω or less to minimize electrode-related artifact.
2. An upward deflection reflects a surface negative event.
3. The lower limit of normal for the adult waking posterior rhythm (the alpha rhythm) is 8 Hz. It is most prominently seen in the posterior channels and exhibits physiologic reactivity, specifically attenuating with eye opening or other mental tasks.
4. The alpha amplitude is said to be abnormally asymmetric if there is a greater than 50% discrepancy between the hemispheres. Particularly in right-handed people, the right side is usually of higher amplitude.
5. Benzodiazepines and barbiturates are most often associated with excessive beta activity. Beta activity can be a normal finding, and may be state dependent, because it is more often noted in drowsy tracings, especially in frontal channels.
6. Planning a movement with the contralateral hand or executing such a movement (e.g., make a fist) will attenuate the mu rhythm.

7. Hyperventilation should be avoided in the very elderly, in those suspected of an intracranial mass lesion, or in those with recent cerebral ischemia.
8. Photic driving responses are a normal phenomenon. However, their absence is common and is not pathological. When present, they should be fairly symmetrically evident. They are most common at close to the patient's alpha frequency.
9. Spindles are the defining element of Stage II sleep. Vertex waves are also abundant, as are K-complexes. Vertex waves may be seen in isolation in deeply drowsy (Stage Ib) subjects.
10. Stage III sleep entails delta activity involving 20 to 50% of the tracing, whereas Stage IV sleep exhibits greater than 50% delta activity.

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