4 Electrode Placement Systems and Montages

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4.1 Traditional International 10-20 System

When Hans Berger recorded the first human EEG, he only had two electrodes available, positioned them in the anterior and posterior regions of the head. Berger kept using this method for many years, considering it an efficient system to measure the global cortical activity. Later on, other researchers highlighted how, in reality, EEG activity varied significantly depending on the area of the scalp from which it was recorded. Observation of different regional cerebral rhythms encouraged the use of multiple electrodes and of more recording channels, but standardization of the recording methods soon became necessary, so that the resulting data could be comparable with one another. A committee of International Federation of Societies for EEG and Clinical Neurophysiology (IFSECN), led by H. Jasper, started then working on a specific electrode positioning system to be used in all laboratories. The first standardized system was presented at the 2nd International Congress of IFSECN in Paris in 1949 and published by Jasper in 1958; it is still universally used and known as the International 10-20 System (IS 10-20) [1].

In the development of IS 10-20, the following concerns were addressed:

- Definition of a measuring system for electrode positioning, taking into account clearly defined anatomical landmarks, so that the measurements were as proportional as possible to the shape of the skull
- Electrode distribution in order to guarantee that they cover every part of the skull and electrode identification according to standard positions, regardless whether all, or only some, are used in a specific recording
- Identification of the various electrode positions depending on the underlying brain area (frontal, central, temporal, parietal and occipital), rather than just using numbers, so that communication is more immediate and intuitive
- Execution of appropriate anatomical studies to safely localize brain area projections which, presumably, match the electrode standard positions.

Correct positioning of the electrodes on the scalp according to IS 10-20 is achieved by tracing imaginary lines, starting from specified anatomical landmarks. These circumferential lines are mutually perpendicular and they are represented by:

– Anteroposterior sagittal midline, connecting nasion to inion, through the vertex. Nasion is the depression between the eyes, just above the nasal bridge, at the insertion of the frontal bone and the nasal bones. Inion is the highest point in the midline of the protuberance of the occipital bone.
– Along this sagittal midline, there are five standard positions called frontopolar (Fpz), frontal (Fz), central (Cz), parietal (Pz) and occipital (Oz). The letters F, C, P, and O indicate the underlying cerebral area and the letter z stands for zero. Considering the total distance between nasion and inion in centimeters, Fpz and Oz points are located at 10% of the total distance, respectively, from the nasion and the inion. All other positions are calculated at 20% of the distance between Fpz and Oz (the 10-20 denomination originated precisely from this percentage calculation). The ideal placing along the skull would set the central electrode (Cz) exactly in the middle of the line between nasion and inion; anatomical studies showed that C electrodes are located 1 cm within the central sulcus [2] (Fig. 4.1a).

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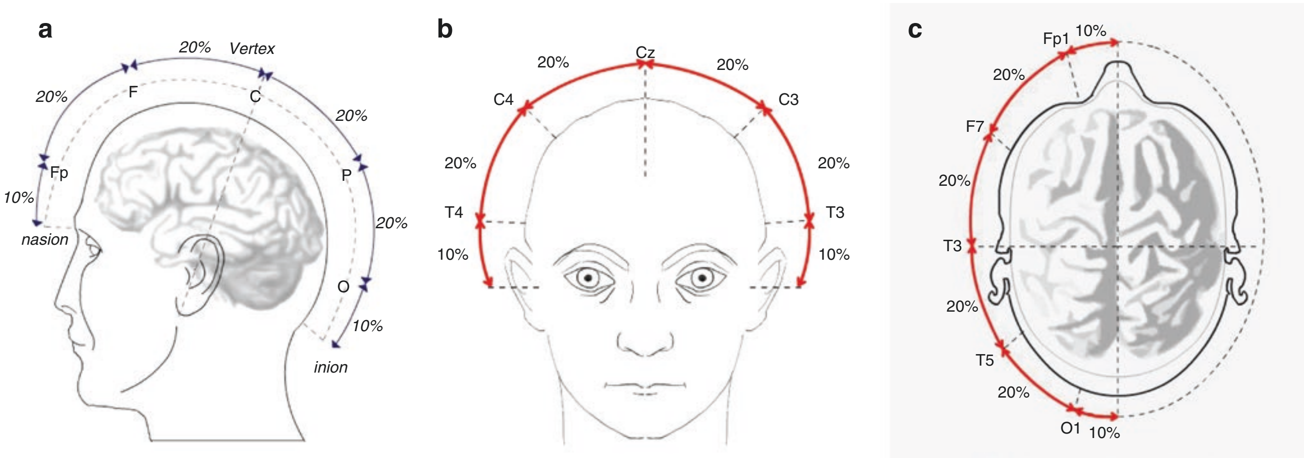

Fig. 4.1 Traditional 10-20 system. (**a**) Anteroposterior mesial line, connecting nasion and inion; (**b**) latero-lateral coronal line, connecting the two preauricular points, through the vertex; (**c**) sagittal lateral longitudinal line, connecting nasion and inion

– Latero-lateral coronal line, from the right to the left preauricular point, through the vertex. The preauricular points are identified as depressions at the root of the zygoma, just anterior to the auditory canal. Along this line, temporal electrodes (T4 to the right and T3 to the left) must be placed at 10% of the total distance, starting from the preauricular point while lateral central electrodes (C4 to the right and C3 to the left) must be placed at 20% from the temporal points (T4 and T3) and from the vertex (Cz) (Fig. 4.1b).

Starting from these two lines(i.e. the antero-posterior sagittal and the latero-lateral coronal) it is then possible to trace another two pairs of circumferential longitudinal lines in the anterior-posterior direction: lateral longitudinal line, from Fp2 to O2, through F8, T4 and T6 on the right; from Fp1 to O1, through F7, T3 and T5 on the left (Fig. 4.1c); longitudinal parasagittal line, from Fp2 to O2, through F4, C4 and P4 on the right; from Fp1 to O1, through F3, C3 and P3 on the left. Frontopolar electrodes (called Fp2 in the right and Fp1 in the left) are placed along the longitudinal line, at 10% of the distance to the side of Fpz, while for occipital electrodes (called O2 and O1) the 10% is measured with reference to Oz. Positions of the inferior frontal electrodes (F8 and F7) and posterior temporal electrodes (T6 and T5) are calculated at 20% of this line starting, respectively, from Fp2/Fp1 and O2/O1. The remaining frontal electrodes (F4 and F3) and parietal electrodes (P4 and P3) are placed along the frontal and parietal coronal lines, equally distant between the mesial and temporal lines on each side.

Standard numbering of the traditional 10-20 system establishes the disposition of even-numbered electrodes on the right side of the skull and of odd-numbered electrodes on the left side, identifying with letters the brain area above which they are positioned: Fp2, F4, F8, C4, P4, T4, T6 and O2 for the right hemisphere and Fp1, F3, F7, C3, P3, T3, T5 and O1 for the left hemisphere.

This measuring system identifies 21 standard electrode positions, including electrodes on the medial line (Fz, Cz, and Pz) and two reference auricular electrodes (A2 and A1) (Fig. 4.2a).

The International 10-20 system defined, in a short period of time, a standard scalp electrode positioning, allowing reliable comparisons of the acquired data from the various laboratories around the world. Nevertheless, the system is not exempt from criticisms. First of all, this system does not take into account that most human heads are asymmetrical. The posterior part of the skull is larger than the anterior one. Moreover, when dividing the skull in four quadrants (starting from nasion, inion and preauricular points), it can be noted that right-handed patients' heads temd to have a larger posterior quadrant on the left side and a larger anterior quadrant on the right side. For this reason, it would be necessary to arrange the electrodes proportionally not to the whole skull, but dividing it into four quadrants, meaning that the montage should be individualized.

For this reason, it is impossible that the interelectrode distances are the same along the longitudinal and transverse lines and, since interelectrode distance has a significant effect on the amplitude of the recorded signal, this problem should be carefully considered.

Furthermore, the relationship between the superficial positioning of the electrodes and the underlying anatomical structure was not correctly identified and, for this purpose, modern neuroimaging techniques should be better utilized. The 21 standard electrodes montage is not necessarily extensive enough to overlay all brain areas. For a correct detection of basal frontotemporal and mesial temporal areas, for example, specific additional electrodes are required.

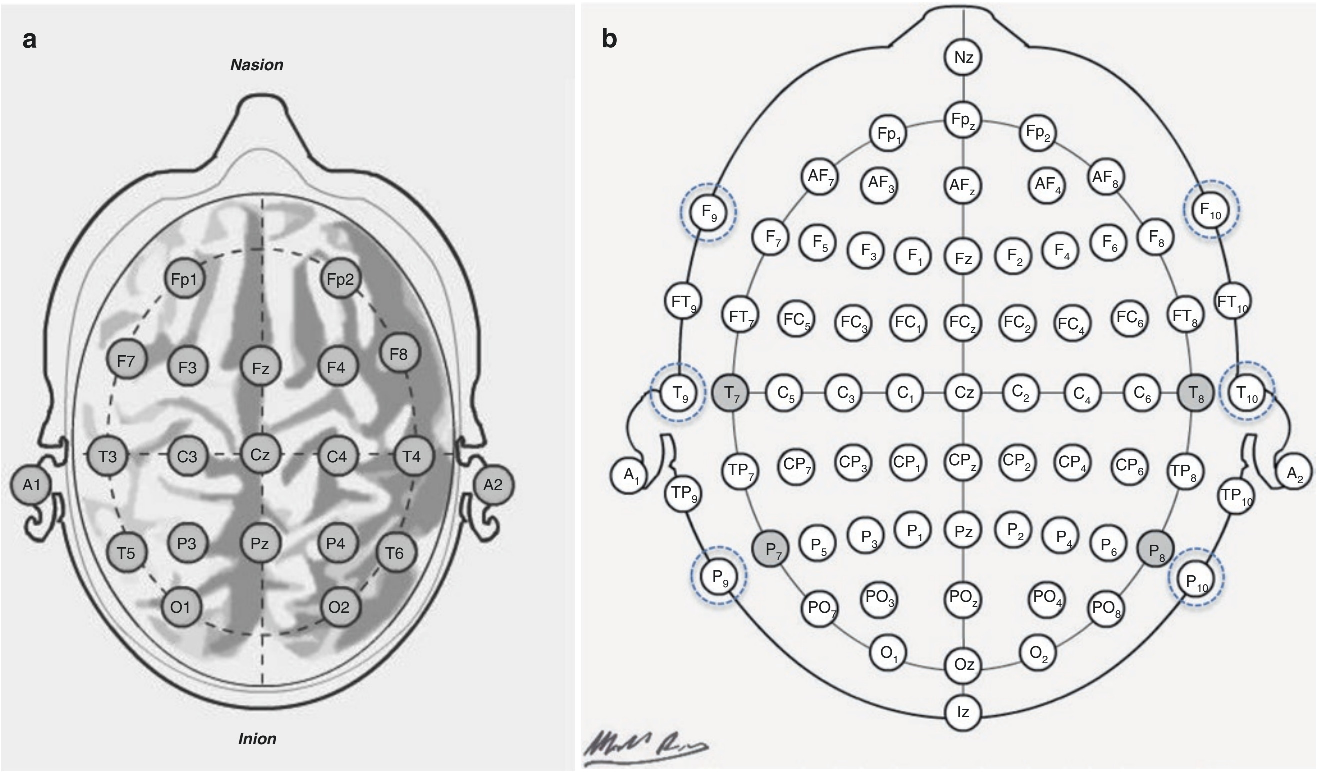

Fig. 4.2 (**a**) Standard positions of the 19 scalp electrodes and of the 2 ear reference electrodes, according to traditional 10-20 system; (**b**) modified 10-10 system, with 73 electrode positions on the scalp and 2 ear reference electrodes (note that the electrodes T8, P8, T7 and P7 replace the electrodes formerly named T4, T6, T3 and T5); the electrodes of the inferior temporal chain F10, T10, P10, F9, T9 and P9 (dotted circles) are actually recommended as new standard montage with 25 electrodes

4.2 Modification of 10-20 System (10-10 System)

Digital-EEG development and the introduction of high-density EEG and source localization methods made it necessary to increase the electrode arrays. Therefore, a modification of 10-20 nomenclature with the definition of 10-10 combinatorial nomenclature has been proposed and accepted by the American Clinical Neurophysiology Society (ACNS) and by the International Federation of Clinical Neurophysiology (IFCN) [3–7].

The modified combinatorial nomenclature is an extension of the 10-20 system and it entails the positioning on the scalp of more than 70 electrodes, placed along 11 sagittal chains and 9 coronal chains. The modified 10-10 terminology replaces the inconsistent T4/T3 and T6/T5 terms with the consistent T8/T7 and P8/P7 (Fig. 4.2b). The advantage of this new labelling is that all electrodes designated by the same letter are placed in the same coronal line and that all electrodes positioned along the same sagittal line have the same post-scripted number (except for Fp2/Fp1 and O2/O1); however, the disadvantage of the new nomenclature is represented by the fact that the letter "P" might suggest a *parietal* location, whereas P8/P7 are electrodes placed over the posterior temporal lobe. According to ACNS guidelines in the clinical context, it is still an acceptable alternative to continue to use T4/T5 and T6/T7 [6]. Electrodes between the frontal and central rows are named "FC", between the frontal and temporal rows "FT", between the central and parietal rows "CP" and between the parietal and occipital rows "PO". The electrodes between the frontopolar and frontal rows are named "AF", indicating "Anterior Frontal" placement [7].

The 10-10 system added also 10% contacts that are inferior to the standard frontotemporal and temporal-occipital chain. These electrodes are named F10/F9, FT10/FT9, T10/T9, TP10/TP9 and P10/P9. This inferior temporal chain may be completed with electrodes Fp10/Fp9, AF10/AF9, PO10/PO9 and O10/O9.

During the routine recordings with the traditional 10-20 system, the placement of the 19 standard scalp electrodes does not always detect the activity originating or propagating from mesial temporal structures. For this reason, the IFCN recommends a new standard array for clinical practice that includes the six electrodes of inferior temporal chain (F10/F9, 10% inferior to F8/F7; T10/T9, 10% inferior to T8/T7; P10/P9, 10% inferior to P8/P7): this results in a total of 25 electrodes placed on the scalp (Figs. 4.2b, 4.3 and 4.4) [7].

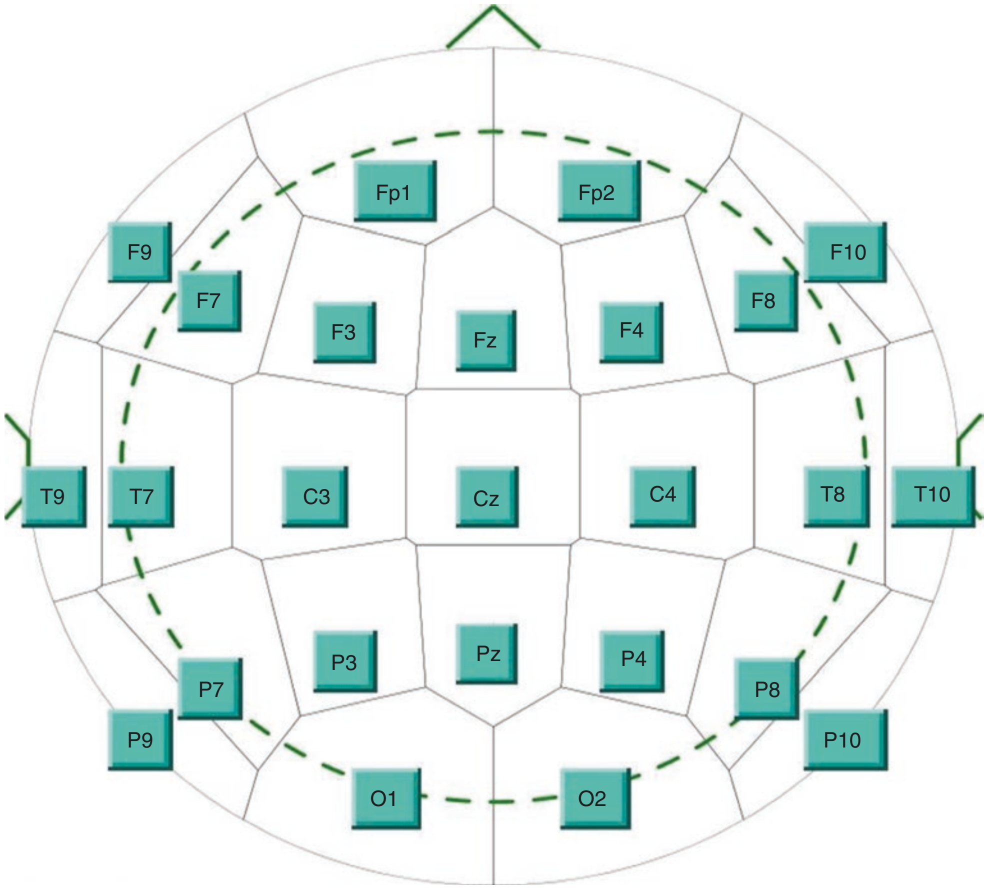

Fig. 4.3 New standard montage with additional coverage of the inferior and anterior brain regions, according to the recent recommendations of International Federation of Clinical Neurophysiology (from ref. [7], with permission)

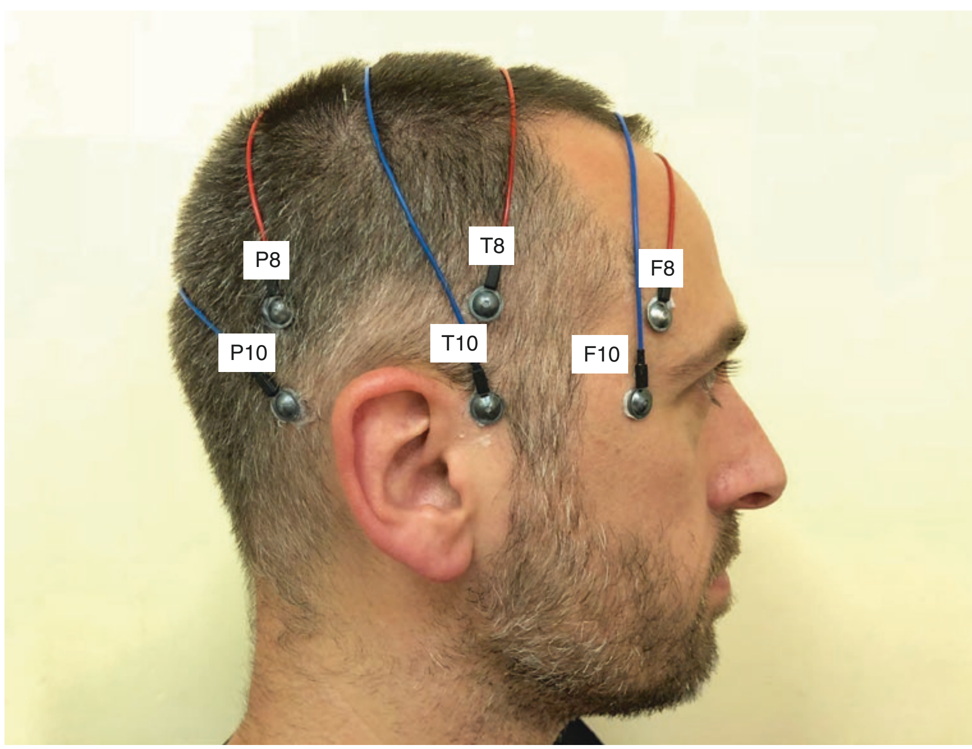

Fig. 4.4 Electrodes of the right inferior temporal chain according to new recommendations of IFCN (T8 = ex T4; P8 = ex T6)

Recently, it has been demonstrated that adding six electrodes in the inferior temporal chain to the traditional 10-20 system improves the identification of EEG abnormalities originating from the basal part of the temporal lobes [8].

4.3 Proposed 10-5 System for High-Resolution EEG

A further extension of 10-10 system, named 10-5 system, was proposed in 2001, but it has not yet been accepted by ACNS and IFCN [9]. The 10-5 proposed extension defines the position and nomenclature of 345 locations on the head and it can accommodate a homogeneous distribution of a subset containing, for example, 128 or 256 electrodes (Fig. 4.5a, b). The nomenclature of this system uses the combination of two letters to indicate the contours lying halfway between the original 10-20 system contours (the electrodes between the F and C contour were labelled FC and so on for others) [9]. In this way, the locations for the coronal contours from anterior to posterior were named: AF, AFF, F, FFC, FC, FCC, C, CCP, CP, P, PPO and PO. Electrodes for high-density EEG are applied by using expandable nets or caps with embedded electrodes and their localization is determined by digitization in three-dimensional space (Figs. 4.6 and 4.7).

4.4 Final Recommendations

Although in clinical practice the electrode placement method should be individualized on the basis of the clinical needs of the individual patient, the following recommendations should be considered, according to the guidelines of ACNS and IFCN: [6, 7].

- The 10-20 traditional system (21 electrodes) may be adequate for most of the patients, even for ambulatory or video-EEG long-term monitoring.
- In the suspicion of epilepsy or in epileptic patients without a clear visualization of the epileptic focus, supplementing the 10-20 EEG array with six electrodes for the inferior temporal chain (25 electrodes in total) is recommended.
- In children, except for special cases, the same number of electrodes as in adults is usually recommended.
- The 10-10 system should be used in epileptic patients undergoing pre-surgical evaluation and for source localization purpose.
- For the transition from the traditional system to the new larger arrays, the modification of EEG machine headboxes and a gradual process of educating operators on the new terminology are necessary.

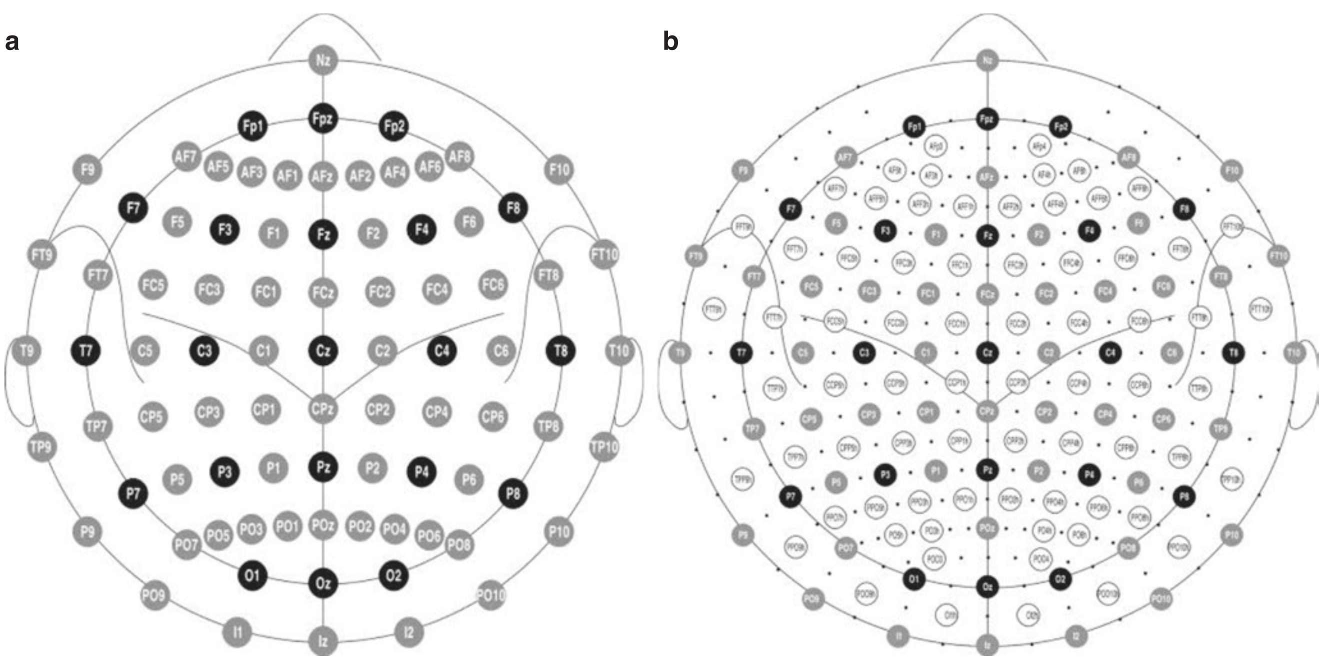

Fig. 4.5 The 10-10 and 10-5 extension of traditional 10-20 system. In (**a**) black circles indicate positions of the original 10-20 system and grey circles indicate additional positions introduced in the 10-10 extension. In (**b**) electrode positions in the proposed 10-5 system: additional positions to the 10-10 system are indicated with dots; a selection of additional positions useful for a 128 channel EEG system is indicated with open circles (from ref. [9], with permission)

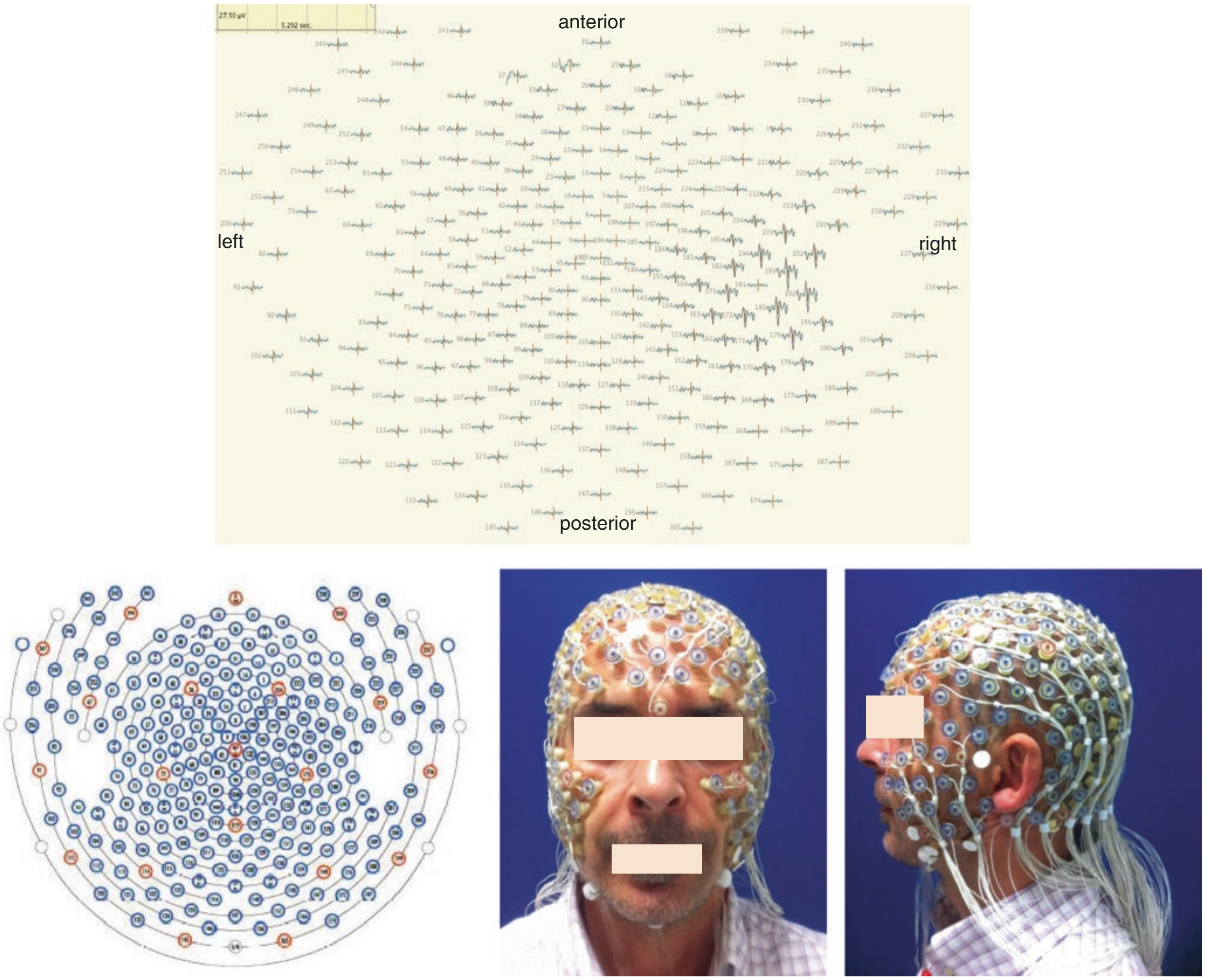

Fig. 4.6 An example of 256-channel high-density EEG, with projected locations of the electrodes on the scalp (courtesy from: Paolo Manganotti, Clinical Neurology Unit, University of Trieste—Italy)

4.5 Electrode Derivations and Montages

Brain electrical signals are displayed on the monitor depending on how the electrodes are connected to the amplifiers. Each amplifier has two electrode inputs (1 and 2) and the *potential measurement* represents the *potential difference* between these two points. From the electrical point of view, one of these points is called "common" or "ground" and its potential is deemed to be *zero*: unfortunately, ground points generate potentials and do not correspond to a real zero. This can be overcome by connecting two amplifiers together at the ground point and comparing the potential difference between their active inputs. Then, if two amplifier inputs (1 and 2) have the same polarity and voltage, the output will be zero (*in-phase rejection*) while, when these potentials are different, the recorded output value will be proportional to the difference between the two input values. Using differential amplifiers, only the difference between two inputs is known and not the absolute value of the potentials of electrodes attached to either inputs 1 or 2. Comparing a large number of electrode positions, EEG allows—with a good approximation—the localization of an abnormal activity on the scalp. In summary, on the monitor or recording paper, the signal is displayed with two fundamental characteristics: voltage and polarity. With regard to polarity, by convention, if the relative voltage difference is negative, the signal deflects upward and, if the voltage difference is positive, it goes downward. Therefore, if input 1 is more negative than input 2, the output signal will deflect upward, whereas if input 1 is more positive than input 2, the output signal will deflect downward. Finally, when inputs 1 and 2 have the same polarity and voltage, the output signal will be a flat line (Fig. 4.8).

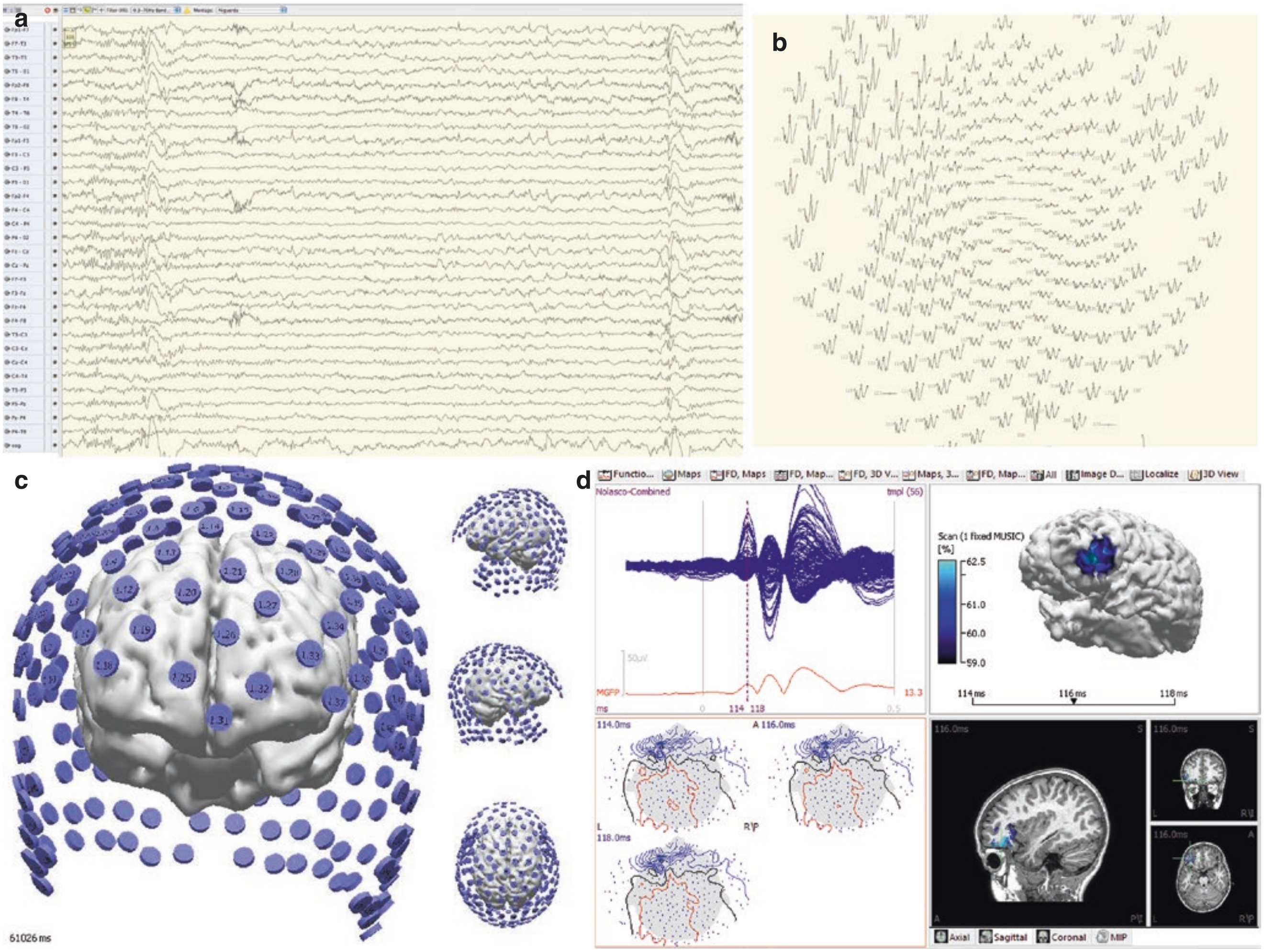

Fig. 4.7 Comparison of standard and high-density EEG in a patient with epileptic left temporal focus; (**a**) standard EEG recording with placement of electrodes according to 10-20 system; (**b**) recording of a single spike by 256 electrodes placed on the scalp; (**c**) the 256 placed electrodes projected onto a 3D image of the patient's brain, obtained by MRI; (**d**) source analysis of epileptic focus (56 spikes average) (courtesy from: Annalisa Rubino, Lino Nobili, Epilepsy Surgery Centre—Niguarda Hospital, Milan, and Child Neuropsychiatry, Department of Neurosciences, University of Genoa)

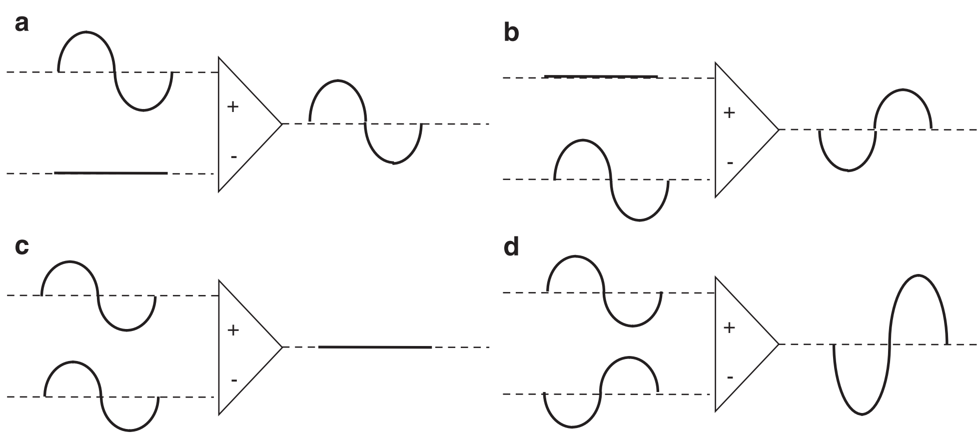

Fig. 4.8 Morphology and amplitude of different input signals of differential amplifiers and the respective output signals. The figure shows obviously ideal circumstances. If the signal is confined to a single channel (**a**, **b**), the output signal will have a different polarity, depending on the characteristics of input signal. If, instead, the two input signals are identical (with the same polarity), the output will be zero (**c**). Finally, if the two input signals have different polarity, the output signal will be the result of their summation (**d**)

Since there are endless input combinations that can generate the same output value, it is impossible to know the value of two inputs only knowing the output value of a differential amplifier. Back to EEG, if we imagine the electric fields on the surface of the scalp as the surface of the sea, rippled by waves of different sizes intersecting with each other, an EEG is rarely like a pond with almost imperceptible waves (when this happens, it means we are close to cortical activity suppression, characteristic of severe clinical conditions as brain death). Continuing with this analogy, electrodes are like corks, floating on the water, and the only thing we can do is to measure the height differences among them. This analogy would be perfect if the corks were correctly positioned, with regular distances, and if they were arranged in an orthogonal grid. A fixed point is then needed, as the shore to which all corks should refer.

In electroencephalography, aside from electrode positioning on the scalp (according to IS 10-20), a fundamental role is played by electrode combination (montage) and their type of connection to the amplifier (derivation). For historical and practical reasons, EEG is usually displayed as a set of traces showing how potential differences change over time. In a traditional EEG tracing (analog EEG), each trace is the result of the connection of two electrodes to the amplifiers and filters, with the signal sent to the galvanometer and to the writing device. With the introduction of digital EEG, the whole system has been replaced by computer software and hardware, but every trace continues to be called *channel*.

4.5.1 Reference Derivations

4.5.1.1 Common Reference

With this recording method, each electrode placed on the scalp is referred to as a common electrode, placed at a point x, on the scalp or elsewhere. The principle is similar to a geographical map, where the altitude of every location is measured in relation to the sea level. The common reference electrode should be as neutral as possible from the electrical point of view (not contaminated by cerebral electric potential nor by other biological electrical signals), which is a really rare occurrence. Fig. 4.9 shows the fundamental principles of the so-called "*inactive*" *common reference.* A potential with a negative voltage peak at the F3 electrode generates a surrounding electric field with gradient marked by the circular lines. The bilateral occipital and right parietotemporal areas are considered to have a uniform potential, which we can arbitrarily establish as zero. Therefore, the scalp electrodes T4, T6, P4, O2 and O1 and the A2 ear reference electrode have zero potential and they are consequently positive when compared to the other cerebral electrodes; they are also very different from F3 (which has the maximum negative peak). Starting from this situation, any point of the head can be chosen as a reference but, to better demonstrate the distribution of the potential generated under F3, the best option would be to choose an electrode not "contaminated" by this activity, like the A2 contralateral ear electrode or non-

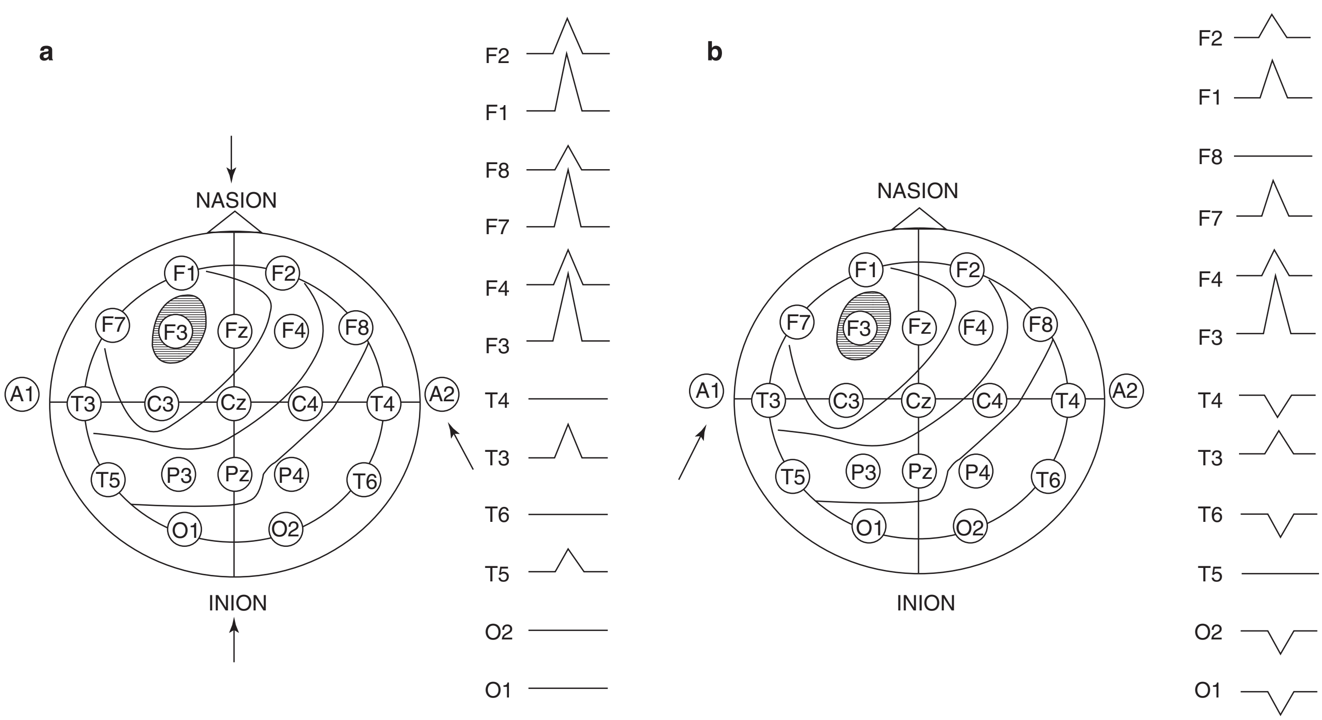

Fig. 4.9 Common reference recording (see text for explanation; F2 and F1 = Fp2 and Fp1). (**a**) reference electrode A2; (**b**) reference electrode A1

cephalic reference. Using A2 as a reference, the signals in this virtual situation would be displayed like in Fig. 4.9a.

Choosing the A1 left ear electrode as a reference, which is located inside the F3 electrical field and which has a low-amplitude negative potential when compared to the arbitrary zero (a common occurrence in normal practice), a very different pattern will be drawn: the channels showing lack of activity will be the ones with the same potential as the reference and, therefore, will be evened out; a downward deflection, caused by the relative negativity of the common reference, will be found instead on the electrodes placed in the area of zero potential (Fig. 4.9b).

An active scalp electrode can also be chosen as the *active common reference*. Figure 4.10 shows a virtual situation in which the electrode placed at F3 is chosen as the common reference. F3 is over the maximum electrical field on the scalp and it records the highest negative signal. Since, in this case, the reference is negative in comparison to other electrodes, all amplifiers will produce downward deflections. Moreover, since the electrodes surrounding the activity peak (F1, Fz, F7, C3) differ only slightly in potential from the reference, their corresponding channels will show smaller deflections than the ones farther away (the longer the distance from the reference, the higher the deflection).

The major drawback produced by active common reference is the *reference contamination*: when the reference electrode is placed close to a maximal peak potential, all the

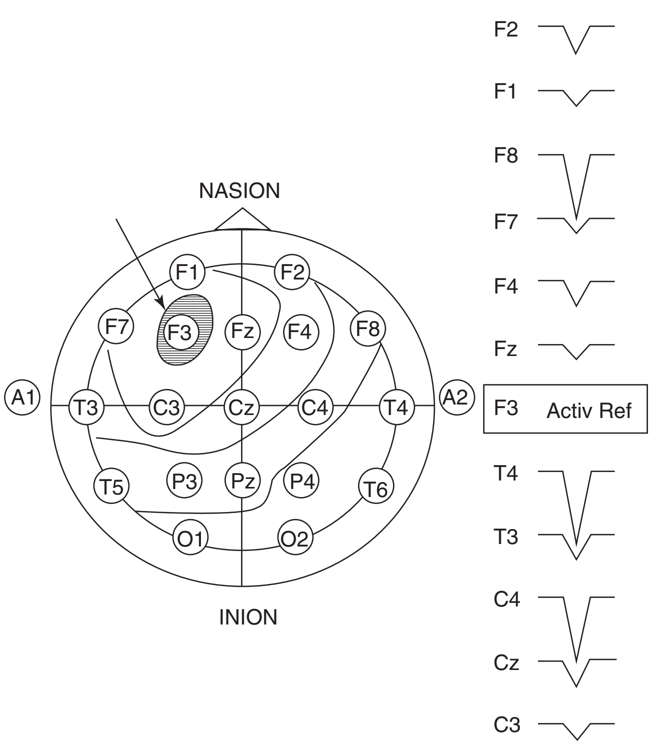

Fig. 4.10 Active common reference recording (see text for explanation; F2 and F1 = Fp2 and Fp1)

corresponding electrodes will be subjected to a change in voltage; all electrodes equipotential to the reference will be evened out, while the one least affected by the reference will show a pseudo-positivity. So, theoretically, given a known electric field (see Fig. 4.9), it would not be hard to estimate the shape of the wave that will appear on the EEG channel, depending on the reference. In practice, the concept must be reversed as we need to understand the distribution of the potentials on the scalp without knowing *a priori* - in a better way - the precise localization and the origin of the signal nor its positive or negative polarity.

There are, however, more complex conditions than those mentioned above. For example, when it is necessary to analyse multiple events, localized to various electrodes, both synchronous and asynchronous, it could be difficult to interpret the resulting patterns.

All the problems analysed so far could be overcome by choosing an acceptable inactive reference electrode, placed in non-cephalic areas, named *physical* reference (neck-chest reference). Auricular or nuchal electrodes can be also chosen as the reference, but they cannot be considered completely "inactive". For example, electrical events generated from the temporal lobes can be recorded with auricular or mastoid electrodes; also nasal or mental electrodes can record activities originating from the orbital surfaces of the frontal lobes. On the other hand, when using a non-cranial reference, there is the risk of recording many artifacts: when they are in-phase in all channels, there is no problem for the interpretation, but when this does not occur, the EEG tracings can be completely obscured. Vertical eye movements produce high potential differences between scalp electrodes and the nasal or mental reference. Equally important are interferences produced by muscles and the ECG.

In conclusion, common reference tends to "contaminate" differential amplifiers, reducing in-phase rejection and increasing interferences; for this reason, depending on the particular situation, a specific reference should be chosen: auricular lobe or mastoid, omolateral or contralateral to the analysed activity (not recommended in the case of bilateral activity); electrodes placed along the mesial line in frontal region or at the vertex (not recommended in case of drowsiness or sleep because arousal phenomena mostly affect the reference electrode); nasal or mental electrodes (not recommended for alert patients because they produce larger artifacts).

Current digital EEG systems always refer the cerebral bioelectric signal to a common reference electrode, which typically has an input in patient headbox named G2 and which can be positioned on the scalp or elsewhere (usually, it is placed medially on the scalp, anterior to Fz or between Fz and Cz). The G2 common electrode is the common point referring to which all potentials of the single electrodes are measured (Fig. 4.11).

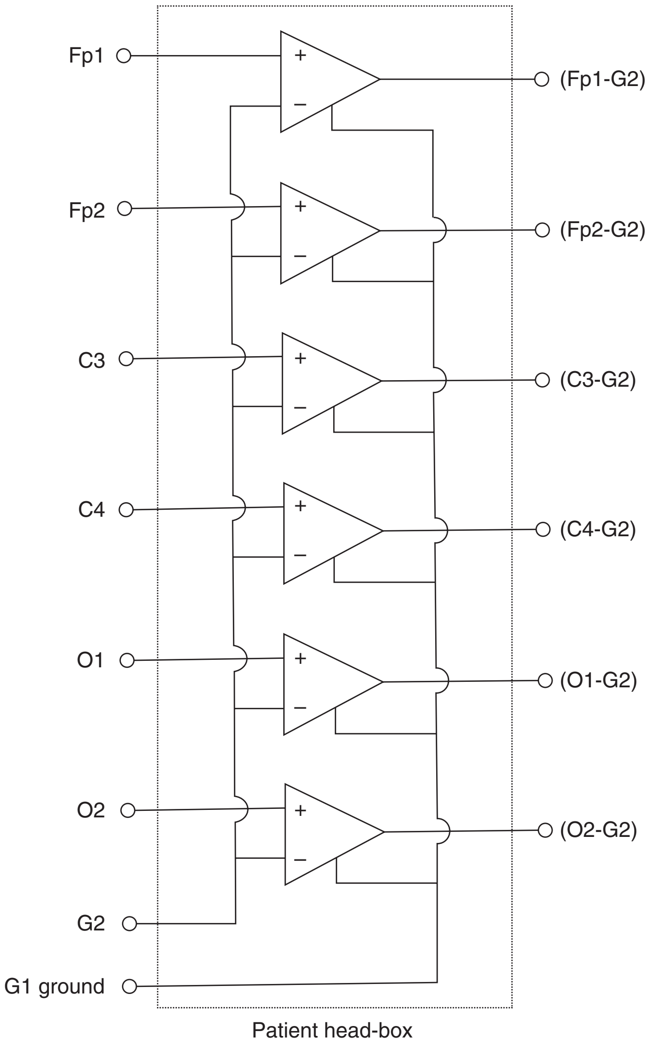

Fig. 4.11 G2—common reference recording. G2 electrode is connected to the inverting input (negative) of all amplifiers, while the electrode to be measured is connected to the non-inverting input. What the machine physically measures is the potential difference between each electrode and G2 (Fp1–G2, etc.)

4.5.1.2 Common Average Reference

Many of the problems encountered with the use of common reference can be overcome by average reference (AVG), a mathematical reference, introduced in electroencephalography by Goldman and Offner in 1950 [10, 11]. In this case, the potentials of single electrodes are referred to an instant average value obtained by adding together the potentials of all applied electrodes. The higher the number of electrodes, the closer to zero the reference average potential will be. In fact, one of the properties of the mathematical average of a series of numerical values is that the sum of the average differences equals zero. Regarding the results on the EEG tracings, this means that we will always have positive or negative deflections, with respect to the zero value of the reference.

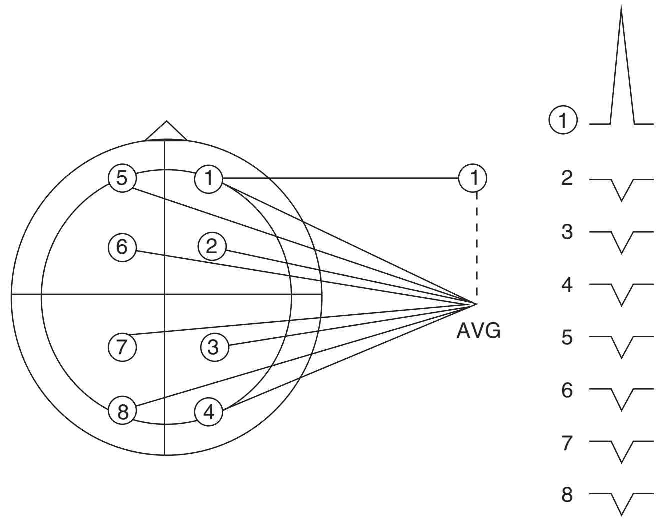

Fig. 4.12 Average reference (AVG) recording (see text for explanation)

In analog systems, this derivation method is achieved by joining all electrodes to a high resistor placed in a common place inside the device. Modern digital systems calculate the mathematical average of the potential differences of all the electrodes used at the same time, and moment by moment. Figure 4.12 exemplifies how AVG reference works. In this case, an ideal situation is presented with only eight electrodes applied to the scalp; electrode 1 has a more significant potential difference than the others (−80 μV), while the other electrodes remain at arbitral values of *zero*. The average of all electrodes will be:

$$\frac{-80+0+0+0+0+0+0+0}{8} = -10\mu V$$

As a result, electrode 1 will have a negative potential equal to:

$$-70\mu V \to \left[-80-\left(-10\right)=-70\mu V\right],$$

other electrodes will have a small positive potential equal to:

$$10\mu V \to \left[0-\left(-10\right)=10\mu V\right]$$

Therefore, the first electrode will have an upward deflection equal to −70 μV, while other electrodes will have a downward deflection equal to 10 μV.

More generally, when an electrode has a potential of value *P*, the AVG reference of that electrode will record a potential difference P_1 equal to:

$$\frac{P\left(n-1\right)}{n}$$

The higher the value of n, the closer P_1 will get to the value of P and the lower the deflections on the other channels will be. This means that the number of electrodes which contribute to average calculation should be as high as possible.

In digital electroencephalography, calculation of the average reference is achieved as follows (in this case, with application of 19 standard electrodes):

$$\frac{\left[(\mathrm{Fp1}-\mathrm{G2})+\mathrm{Fp2}-\mathrm{G2})+\ldots+(\mathrm{O1}-\mathrm{G2})\right)}{19}$$
$$=\frac{\left[\mathrm{Fp1}+\mathrm{Fp2}+\ldots+\mathrm{O1}+\mathrm{O2}\right]}{19}-\frac{19\times\mathrm{G2}}{19}=\frac{[0]}{19}-\mathrm{G2}=-\mathrm{G2}$$

All above described is valid assuming that the average value of the 19 electrodes is 0. In this case, AVG value constitutes the absolute value of point G2. The AVG reference trace tells us that:

$$(\mathrm{Fp1}-\mathrm{AVG})=(\mathrm{Fp1}-\mathrm{G2})-(-\mathrm{G2})=\mathrm{Fp1}-\mathrm{G2}+\mathrm{G2}=\mathrm{Fp1}$$

The recorded potential should then be the absolute potential of the Fp1 electrode.

Some systems are equipped to eliminate some of the electrodes from the total summation, but this can cause reviewing errors. Every average common derivation, whose deflections summation is other than zero, should be carefully and cautiously evaluated.

When we use an AVG reference, a localized event affects multiple channels, though the electrodes directly above the focal fields can usually be identified as the ones with higher amplitude deflections and of opposite polarity, compared to the majority of the other electrodes.

An accurate localization of a specific event is not easy in the case of multifocal and not in-phase potentials recorded by various electrodes, which will lead to activity resets.

Furthermore, the problem of contamination exists also in this case and it is accentuated in the case of high-amplitude localized activities on the scalp, including artifactual activity. To avoid this, the *correct average reference* can be calculated by excluding, from the average, the electrodes in which an excessively high-voltage or artifactual activity is recorded.

4.5.1.3 Source Derivation

Finally, a particular type of average reference is source derivation, introduced for the first time by Hjorth in 1975 [12] to improve the localization of focal activity on the scalp.

In this case, each electrode potential is referred to a reference making the weighted average of the electrodes around it. Its basic principle is that each cerebral generator causes a wave, which is much wider than the starting focal point. Source derivation tries to view focal generators as radial currents, travelling along the scalp, starting from the generator itself. This method is based on the application of Laplace's equation, according to which the radial current of a given point can be calculated by the second derivative of the electric field potential of that point. Basically, the radial current is calculated by the summation of the potential differences of the dipole created by the electrode in question and by the four surrounding electrodes. The resulting currents are called Laplacian. In the ideal situation where the focal point is located underneath the electrodes that are being observed, the Laplacian current will be the only visible one, while the value of the currents underneath the neighbouring electrodes will be zero. Source derivation, then, is nothing more than the visualization of a single electrode potential, compared to the weighted average of its neighbouring electrodes and the average weightings are inversely proportional to the distance between the electrode in question and its neighbours, from which the reference is calculated.

However, this technique has considerable limitations, including alteration of the real width of a potential and the generation of false opposition of polarity.

Figure 4.13a shows the differences that can be encountered using source derivation, starting from an "ideal" situation in which a high potential, placed under the F3 electrode and transmitted to the neighbouring electrodes in a variable manner, is recorded on the scalp with common reference (the F3 absolute potential is of 100 μV). With the source derivation method, considering the potential of F3 with respect to the weighted average of the four surrounding electrodes (Fp1, F7, C3, Fz), the resulting potential will be of 20 μV, significantly lower than the one we started from.

$$\mathrm{F3}=100-\frac{80+80+80+80}{4}=20\mu V$$

Conversely, if the electrode F8 has an absolute potential of 0 (as in Fig. 4.13b), with source derivation method an opposite polarity (−40 μV) will be obtained, in comparison to the weighted average of the surrounding electrodes Fp2, F4, C4 and T4.

$$\mathrm{F8}=0-\frac{40+80+40+0}{4}=-40\mu V$$

4.5.1.4 Bipolar Derivations

In bipolar derivations, the potential difference is calculated between electrode pairs, placed along chains (longitudinal or transversal) in which an electrode is shared with two following channels.

In this way, an event localized underneath a specific electrode will generate a deflection with the same voltage, but opposite polarity, in the two adjacent points in the chain of the electrode.

Figure 4.14a shows how the previously described theoretical example of common reference (maximum negative potential at F3 electrode) appears using bipolar derivation. The phenomenon known as *phase-reversal*, typical of bipo-

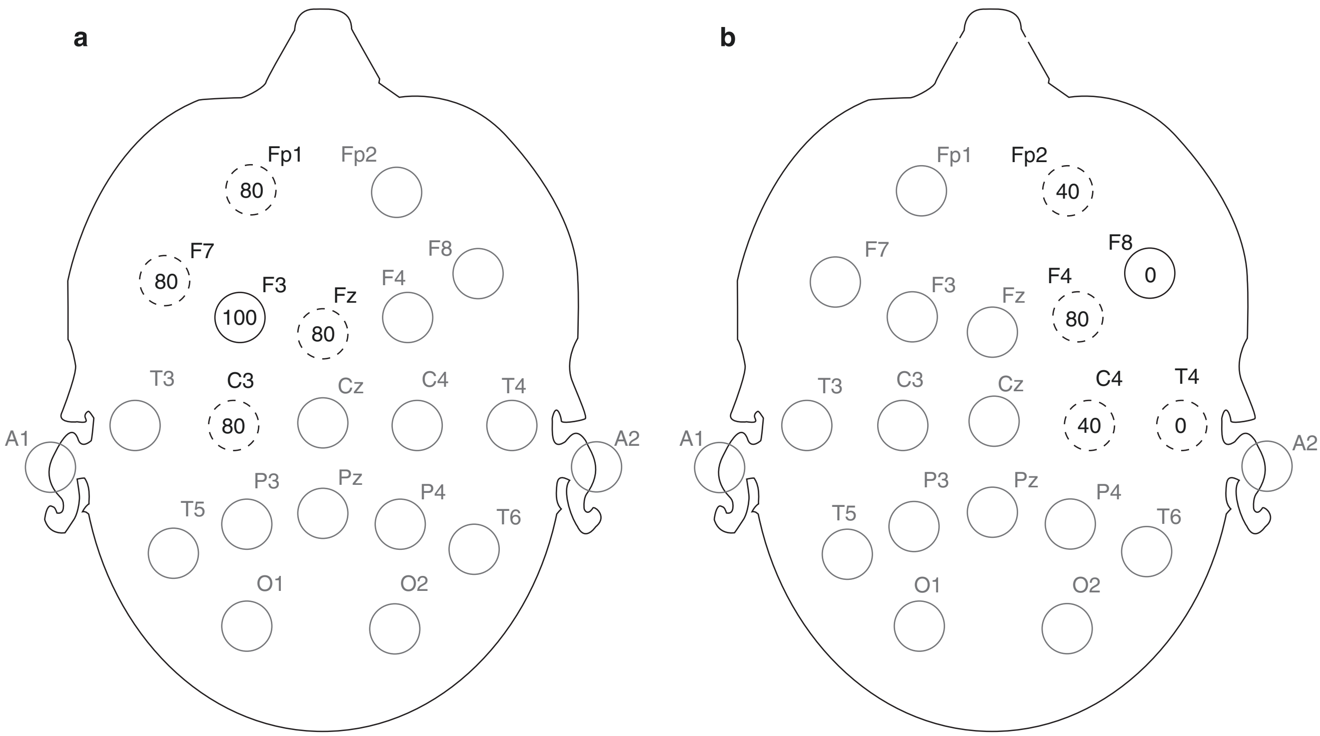

Fig. 4.13 Comparison between the absolute potential of F3 and F8 obtained with "inactive" common reference (CR) and that deriving from source derivation (SD) method. The dotted circles indicate the electrodes used for the source derivation. In (**a**) the absolute potential of F3. In (**a**) the absolute potential of F3 with CR is 100 μV and with SD 20 μV. In (**b**) the absolute potential of F8 is 0 μV with CR and—40 μV with SD

lar montages and caused by the fact that an electric event affects the electrode in the middle of the chain, occurs between channels 1 and 2. In this case, F3 localizes the maximum field and the reverse phase is due to the fact that it is a common electrode to the first and second channel. This is an *instrumental phase reversal,* because it is the instrument that causes the phase reversal; it must be distinguished from a *true phase reversal*, due to two different polarities simultaneously present in adjacent cortical areas.

When the maximum potential field is equally distant from the F3 and C3 electrodes (Fig. 4.14b), the second channel will not record any potential difference (zone of isopotentiality), while the phase reversal will be observed between the first and the third channel. Finally, if the maximum potential field takes place at the end of the chain (Fig. 4.14c), the only positive deflection will be detected in the channel connecting C3 with P3, possibly causing a wrong interpretation of the phenomenon. The phenomenon of phase reversal is shown also in Fig. 4.15.

Using bipolar derivations for a correct focal localization of the bioelectrical events, it is necessary to simultaneously display two electrode chains, placed perpendicular to each other: an accurate and exact localization is possible only when the phase reversal occurs at the point where the two lines intersect. In Fig. 4.16, the maximum focal field is localized in the quadrangle enclosed between the Fz, F4, C4 and Cz electrodes, with its relating isoelectric line on the channels connecting orthogonally the F4–C4 and C4–Cz electrodes. In conclusion, bipolar derivations have a remarkable localization ability but, in order to achieve this, it is essential that the various interelectrode chains are displayed simultaneously (anteroposterior and transversal).

With the bipolar montage, it is harder to compare the asynchrony between two homologous regions and it is difficult to map the voltage of a specifically localized event. It is also important to remember that in-phase activities affecting both inputs of the differential amplifier are evened out: therefore, spikes generating a fairly extensive area can be completely obscured or only partially shown. The opposite can also happen though: if a spike is positive in F4 and negative in C4, by pairing F4–C4 we will see a "false" spike of higher amplitude (addition-out-of-phase).

As already pointed out, recent digital EEG systems always use a reference derivation in signal acquisition, measuring the potential of each electrode with reference to a common electrode (G2).

With these systems it is possible, both online and offline, to reformat any type of montage and, thus, to display the tracing both in reference (common or AVG) and in bipolar derivation. To reformat a bipolar derivation starting from the one using G2 as a common electrode, the computer executes the following process:

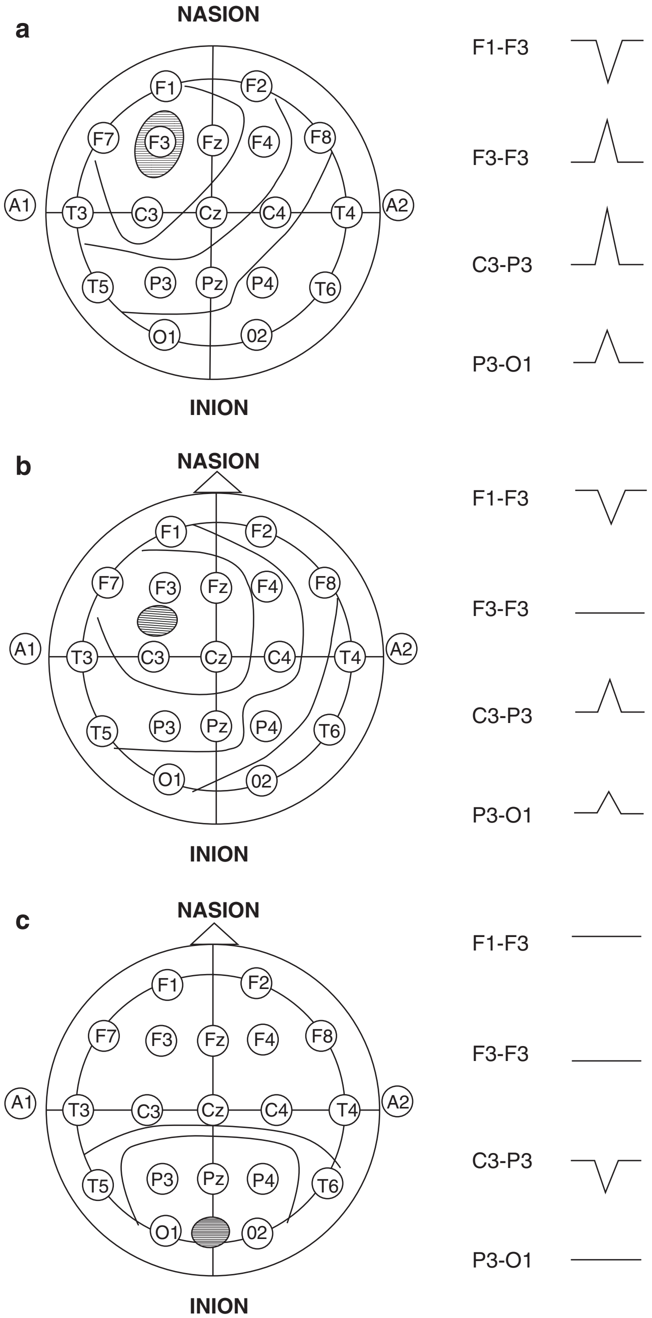

Fig. 4.14 Bipolar derivation recording (see text for explanation). (**a**) maximum negative potential at F3 electrode, phase reversal phenomenon; (**b**) zone of isoipotentiality when maximum potential field is equally distant from F3 and C3; (**c**) maximum potential field at the end of the chain: only positive deflection will be detected in the channel connecting C3 with P3

$$(\mathrm{Fp2} - \mathrm{G2}) = \mathrm{A}$$

$$(\mathrm{F4} - \mathrm{G2}) = \mathrm{B}$$

$$\mathrm{A} - \mathrm{B} = (\mathrm{Fp2} - \mathrm{G2}) - (\mathrm{F4} - \mathrm{G2}) = \mathrm{Fp2} - \mathrm{G2} - \mathrm{F4} + \mathrm{G2}$$
$$= \mathrm{F2} - \mathrm{F4}$$

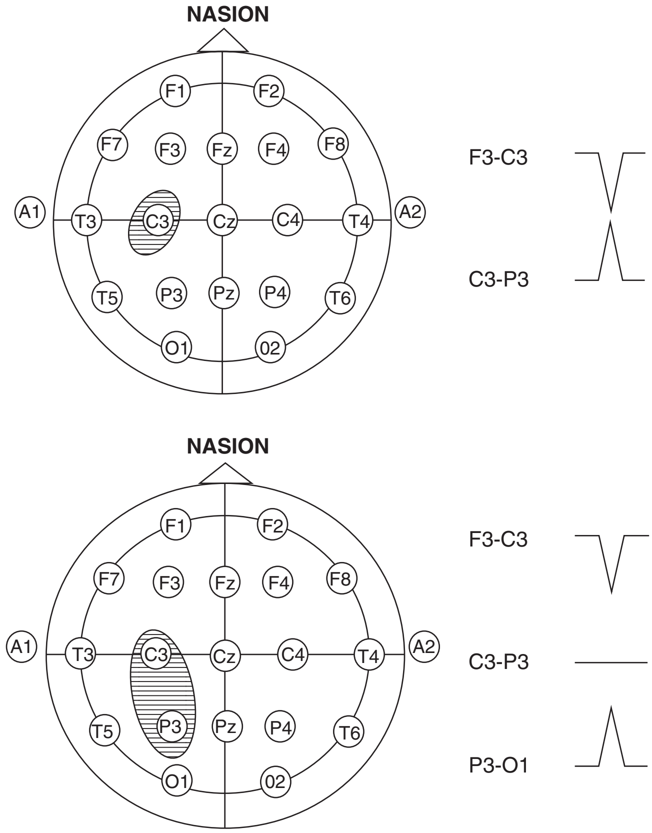

Fig. 4.15 Schematic representation of an instrumental phase reversal phenomenon between F3–C3 and C3–P3 channels. A maximum field potential underneath C3 will be observed in phase reversal on the two channels having C3 in common (*above*) while, if the event equally affects the two adjacent electrodes C3 and P3, the potential will be cancelled on the channel connecting these two electrodes (*below*)

Through this simplified mathematical calculation, the computer is able to reformat the montage and show it as bipolar, subtracting the value of G2 electrode, used as reference.

4.5.1.5 Choice of Derivation in Clinical Practice

Since EEG patterns are variable (focal or diffuse, transient or persistent), there is not one single ideal derivation to highlight all cerebral activities. A first important factor to take into account in the choice of derivation is the *interelectrode distance*, and this is particularly valid for active common references and bipolar derivations. In bipolar derivations, distances between the paired electrodes are small and equal, favouring the detection of the fast EEG activities; in active common reference, distances are bigger and unequal, facilitating the amplification of the signal, thus better showing the slower activities.

Focal epileptic activity is a phenomenon that provokes a change in the potential, limited to a small part of the scalp. In order to accurately localize a strictly isolated focal potential with bipolar derivations, it is necessary to demonstrate the simultaneous phase reversal at the point of intersection between two electrode chains placed perpendicular to each

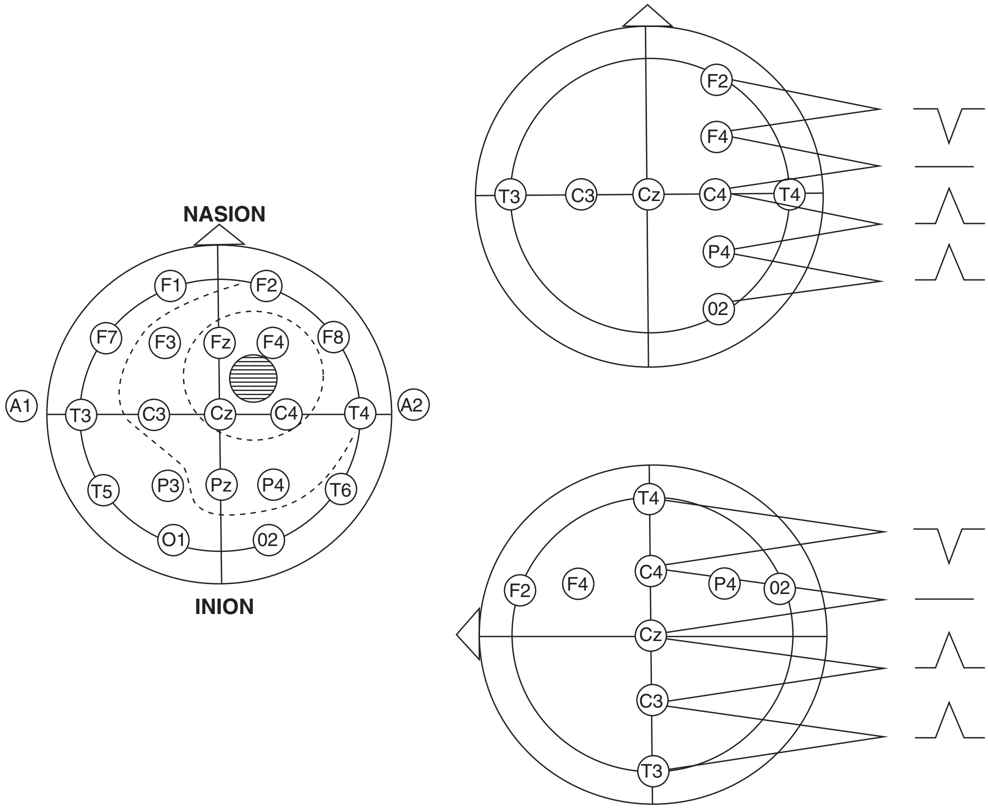

Fig. 4.16 In bipolar derivations the correlation between longitudinal and transversal interelectrodic chains allows a more accurate localization of focal event with the identification of phase reversal and isopotentiality phenomena (see text for further explanation)

other: therefore, it is necessary to use a suitable montage and, sometimes, to also apply additional electrodes.

Common reference does not present such limitations and it has some advantages, especially for the detection of an epileptic activity with a not very good localized focus; it is important, though, to be sure that the chosen reference is not contaminated by the activity of the phenomenon itself (e.g., in case of a focus with centrotemporal spikes, the ideal common reference is placed on the contralateral auricular lobe).

Average reference seems to be the preferable technique, even if the problem of contamination still exists for all channels (it is thus advisable to calculate the correct average reference, obtained by excluding the most active electrodes from the average calculation). When the focus is recorded by multiple electrodes, the phenomenon is better showed using common reference (preferably inactive), which provides a better definition of the potential distribution and of the shape of the wave.

In order to correctly identify and localize any focal activity, it should always be best to use more than one derivation. Generally, it is important to bear in mind some important considerations:

– Common reference allows to locate focal activity with higher voltage and with the same polarity.
– Average reference shows a wider signal underneath one or more electrodes, but of opposite polarity than the majority of other electrodes.
– Bipolar derivation localizes focal activity highlighting the phase reversal or cancellation of the signal (zone of isopotentiality).

Figure 4.17 shows how visualization of a real right temporal epileptic focus, recorded with a digital system, which varies depending on the displayed derivations.

Most of EEG diffuse activities are correctly evidenced by bipolar derivations, while average reference (AVG) can be misleading, possibly showing a localized phenomenon as a diffuse one. However, with bipolar derivation, the potential differences between adjacent electrodes are recorded and there are no indications regarding the activity of each electrode with respect to a distant reference point; in addition, bipolar derivation can show a reduction in signal amplitude or, within a widespread pattern, it can underestimate focal amplitude reductions, which has the same localization value as spikes. Generally, EEG diffuse activities are better evidenced by a common reference derivation, but the reference electrode should not be affected by the studied activity and so, when this is not possible, it should be placed in a way that allows equal recording of both hemispheres. An extracranial medial reference, for example, can be used. Fig. 4.18 shows a widespread spike-wave discharge, predominant anteriorly, with the three recording methods.

To summarize, the main advantages and disadvantages of the derivation systems are the following:

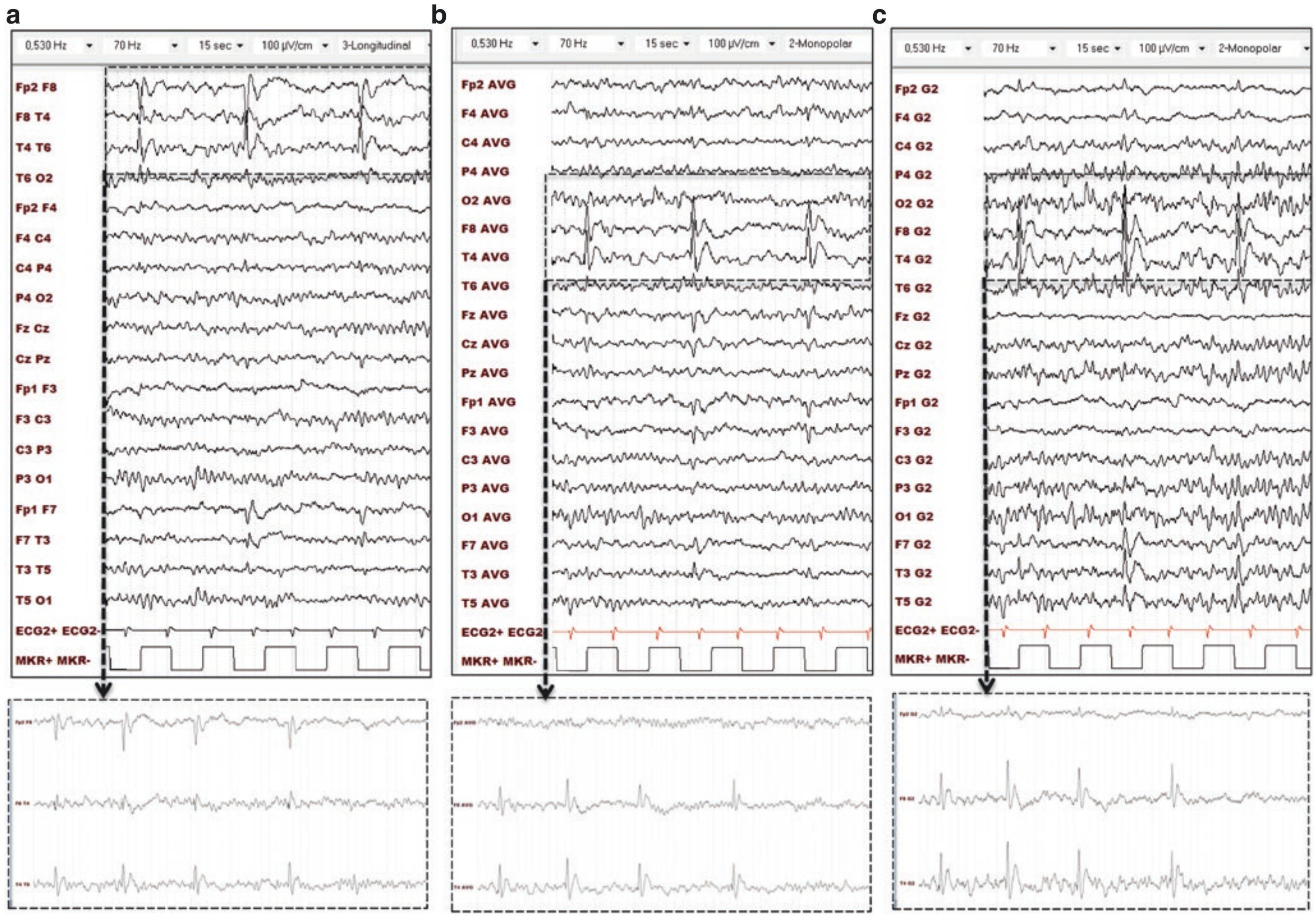

Fig. 4.17 The same EEG epoch of 5 s shows a right temporal epileptic focus in bipolar, AVG reference and common active reference derivations. In (**a**) (bipolar derivation) the phase reversal phenomenon in the first and third channel is evident, with almost total cancellation of the spikes in the intervening channel F8–T4 (these electrodes are placed over the focus and their potentials presumably have the same polarity and voltage as input to the differential amplifiers); note the poor spread of spikes to the homologous contralateral areas. The AVG reference derivation (**b**) confirms the higher negative signals at F8 and T4 electrodes; note, however, that positive signals are present also in Fz, Cz, Fp1 and F3, and negative in F7 and T3. When a common active electrode of reference is used (**c**) (G2, placed on midline in Fpz), the signal shows the same negative higher voltage in F8 and T4, with the evidence of synchronous lower negative signals contralaterally in F7, T3 and T5. However, in this practical example, all three derivations allow to localize the epileptogenic focus with good reliability (T4, T6, T3, T5 = T8, P8, T7, P7 according to the new nomenclature)

1. Common reference derivation.
   (a) Good localization of any kind of focal activity (including low-voltage or flat activity).
   (b) Good wave-shape definition.
   (c) Acceptable localization of the most common artefacts.
   (d) Good mapping of diffuse activity.
   (e) Acceptable evaluation of bilateral synchrony of homologous areas.
   (f) If the reference is not inactive, its activity will "contaminate" the related electrodes, compromising the above-listed advantages.
2. Average reference derivation.
   (a) Acceptable localization of transient focal graphoelements
   (b) Poor wave-shape definition (except for sharp focal potentials on a low-voltage background activity)
   (c) Unsatisfactory highlighting of areas with low-voltage activity
   (d) Poor artifact localization
   (e) Unreliable in cases with high-voltage asynchronous diffuse activity
   (f) Unreliable when one or several electrodes record high-amplitude activity, influencing the calculation of the average too much
3. Bipolar derivation
   (a) Good localization of transient focal activity
   (b) Good definition of bilateral synchrony-symmetry of homologous areas
   (c) Good localization of the most common artefacts

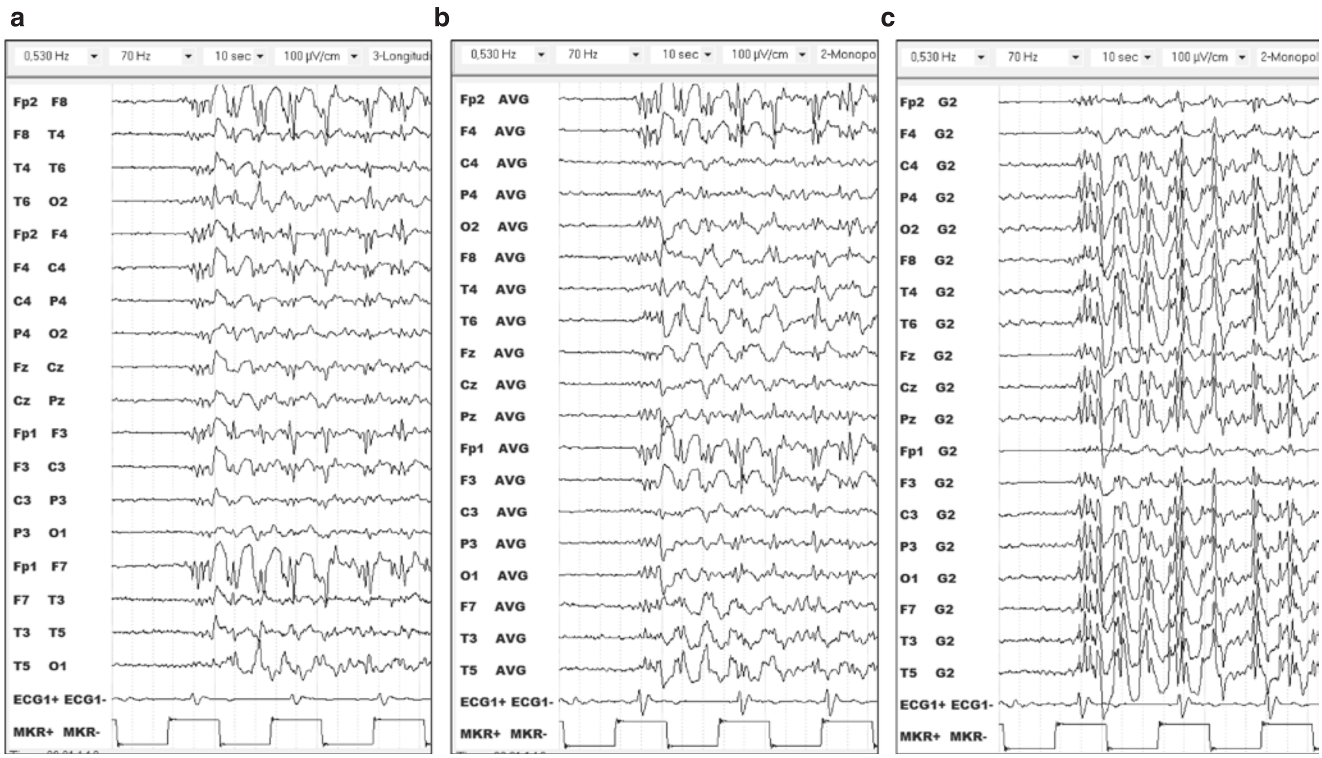

Fig. 4.18 Diffuse discharge of polyspikes and spike-and-wave complexes, predominantly in anterior areas. The bipolar (**a**) and AVG reference derivation (**b**) show the real characteristic of discharge, while the common active reference derivation (with G2-reference electrode placed in Fpz) is misleading (**c**). In (**c**) the contamination reference is very evident and the electrodes with larger signals are precisely those closest to the reference electrode; in them, therefore, the recorded activity is significantly reduced in voltage (T4, T6, T3, T5 = T8, P8, T7, P7 according to the new nomenclature)

(d) Poor mapping of diffuse activity
(e) Poor or non-existent emphasizing of areas with absence or reduction in signal voltage
(f) Suppression or reduction in amplitude of in-phase activity on a pair of electrodes (isopotentiality areas)
(g) Not always good wave-shape definition

4.5.2 Montages

A montage is the specific method of electrode connection to the recording channel of the electroencephalograph. With 21 electrode positions in the 10-20 system and 16 channels on display, the number of possible montages is 21. The 10-10 system, with more than 70 electrode positions, allows the creation of an even higher number of montages and the modern digital EEG machines allow the display of up to 256 channels.

A wide range of montages, many of which are complex and inadequate, is used in EEG laboratories for routine recordings. This dissimilarity prevents the correct exchange of information between experts in the field. To counteract this, both the International Federation of Clinical Neurophysiology (IFCN) and the American Clinical Neurophysiology Society (ACNS) have published some guidelines which include ad hoc recommendations [7, 13].

The montages for routine EEG recording are designated as Longitudinal Bipolar (LB), Transverse Bipolar (TB), or Referential (R). Montages are designed for 18, 20, 26 and more channels. Here we report a list of the main recommendations drawn from the above-mentioned guidelines:

– Not less than 16 channels of simultaneous recording should be used (a larger number of channels would be encouraged).
– At least 21 electrodes should be placed following the 10-20 system (the IFCN recommend at least 25 electrodes, including the inferior temporal chain) [7].
– Both bipolar and referential montages should be used for clinical interpretation.
– The electrode derivations of each channel should be clearly identified at the beginning of each montage, so that the pattern of electrode connection is made as simple as possible and easily comprehensible.
– In bipolar derivations, electrode pairs should run in straight lines and their interelectrode distance should be kept equal.
– Channel progression must be anterior-posterior.

Guidelines also recommend that a single channel Electro Cardio Gram (ECG) should be included on one EEG channel.

According to IFCN and ACNS, channels obtained by connecting the left-side electrodes should be above the right-sided ones. This recommendation coincides with the prevailing practice of the vast majority of EEG laboratories in North America and in other areas, but it is not followed in Italy and in many other European countries. In this book, according to the tradition of the Italian and European neurophysiological academic school and the totality of clinical practice in our country, the right-sided leads are placed above the left-sided leads for either blocks of derivations.

Regarding referential montages, the choice of reference is critically important. For the ACNS, a midline electrode (as Cz) would be a better choice of reference than A1 or A2. However, the referential suggested montages by ACNS establish the right auricular electrode (A2) as reference for the electrodes on the right side and the left auricular electrode (A1) for the ones on the left side.

Currently, in digital electroencephalography, the G2 reference electrode can be used as an "active" reference, placing it on the midline, anteriorly to Fz.

Figures 4.19 and 4.20 show suggested bipolar longitudinal and transverse montages with the extended standard array. Table 4.1 shows bipolar (old and new) and referential suggested montages. According to 10-10 position nomenclature, T4, T6, T3 and T5 should be changed to T8, P8, T7 and P7.

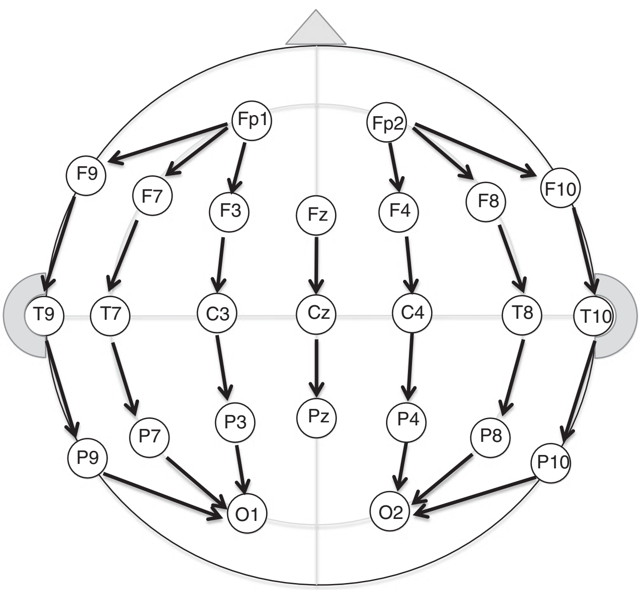

Fig. 4.19 New longitudinal bipolar montage proposed by International Federation of Clinical Neurophysiology (IFCN) [7]

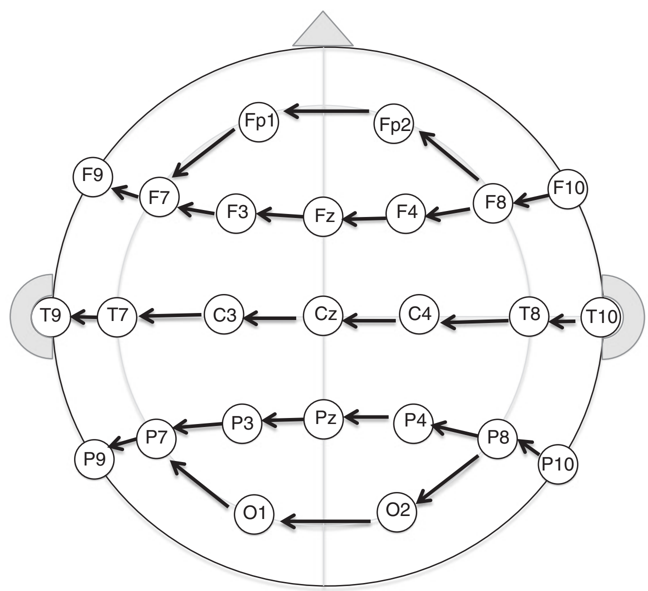

Fig. 4.20 New transverse bipolar montage proposed by International Federation of Clinical Neurophysiology (IFCN) [7]. Note that the interelectrode distance between the inferior and superior temporal electrodes is shorter (10%) compared to the other interelectrode distances (20%)

Table 4.1 Suggested old/new Longitudinal Bipolar (LB) and Transverse Bipolar (TB) and referential montages with the extended standard array [7]

No. channel	LB montage (old)	No. channel	LB montage (new)	No. channel	TB montage (old)	No. channel	TB montage (new)
1	Fp2—F8	1	Fp2—F10	1	F8—Fp2	1	F8—Fp2
2	F8—T8 (F8–T4)	2	F10—T10	2	Fp2—Fp1	2	Fp2—Fp1
3	T8—P8 (T4–T6)	3	T10—P10	3	Fp1—F7	3	Fp1—F7
4	P8—O2(T6–O2)	4	P10—O2	4	F8—F4	4	F10—F8
5	Fp2—F4	5	Fp2—F8	5	F4—Fz	5	F8—F4
6	F4—C4	6	F8—T8	6	Fz—F3	6	F4—Fz
7	C4—P4	7	T8—P8	7	F3—F7	7	Fz—F3
8	P4—O2	8	P8—O2	8	T8—C4 (T4–C4)	8	F3—F7
9	Fz—Cz	9	Fp2—F4	9	C4—Cz	9	F7—F9
10	Cz—Pz	10	F4—C4	10	Cz—C3	10	T10—T8
11	Fp1—F3	11	C4—P4	11	C3—T7 (C3–T3)	11	T8—C4
12	F3—C3	12	P4—O2	12	P8—P4 (T6–P4)	12	C4—Cz
13	C3—P3	13	Fz—Cz	13	P4—Pz	13	Cz—C3
14	P3—O1	14	Cz—Pz	14	Pz—P3	14	C3—T7
15	Fp1—F7	15	Fp1—F3	15	P3—P7 (P3–T5)	15	T7—T9
16	F7—T7 (F7–T3)	26	F3—C3	16	P8—O2 (T6–O2)	16	P10—P8
17	T7—P7 (T3–T5)	27	C3—P3	17	O2—O1	17	P8—P4
18	P7—O1 (T5–O1)	18	P3—O1	18	O1—P7 (O1–T5)	18	P4—Pz
19	ECG	19	Fp1—F7	19	ECG	19	Pz—P3
		20	F7—T7			20	P3—P7
		21	T7—P7			21	P7—P9
		22	P7—O1			22	P8—O2
		23	Fp1—F9			23	O2—O1
		24	F9—T9			24	O1—P7
		25	T9—P9			25	ECG
		26	P9—O1				
		27	ECG				

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