Clinical Neurophysiology 128 (2017) 2070–2077

Contents lists available at ScienceDirect

Clinical Neurophysiology

journal homepage: www.elsevier.com/locate/clinph

Guidelines

The standardized EEG electrode array of the IFCN

Margitta Seeck [a,*], Laurent Koessler [b], Thomas Bast [c], Frans Leijten [d], Christoph Michel [e], Christoph Baumgartner [g], Bin He [f], Sándor Beniczky [h]

[a] EEG & Epilepsy Unit, University Hospital of Geneva, Switzerland
[b] CNRS, CRAN, UMR7039, Vandoeuvre-lès-Nancy, & Neurology Department, University Hospital, Nancy, France
[c] Epilepsy Center Kork, Kehl, Germany
[d] Brain Center Rudolf Magnus, University Medical Center Utrecht, The Netherlands
[e] Department of Basic Neuroscience, University of Geneva, Switzerland
[f] Department of Biomedical Engineering, University of Minnesota, Minneapolis, USA
[g] Neurological Department, General Hospital Hietzing with Neurological Center Rosenhügel, Karl Landsteiner Institute of Clinical Epileptology, Sigmund Freud University, Vienna, Austria
[h] Danish Epilepsy Centre, Dianalund, Denmark and Aarhus University, Aarhus, Denmark

See Editorial, pages 2068–2069

ARTICLE INFO

Article history:
Accepted 20 June 2017
Available online 17 July 2017

Keywords:
Scalp
Routine EEG
Montage
Temporal
Electrodes
10–10-system
10–5-system
High density EEG
Standard EEG

HIGHLIGHTS

- An array of 25 electrodes is recommended for standard EEGs with inferior temporal electrodes.
- Due to thinner skulls (spatial aliasing), pediatric EEG requires as many scalp electrodes as in adults.
- Arrays with higher electrode numbers (64–256 electrodes) allow source imaging at sublobar level.

ABSTRACT

Standardized EEG electrode positions are essential for both clinical applications and research. The aim of this guideline is to update and expand the unifying nomenclature and standardized positioning for EEG scalp electrodes. Electrode positions were based on 20% and 10% of standardized measurements from anatomical landmarks on the skull. However, standard recordings do not cover the anterior and basal temporal lobes, which is the most frequent source of epileptogenic activity. Here, we propose a basic array of 25 electrodes including the inferior temporal chain, which should be used for all standard clinical recordings. The nomenclature in the basic array is consistent with the 10–10-system. High-density scalp EEG arrays (64–256 electrodes) allow source imaging with even sub-lobar precision. This supplementary exam should be requested whenever necessary, e.g. search for epileptogenic activity in negative standard EEG or for presurgical evaluation. In the near future, nomenclature for high density electrodes arrays beyond the 10–10 system needs to be defined, to allow comparison and standardized recordings across centers. Contrary to the established belief that smaller heads needs less electrodes, in young children at least as many electrodes as in adults should be applied due to smaller skull thickness and the risk of spatial aliasing.

Contents

* Corresponding author at: EEG and Epilepsy Unit, Department of Neurology, University Hospitals of Geneva, Rue Gabrielle-Perret-Gentil 4, CH-1211 Geneva, Switzerland. Fax: +41 22 372 8340.
E-mail address: Margitta.Seeck@hcuge.ch (M. Seeck).

http://dx.doi.org/10.1016/j.clinph.2017.06.254

1. History

Standardising the position and nomenclature of scalp electrode arrays was an important step in the development of electroencephalography. First, the 10–20 system of the International Federation was developed by Herbert H. Jasper and his co-workers (Jasper, 1958), resulting in the first published guidelines in 1999 (Klem et al., 1999). Early on the lack of proper coverage of the temporal lobe was criticized, resulting in the proposition of the 'Maudsley electrodes' to sample the temporal pole (Binnie et al., 1982). Later, the 10–20 system was extended with the 10% electrode positions of the modified combinatorial nomenclature. With the advent of source imaging, high density EEG electrode arrays including 5% electrode positions, were developed, resulting in electrode arrays of up to 345 positions (Oostenveld and Praamstra, 2001). Due to engineering advances in EEG amplifiers, a much higher number of electrodes can be simultaneously recorded, and currently available systems allow EEG recording from up to 256 locations on the scalp. However, such a large array is reserved for specific applications, such as electric source imaging for presurgical evaluation.

In this guideline we define the minimum number, position and nomenclature of scalp electrodes for standard recordings and discuss the yield of higher electrode numbers for special clinical questions. This paper presents a unified approach for the use of electrode arrays, ranging from the basic array (25 electrodes, including six electrodes in the inferior temporal chain), through an extended version of the modified combinatorial array to the high-density array (currently commercial systems accommodate up to 256 electrodes).

2. Basic electrode array and nomenclature of the 10–20 system

Electrode positions are based on percentages of the circumferential measurements from cephalometric landmarks of the skull (Klem et al., 1999). The electrode names consist of letters and numbers. The letters (F, T, P, O) indicate the underlying lobe (exception: P7/8, overlying the posterior temporal lobe). C indicates the central region. Anatomical studies showed that using the measurements described here, C electrodes are located 1 cm within the central sulcus (Klem et al., 1999). Fronto-polar electrodes are annotated Fp. Odd numbers are on the left side, and even numbers on the right side. Electrodes in the midline are annotated with z (for zero). Landmarks on the skull are: the left and right preauricular points (depressions at the root of the zygoma, just anterior to the tragus), nasion (depression between the eyes, just superior to the bridge of the nose, at the intersection of the frontal bone and the nasal bones) and inion (the highest point of the protuberance of the occipital bone, in the midline; Fig. 1).

Based on the anatomical landmarks detailed above, the following measurements have to be obtained.

The first (longitudinal) circumferential measurement is in the sagittal plane, in the midline of the skull, from the nasion, through the vertex (the uppermost point of the head) to the inion (Fig. 1-A). Considering this distance as 100%, five points are marked between the nasion and inion, in the anterior-posterior direction, giving the level (longitude) of the following points: Fpz (10% from the nasion), Fz (20% from Fp), Cz (20% from F), Pz (20% from C) and Oz (20% from P and 10% anterior to the inion).

The second (transversal) circumferential measurement is in the coronal plane, from the left to the right preauricular point, through the vertex (Fig. 1-B). Considering this distance as 100%, seven points (latitudes) are marked in this direction: T9 (at the left preauricular point), T7 (10% from the preauricular point), C3 (20% from T7), Cz (20% from C3, at the intersection of the first and second circumferential measurement), C4 (20% from Cz), T8 (20% from C4) and T10 (10% from T8, at the right preauricular point).

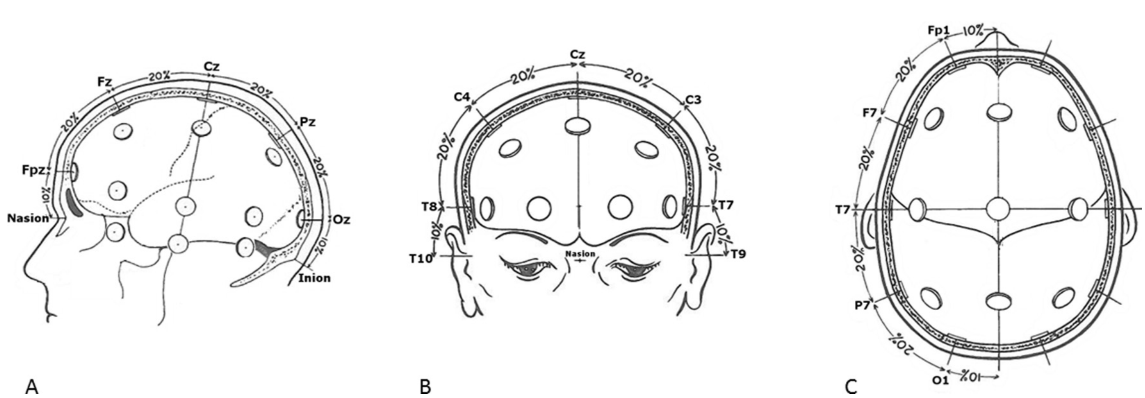

Fig. 1. A-C: Placement of the standard electrodes of the 10–20-system (modified from Klem et al., 1999, with permission). A: lateral view, B: frontal view, C: from the top.

The third circumferential measurement (Fig. 1-C) is taken from Fpz to Oz, on the left side (through T7) and on the right side (through T8). In the anterior-posterior direction, points are marked on left/right side for 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).

The fourth measurement is performed in the parasagittal, oblique plane, on the left side (from Fp1 to O1, through C3) and on the right side (from Fp2, through C4 to O2). This represents 80% of the distance from Fpz to Oz, through C3/4, therefore 20% of the Fpz to Oz distance is the same as 25% of the parasagittal measurement from Fp1/2 to O1/2. At 25% segments of the parasagittal measurement, the following positions are marked in the anterior-posterior direction: F3/4, C3/4, P3/4.

3. Modification of the 10–20 nomenclature

It was felt that the labels T3/T4 and T5/T6 were inconsistent with respect to the other labels in the same sagittal line (Acharya et al., 2016). As can be seen in the head diagram of the modified combinatorial system, all electrodes on the sagittal line are labelled 7, if on the left hemisphere, and 8 if on the right hemisphere. The only exceptions are the electrodes Fp1/Fp2 and O1/O2. Thus, instead of T3/T4, the midtemporal electrodes are labelled T7/T8 and T5/T6 become P7/P8 (Fig. 2). The disadvantage of the new labelling is that the letter "P" might suggest parietal location, whereas P7/P8 are rather placed over the posterior temporal lobe. However, the new nomenclature is internally logic, which is why we strongly recommend to use the new electrode names, in agreement with the guidelines from the American Clinical Neurophysiology Society (Acharya et al., 2016). It should be kept in mind that the peak negativity at an electrode does not necessarily imply that the source is at the underlying brain region or lobe. This is only true for sources with radial orientation. The peak negativity generated by a tangentially oriented source can be located above a different lobe (for example Rolandic spikes generated in the anterior wall of the central sulcus, i.e. frontal lobe, induce a peak negativity at the parietal electrodes). Thus, the 1:1 relationship between the electrode positions and the underlying brain regions needs to be de-emphasized.

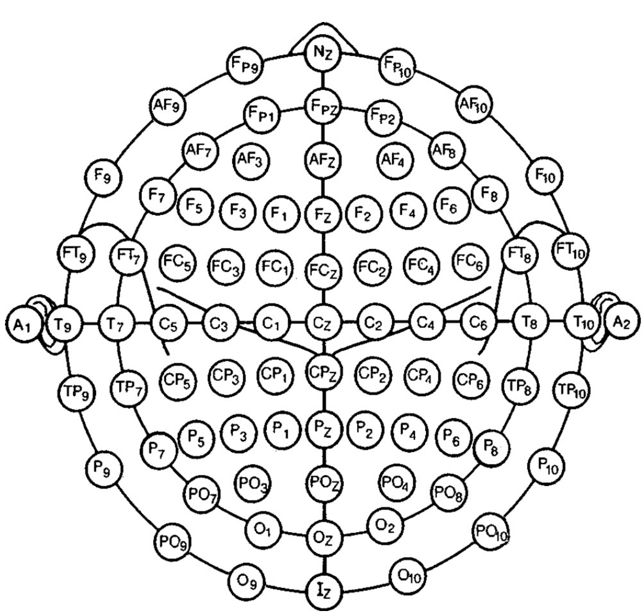

Fig. 2. Modified combinatorial nomenclature of the 10–10-system, extended with anterior and posterior electrodes in the inferior chain.

4. Extension to 10–10 combinatorial nomenclature

The modified combinatorial nomenclature (American Electroencephalographic Society, 1994) is an extension of the 10–20 system and adds electrodes placed in addition to the 19 electrodes considered the standard set-up currently used in clinics. The previously unnamed 10% electrodes were labelled using combination of letters together with numbers, that are consistent with the terminology of the standard set-up. Electrodes between frontal and central rows are named "FC", between frontal and temporal rows "FT", between central and parietal rows "CP" and between parietal and occipital rows "PO". The only exceptions are electrodes between the frontopolar and frontal rows, for which "AF" rather than "FP" is used, indicating anterior frontal placement. The reasons are to avoid three letters, like FPF, or two identical letters like FF. The modified combinatorial nomenclature of the 10–10-system added also contacts 10% inferior to the standard fronto-temporal and temporo-occpital chain which are designated with the numbers 9 (left) and 10 (right), to give rise to F9/F10, FT9/FT10, T9/T10, TP9/TP10, P9/P10. However, in the modified combinatorial nomenclature, this inferior temporal chain, remained open anteriorly and posteriorly. Recordings using high-density electrode arrays showed that voltage-maxima often were recorded at these electrode positions (for example orbitofrontal sources giving peak negativity at infraorbital positions on the cheek). Therefore, the inferior temporal chain is now completed, with electrodes Fp9/10, AF9/10, PO9/10 and O9/10 at this level (Fig. 2).

5. Recommended standard set-up

The standard 10–20 system did not include electrodes in the inferior chain (at the level of the preauricular point). Thus the inferior-basal and anterior part of the temporal lobe, which preferentially picks up activity originating or propagating from the mesial temporal structures, was not sampled (Rosenzweig et al., 2014; Koessler et al., 2015). Given that several diseases (e.g. temporal lobe epilepsy due to hippocampal sclerosis, autoimmune epilepsy, Alzheimer's disease) are characterized mainly by mesial temporal pathology, this region needs to be targeted through additional scalp electrodes in standard recordings. Thus, derived from the 10–10-system, we propose to add T9/T10 (10% inferior to T7/T8), F9/F10 (20% anterior to T9/10, or 10% inferior to F7/F8) and P9/P10 (10% inferior to P7/P8 or 20% posterior to T9/T10). The new basic array for clinical practice includes these six electrodes of the inferior temporal chain, which results in a total of 25 positions (Fig. 3). *For the reasons outlined above, we strongly recommend to use these 25 electrodes as a minimum for all standard recordings.* The use of fewer electrodes, but no less than 19 electrodes, is acceptable if technical limitations do not permit the use of the full 25-array (e.g. machine does not allow more recordings). Clinically useful montages are proposed in Table 1.

Modern EEG systems are equipped with cameras allowing simultaneous video recordings. The task force strongly recommends the use of video recordings for all EEG recordings, even for short standard EEGs and for seizure monitoring, including in intensive care units. Only with careful video-analysis of events of doubtful origin, a cerebral cause can be differentiated from an extracerebral cause, be it cardiac, psychogenic or other. The correspondence between the semiology and EEG gives valuable information for the characterization of the recorded episodes (e.g. seizure classification).

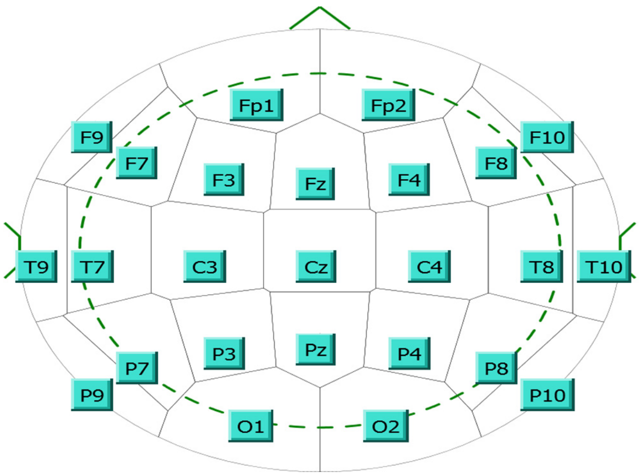

Fig. 3. New standard montage, with the additional coverage of the inferior and anterior brain regions.

6. High density recordings

Standard electrode set-ups provide an incomplete coverage of the patient's brain but represent a compromise between the everyday routine, given that additional electrodes require additional time and effort of technicians, and reliable detection of all epileptogenic activity. Indications for standard EEG include several settings, like diagnosis of encephalopathy, coma monitoring, search for generalized discharges, etc. which may not need extensive coverage. However, it should be kept in mind that coverage by standard montages is limited and epileptogenic activity may be overlooked if present only at distinct contacts (Fig. 4). *If there is a high suspicion of epilepsy, but no epileptiform discharges can be detected in standard EEG, or precise localization of the epileptic focus is necessary, recordings with electrodes from the full modified combinatorial 10–10-system or use of high density recording systems with even more electrodes is recommended by the task force.*

High density EEG (HD-EEG) which refers to the use of 64–256 electrodes has become an established tool over the past 10 years. Technical developments have made it easier to apply a large number of electrodes, which is particularly helpful in the clinical context. Geodesic electrode systems is a term used for equally distributed electrodes over a curved space, like the head. These systems provide dense and even sampling over the entire scalp, neck, cheeks, allowing to detect brain activity which could be otherwise missed (Fig. 5). Electrodes can be measured and attached individually on the scalp (cumbersome, usually very difficult beyond 64 electrodes) or applied by using expandable nets or caps which allow coverage within 30 min. Large electrode arrays cover more brain regions, and logically, allows better localization and definition of epileptogenic sources.

While visual analysis alone is possible for aiding localization, it can be very difficult. Therefore source localization algorithms, also called high density electrical source imaging (HD-ESI), have been developed to estimate the brain sources that give rise to certain scalp EEG distributions (Michel et al., 1999; Pittau et al., 2014; Michel and He, 2011; Plummer et al., 2008). HD-ESI is mostly used in the context of presurgical evaluation with the aim to identify the electric sources underlying epileptogenic activity guiding surgical resection of this zone.

There are two classes of source imaging algorithms: 1. equivalent current dipole models (He et al., 1987) that were used in the early EEG source localization studies and are still prevalent in

Table 1
Suggested montages with the extended standard array.

	Bipolar old longitudinal	Bipolar new longitudinal	Bipolar old transverse	Bipolar new transverse	Referential
1.	Fp2-F8	Fp2-F10	F7-FP1	F7-FP1	FP2
2.	F8-T8	F10-T10	FP1-FP2	FP1-FP2	F10
3.	T8-P8	T10-P10	FP2-F8	FP2-F8	F8
4.	P8-O2	P10-O2	F7-F3	F9-F7	T10
5.	Fp2-F4	Fp2-F8	F3-FZ	F7-F3	T8
6.	F4-C4	F8-T8	FZ-F4	F3-Fz	P10
7.	C4-P4	T8-P8	F4-F8	Fz-F4	P8
8.	P4-O2	P8-O2	T7-C3	F4-F8	F4
9.	Fp1-F3	Fp2-F4	C3-CZ	F8-F10	C4
10.	F3-C3	F4-C4	CZ-C4	T9-T7	P4
11.	C3-P3	C4-P4	C4-T8	T7-C3	O2
12.	P3-O1	P4-O2	P7-P3	C3-Cz	FP1
13.	Fp1-F7	Fp1-F3	P3-PZ	Cz-C4	F9
14.	F7-T7	F3-C3	PZ-P4	C4-T8	F7
15.	T7-P7	C3-P3	P4-P8	T8-T10	T9
16.	P7-O1	P3-O1	P7-O1	P9-P7	T7
17.	Fz-Cz	Fp1-F7	O1-O2	P7-P3	P9
18.	Cz-Pz	F7-T7	O2-P8	P3-Pz	P7
19.	ECG	T7-P7	ECG	Pz-P4	F3
		P7-O1			
20.		Fp1-F9		P4-P8	C3
21.		F9-T9		P8-P10	P3
22.		T9-P9		P7-O1	O1
23.		P9-O1		O1-O2	Fz
24.		Fz-Cz		O2-P8	Cz
25.		Cz-Pz		ECG	Pz
26.		ECG			ECG

Here we propose bipolar montages from right lateral → right parasagittal → left parasagittal → left lateral → midline electrodes. Any other arrangement is possible (e.g. left to right) and left to the discretion of the user.
Transverse montage: attention is drawn to the fact that inter-electrode distance between the inferior and superior temporal electrodes is shorter (10%) compared to the other inter-electrode distances (20%). However, this montage has shown its usefulness for identifying basal temporal and orbito-frontal discharges, due to the large voltage-gradient in these areas.
Regarding referential montages, it is well established that the reference electrode should be remote from the underlying source. Since the localization of the interesting source is often not known or might change, we recommend the use of average reference, i.e. average of all active scalp electrodes.
We do not recommend the recording with linked earlobes as reference, due to its potential difficulty for source localization applications.

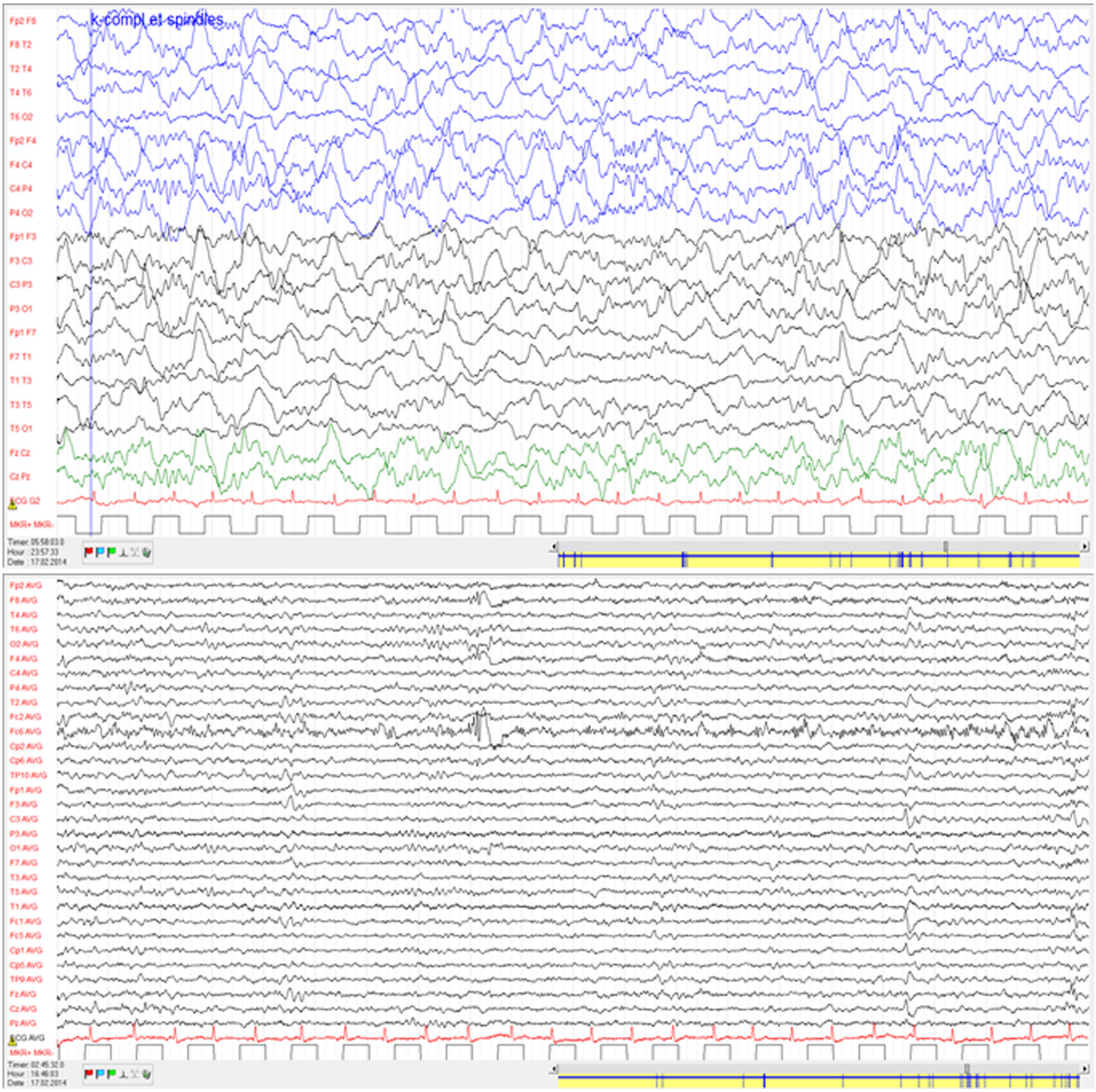

Fig. 4. Top: 11 year old boy with focal epilepsy. Negative scalp EEG, including sleep recordings using "double banana montage" from 31 scalp electrodes. Bottom: careful review of the monopolar montage (average reference) of the 31 electrodes showed a circumscribed focus, essentially restricted to FC6 with occasional spreading to F8. FC6 is not part of the usual clinical set-up which is why the epileptic focus was never seen in standard scalp recordings.

magnetoencephalographic source imaging; 2. distributed current source models (Pascual-Marqui et al., 1994; Dale and Sereno, 1993) which parcel the whole brain (or cortex) into small regions and determine which electrical current distribution in each of these regions most likely gives rise to the measured scalp field. The advantage of distributed source models is that calculations can be done without a priori assumptions on the number of equivalent dipoles. ESI solutions need then to be coregistered with a human brain's anatomy, ideally from the patient's own MRI, using so-called realistic head models.

Recent prospective studies showed that 128–256 electrodes provided more accurate ESI localizations compared to 29–31 electrodes (Brodbeck et al., 2011; Lascano et al., 2016)[1], including patients with negative MRI (Brodbeck et al., 2010; Rikir et al., 2014). Early simulation studies estimated that the distance between electrodes should be 1–2 cm (Freeman et al., 2003) which would require more than 100 electrodes to cover the whole head. Major localization errors of known epileptic foci were observed when the electric field was sampled with less than 64 electrodes (Lantz et al., 2003). A recent interictal study using 128-electrodes recordings in pediatric and adult epilepsy patients indicated that at least 64–76 electrodes are desirable to avoid significant source localization errors (Sohrabpour et al., 2015). Another ictal ESI study using 76 electrodes reported good results in localizing partial epilepsy (Yang et al., 2011).

In 2001, the 10–5 system was introduced (Oostenveld and Praamstra, 2001). Equidistant electrode positions are added to the 10–10-system, in keeping with the logic of the labeling of the 10–10-system. Similar to geographic directions ("north-north-west"), the authors proposed electrode labels like CCP or FCC,

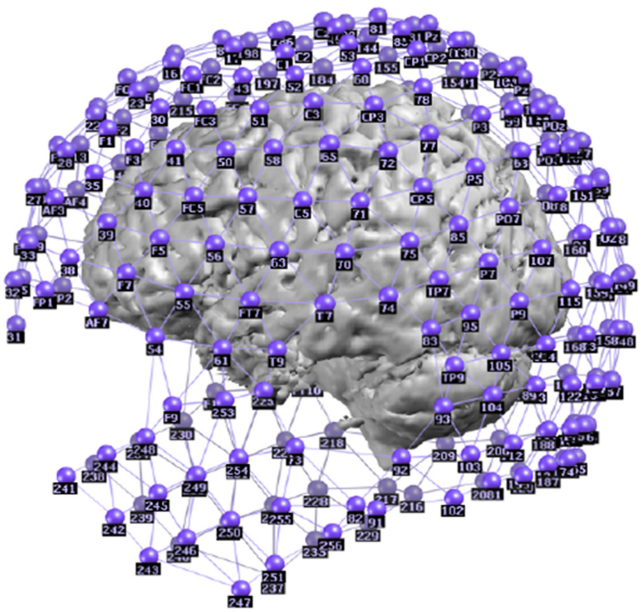

Fig. 5. 256 electrodes projected onto a 3D healthy human brain. Note the improved spatial sampling from most of the cortical areas (by Laurent Spinelli, University Hospital of Geneva).

adding "h" to indicate a position half-way between the 10–10-positions (Fig. 6). They also introduced "Iz" which is placed over the inion and label electrodes below the occipital electrodes O1h and O2h as I1 and I2, or OI1 and OI2. However, the nomenclature was not yet formally accepted by the American Clinical Neurophysiology Society or the International Federation of Clinical Neurophysiology.

Given the surge of commercially available EEG systems allowing rapid application of 128 or more electrodes, a comprehensive and logical naming of electrodes beyond the established 10–10 nomenclature is mandatory. Most systems use simple numbering which necessitates keeping a diagram/code with the patient's recording and/or software solutions to be able to find the correspondence of an EEG-channel with the position of the electrode on the skull. This is cumbersome, but currently there is no accepted nomenclature.

7. Measurement of electrode positions

For standard clinical EEG, precise electrode positions are typically not measured since precise localization of EEG abnormalities is not critical for therapeutic decisions. However, in the context of presurgical evaluation, the exact origin of the epileptogenic sources is highly relevant. In these cases, measurement of electrode positions becomes important especially when further spatial analysis is to be performed upon scalp EEG recordings. These include (1) the surface Laplacian estimate, or current density estimate, to reject far field background activities or noise; and (2) source imaging to estimate the underlying current source distribution by solving the so-called "inverse problem". In order to precisely estimate such brain source distributions (e.g. equivalent dipoles, current density distributions, or cortical potentials), knowledge of the precise locations of the scalp electrodes is crucial.

The EEG electrode positions can be measured using a hand-held FastTrack 3D digitizer. Certain companies are marketing other electrode position measurement devices (see review Koessler et al., 2007) like (i) ultra-sound system with a stylus, a transmitter and receptor system (triangulation-based distance method), (ii) optic system (infrared system, photogrammetry system or 3D Laser scanner) that takes pictures of the head with the scalp

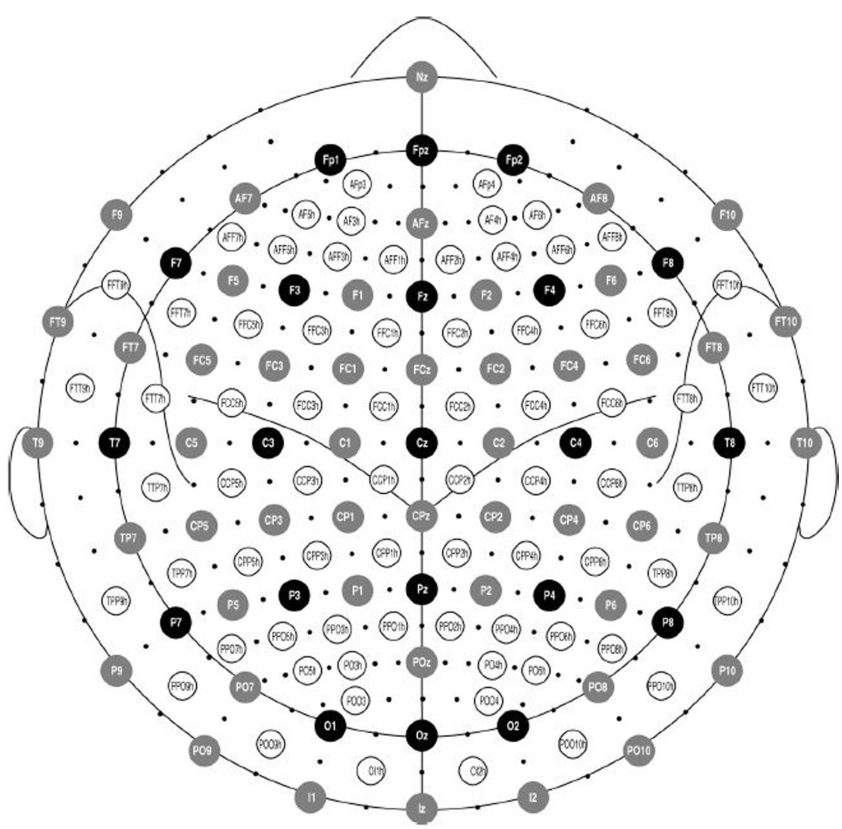

Fig. 6. Full 10–5-system. Additional electrode positions in the 10–5 system are indicated by white circles. Standard and extended electrode arrays are indicated (black electrodes: 10–20 system; gray electrodes: 10–10 system; with permission from Oostenveld and Praamstra (2001)).

electrodes according to different angles (Qian and Sheng, 2011) or (iii) use of specific MR-visible scalp electrodes combined with automated detection and labeling for 3D localizations directly in the individual anatomical space (Koessler et al., 2008; Marino et al., 2016). Finally, standardized 3D coordinates using average positions obtained from healthy controls represent a suitable alternative, but can be misleading in patients with skull deformations or very small/very large skulls.

8. Polygraphic channels

Polygraphy represents the simultaneous recordings of several physiological parameters. The combination of scalp EEG and other electrophysiological signals has two main objectives: first to obtain complementary and additional information from different organs, and second to distinguish physiological artifacts in scalp EEG signals.

Table 2 summarizes the most commonly acquired polygraphic modalities: electrocardiography (ECG), surface electromyography (EMG) and electrooculography (EOG). These modalities are recorded with dedicated pre-amplifiers or input couplers (bipolar channels) due to their amplitude range (from μV to mV) and frequency characteristics (from very slow wave to several hundred Hz). The use of the same recording device as for EEG, allows synchronous recording that permits direct investigation of the co-occurrence of electrophysiological and/or behavioral phenomena without the complex use of time indexing system.

ECG should be recorded whenever technically possible. It is useful for assessment of heart-rate, and identifying ECG artifacts. EMG can be recorded easily using surface electrodes placed directly on the skin, close to relevant muscle groups, for example deltoid muscles (Conradsen et al., 2011). This modality yields highly relevant information in sleep studies, in long term video-EEG recordings, and in pediatric studies. It is particularly relevant for the investigation of myoclonus (Avanzini et al., 2016), epileptic spasms, for differentiation between tonic and atonic seizures and also for differentiation between epileptic and nonepileptic convulsive seizures (Beniczky et al., 2015, 2016). Guiding on the placement of muscle electrodes is given in the Supplementary Fig. S1. In behavioral studies and especially in polysomnography recordings EOG is mandatory. In scalp EEG recording it is useful for identifying eye movement artifacts (Chang et al., 2016) and studying slow waves (Virkkala et al., 2007). Moreover, long-term EEG recording coupled with EOG is capable of differentiating epileptic seizures from syncope, psychogenic or other non-epileptic seizure, in case video of the seizure is not available (Chung et al., 2006). However, usually both eyelid and ocular movements can be detected by EOG (Iwasaki et al., 2005). In practice, Fp1 and Fp2 scalp electrodes could serve for a global eye movement investigation and especially movements in the vertical plane. For precise eye position investigation (especially in the horizontal plane), additional surface electrodes are required especially near the external canthi (Table 2).

Other modalities like body movements (actigraphy), blood pressure (plethysmography), respiration (transducers or pulse oximetry), intracranial pressure or temperature can be coupled to scalp EEG, but their use are less common and are dedicated to special issues, like comprehensive ICU monitoring.

9. Special considerations in children

Although the temptation of reducing the number of electrodes because of potential compliance problems in (small) children sounds reasonable, we recommend to adhere to the standards defined for adults. Low electrode numbers with even less than the defined 10–20 electrodes may lead to significant loss of crucial information with respect to the detection of certain activities and their localization. With regard to EEG source analysis, the general statement that the accuracy correlates with the number of electrodes especially applies to infants and young children because of the higher values of volume conductivity of the skull (Lew et al., 2013; Hoekema et al., 2003; Wendel et al., 2010). Thus, due to thinner skull measurements, children theoretically need *more* electrodes than adults to capture similar signals (risk of spatial aliasing), despite established practice to use fewer electrodes in pediatric EEG (often only 10 or 12 electrodes) because of the smaller heads. However, except neonates or premature babies, 25 electrodes can be easily applied. The number of electrodes for (long-term) EEG may be reduced to 16 in critical ill children (Herman et al., 2015) or even 12 for long-term and EEG-monitoring in neonates (Shellhaas et al., 2011; Kuratani et al., 2016) for practical reasons. In all other settings, we recommend to use at least the same number of electrodes as in adults, i.e. 25 electrodes.

10. Conclusion and recommendations

1. We recommend using at least 25 electrodes, including the inferior temporal chain, in the basic standard EEG array.
2. The risk for spatial under-sampling is particularly true for younger children who have thinner skulls. Thus, pediatric EEG should use at least as many electrodes as in adult group, and not less as it is still common practice.
3. For source localization purpose using source imaging algorithms or as a complement to standard scalp recordings, we

Table 2
Most commonly used polygraphic channels.

Modality	Placement of electrodes	Recording conditions
Electrocardiogram (ECG)	One bipolar recording, corresponding to the orientation of lead-II in standard ECG recordings, is sufficient for assessment of heart-rate. To obtain maximal amplitude, electrodes are placed on the upper third of the sternum and the left 8–12 ribs, under the apex of the heart.	Sampling rate: >128 Hz Filters: 0.3–60 Hz
Electromyography (EMG)	Depending on the semiology and the level of cooperation of the patient, several channels (≥2) can be used. Always record from homologous muscles on both sides; if possible, include antagonistic muscles.	Sampling rate ≥1 kHz
	Place active electrode on the belly of the muscle and the reference electrode on a nearby bone. Polysomnography: electrode on the chin should be included	High-pass filter: 2 Hz (for review, off-line high-pass filters of 20–50 Hz can be used to minimize the movement artifacts)
Electrooculography (EOG)	Place electrodes on both sides, one centimeter lateral and one centimeter below and above the outer canthi (oblique position).	Sampling rate: >128 Hz Filters: 0.3–35 Hz

See also Supplementary Document on placement of EMG electrodes.

recommend the use of the entire or parts of the 10–10 system or high density systems with 64–128 or more electrodes.

4. Modification of labeling of electrodes and headboxes will help to facilitate the transition towards the new standard array and also towards larger arrays, like the 10–10- system, for specific clinical questions.

Acknowledgements

MS was supported by the Swiss National Science Foundation (No 140332).

Conflict of interest

FL holds shares in ProLira, MS holds shares in Epilog. C. Michel is Editor-in-Chief of Brain Topography and remunerated for this appointment by Springer Publishing International. BH is Editor-in-Chief of IEEE Transactions on Biomedical Engineering and remunerated for this appointment by the IEEE.

Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.clinph.2017.06.254.

References

Acharya JN, Hani AJ, Thirumala PD, Tsuchida TN. American clinical neurophysiology society guideline 3: a proposal for standard montages to be used in clinical EEG. J Clin Neurophysiol 2016;33:312–6.

American Electroencephalographic Society. Guideline thirteen: guidelines for standard electrode position nomenclature. J Clin Neurophysiol 1994;11:111–3.

Avanzini G, Shibasaki H, Rubboli G, Canafoglia L, Panzica F, Franceschetti S, Hallett M. Neurophysiology of myoclonus and progressive myoclonus epilepsies. Epileptic Disord 2016;18(S2):11–27.

Beniczky S, Conradsen I, Moldovan M, Jennum P, Fabricius M, Benedek K, et al. Automated differentiation between epileptic and nonepileptic convulsive seizures. Ann Neurol 2015;77:348–51.

Beniczky S, Conradsen I, Pressler R, Wolf P. Quantitative analysis of surface electromyography: Biomarkers for convulsive seizures. Clin Neurophysiol 2016;127:2900–7.

Binnie CD, Dekker E, Smit A, Van der Linden G. Practical considerations in the positioning of EEG electrodes. Electroencephal Clin Neurophysiol 1982;53:453–8.

Brodbeck V, Spinelli L, Lascano AM, Pollo C, Schaller K, Vargas MI, et al. Electrical source imaging for presurgical focus localization in epilepsy patients with normal MRI. Epilepsia 2010;51:583–91.

Brodbeck V, Spinelli L, Lascano AM, Wissmeier M, Vargas MI, Vulliemoz S, et al. Electroencephalographic source imaging: a prospective study of 152 operated epileptic patients. Brain 2011;134:2887–97.

Chang WD, Cha HS, Kim K, Im CH. Detection of eye blink artifacts from single prefrontal channel electroencephalogram. Comput Meth Programs Biomed 2016;124:19–30.

Chung SS, Gerber P, Kirlin KA. Ictal eye closure is a reliable indicator for psychogenic nonepileptic seizures. Neurology 2006;66:1730–1.

Conradsen I, Wolf P, Sams T, Sorensen HB, Beniczky S. Patterns of muscle activation during generalized tonic and tonic-clonic epileptic seizures. Epilepsia 2011;52:2125–32.

Dale AM, Sereno MI. Improved localization of cortical activity by combining EEG and MEG with MRI cortical surface reconstruction: a linear approach. J Cogn Neurosci 1993;5:162–76.

Freeman WJ, Holmes MD, Burke BC, Vanhatalo S. Spatial spectra of scalp EEG and EMG from awake humans. Clin Neurophysiol 2003;114:1053–68.

He B, Musha T, Okamoto Y, Homma S, Nakajima Y, Sato T. Electric dipole tracing in the brain by means of the boundary element method and its accuracy. IEEE Trans Biomed Eng 1987;34:406–14.

Herman ST, Abend NS, Bleck TP, Chapman KE, Drislane FW, Emerson RG, et al. Consensus statement on continuous EEG in critically ill adults and children, part II: personnel, technical specifications, and clinical practice. J Clin Neurophysiol 2015;32:96–108.

Hoekema R, Wieneke GH, Leijten FS, van Veelen CW, van Rijen PC, Huiskamp GJ, Ansems J, van Huffelen AC. Measurement of the conductivity of skull, temporarily removed during epilepsy surgery. Brain Topogr 2003;16:29–38.

Iwasaki M, Kellinghaus C, Alexopoulos AV, Burgess RC, Kumar AN, Han YH, et al. Effects of eyelid closure, blinks, and eye movements on the electroencephalogram. Clin Neurophysiol 2005;116:878.

Jasper HH. The ten-twenty electrode system. Electroencephalogr Clin Neurophysiol 1958;16:371–5.

Klem GH, Lüders HO, Jasper HH, Elger C. The ten-twenty electrode system of the international federation. The international federation of clinical neurophysiology. Electroencephalogr Clin Neurophysiol Suppl 1999;52:3–6.

Koessler L, Benhadid A, Maillard L, Vignal JP, Felblinger J, Vespignani H, et al. Automatic localization and labeling of EEG sensors (ALLES) in MRI volume. Neuroimage 2008;41:914–23.

Koessler L, Cecchin T, Colnat-Coulbois S, Vignal JP, Jonas J, Vespignani H, et al. Catching the invisible: mesial temporal source contribution to simultaneous EEG and SEEG recordings. Brain Topogr 2015;28(1):5–20.

Koessler L, Maillard L, Benhadid A, Vignal JP, Braun M, Vespignani H. Spatial localization of EEG electrodes. Neurophysiol Clin 2007;37:97–102.

Kuratani J, Pearl PL, Sullivan L, Riel-Romero RM, Cheek J, Stecker M, et al. American clinical neurophysiology society guideline 5: minimum technical standards for pediatric electroencephalography. J Clin Neurophysiol 2016;33:320–3.

Lantz G, Grave de Peralta R, Spinelli L, Seeck M, Michel CM. Epileptic source localization with high density EEG: how many electrodes are needed? Clin Neurophysiol 2003;114:63–9.

Lascano AM, Perneger T, Vulliemoz S, Spinelli L, Garibotto V, Korff CM, Vargas MI, Michel CM, Seeck M. Yield of MRI, high-density electric source imaging (HD-ESI), SPECT and PET in epilepsy surgery candidates. Clin Neurophysiol 2016;127:150–5.

Lew S, Sliva DD, Choe MS, Grant PE, Okada Y, Wolters CH, et al. Effects of sutures and fontanels on MEG and EEG source analysis in a realistic infant head model. Neuroimage 2013;1(76):282–93.

Marino M, Liu Q, Brem S, Wenderoth N, Mantini D. Automated detection and labeling of high-density EEG electrodes from structural MR images. J Neural Eng 2016;13:056003.

Michel CM, He B. EEG mapping and source imaging. In: Schomer D, Lopes da Silva F, editors. Niedermeyer's electroencephalography, 6th ed. Wolters Kluwer & Lippincott Williams & Wilkins, Philadelphia; 2011. p. 1179–202 [Chapter 55].

Michel CM, Grave de Peralta R, Lantz G, Gonzalez Andino S, Spinelli L, Blanke O, et al. Spatiotemporal EEG analysis and distributed source estimation in presurgical epilepsy evaluation. J Clin Neurophysiol 1999;16:239–66.

Oostenveld R, Praamstra P. The five percent electrode system for high-resolution EEG and ERP measurements. Clin Neurophysiol 2001;112:713–9.

Pascual-Marqui RD, Michel CM, Lehmann D. Low resolution electromagnetic tomography: a new method for localizing electrical activity in the brain. Int J Psychophysiol 1994;18:49–65.

Pittau F, Grouiller F, Spinelli L, Seeck M, Michel CM, Vulliemoz S. The role of functional neuroimaging in pre-surgical epilepsy evaluation. Front Neurol 2014;5:31. http://dx.doi.org/10.3389/fneur.2014.00031.

Plummer C, Harvey AS, Cook M. EEG source localization in focal epilepsy: where are we now? Epilepsia 2008;49:201–18.

Qian S, Sheng Y. A single camera photogrammetry system for multi-angle fast localization in focal epilepsy. Ann Biomed Eng 2011;39:2844–56.

Rikir E, Koessler L, Gavaret M, Bartolomei F, Colnat-Coulbois S, Vignal JP, et al. Electrical source imaging in cortical malformation-related epilepsy: a prospective EEG-SEEG concordance study. Epilepsia 2014;55:918–32.

Rosenzweig I, Fogarasi A, Johnsen B, Alving J, Fabricius ME, Scherg M, et al. Beyond the double banana: improved recognition of temporal lobe seizures in long-term EEG. J Clin Neurophysiol 2014;31:1–9.

Shellhaas RA, Chang T, Tsuchida T, Scher MS, Riviello JJ, Abend NS, et al. The American clinical neurophysiology society's guideline on continuous electroencephalography monitoring in neonates. J Clin Neurophysiol 2011;28:611–7.

Sohrabpour A, Lu Y, Kankirawatana P, Blount J, Kim H, He B. Effect of EEG electrode number on epileptic source localization in pediatric patients. Clin Neurophysiol 2015;126:472–80.

Virkkala J, Hasan J, Värri A, Himanen SL, Müller K. Automatic detection of slow wave sleep using two channel electro-oculography. J Neurosci Meth 2007;160:171–7.

Wendel K, Väisänen J, Seemann G, Hyttinen J, Malmivuo J. The influence of age and skull conductivity on surface and subdermal bipolar EEG leads. Comput Intell Neurosci 2010;2010:397272.

Yang L, Wilke C, Brinkmann B, Worrell GA, He B. Dynamic imaging of ictal oscillations using non-invasive high-resolution EEG. NeuroImage 2011;56:1908–17.