Full-Band EEG (FbEEG): A New Standard For Clinical Electroencephalography

Sampa Venhatalo, Juha Voipio and Kai Kallio

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ABSTRACT
A variety of neuroimaging techniques, such as functional magnetic resonance imaging (fMRI), positron emission tomography (PET) and magnetoencephalography (MEG), have been established during the last few decades, with progressive improvements and rapidly taking place in the underlying technologies. In contrast to this, the recording bandwidth of the routine clinical EEG (typically around 0.5-50 Hz) that was originally set by technical limitations has remained practically unchanged for over half a decade. An increasing amount of evidence shows that salient EEG signals take place and can be recorded beyond the conventional clinical EEG bandwidth. Thus, physiological and pathological EEG activities range from 0 Hz to several hundred Hz, and they have been demonstrated in recordings of spontaneous activity in the human brain, and during epileptic seizures, sleep, as well as in various kinds of cognitive tasks and states in the adult brain. In the present paper, we will describe the practical aspects of recording the full physiological frequency band of the EEG (full-band EEG: FbEEG), and we review the currently available data on the clinical application of FbEEG.

Recording the FbEEG is readily attained with commercially available direct current (DC) coupled amplifiers if the recording setup includes a sweeping providing a DC-stable electrode-skin interface. FbEEG does not have the drawbacks that could favor any frequency band at the expense of others. We present several arguments showing that elimination of the lower (infra-slow) or higher (ultra-slow) bands of the EEG frequency spectrum in routine EEG has led, and will lead, to situations where salient and physiologically meaningful features of brain activity remain undetected or become seriously attenuated and distorted. With the current available electrode, amplifier and data acquisition technology, it is to be expected that FbEEG will become the standard approach in both clinical and basic science.

INTRODUCTION
When the technical specifications of the "conventional way" of recording clinical EEG were defined more than 50 years ago, the aim was to obtain sufficiently stable conditions for recording of those components in the human EEG that were known at that time, such as alpha or beta oscillations, sleep spindles and K-complexes. The major challenge encountered was to keep the physiographic pens on the paper despite the instability of the amplifiers and electrode-skin interface. A technically primitive, incomplete solution to this problem came from equipping the amplifiers with an in-built high-pass filter which, of course, produced a relatively noisy recording baseline. Unfortunately, this also led to the distortion or distortion of all slow signals, whether physiological or artifacts. Another problem, excessive artifacts that high frequencies generated by muscles and external noise sources, was dealt with by using low-pass filtering at around 30-40 Hz. Thus, in turn, led to the elimination of higher frequency brain activity (e.g., gamma-frequencies oscillations and fast "spikes") currently known to be a significant part in clinical information processing.

In this review, we will present several lines of evidence to show that elimination of the lower (infra-slow) and higher (ultra-slow) ends of the EEG frequency spectrum leads to situations where physiological and pathophysiological important components of the EEG are ignored. By using commercially available clinical amplifiers combined with small, easy-to-install modifications to recording equipment, recording of the full frequency spectrum is available at clinical practice. The generator mechanisms of infraslow and ultra-slow EEG phenomena have been discussed in detail elsewhere.1,7

Sampa Venhatalo is from the Department of Clinical Neurophysiology, University of Tampere, Finland. Juha Voipio and Kai Kallio are from the Department of Biological and Environmental Sciences, University of Tampere, Finland. Address requests for reprints to Sampa Venhatalo, M.D., Dept. of Clinical Neurophysiology, University Hospital of Tampere, P.O. Box 101, 33001, Tampere, Finland.

E-mail: sampav@tvw.isc.ttu.311
Terminology

Due to technical reasons, the terminology related to recording of slow EEG events is somewhat confusing. Much of the present literature has used the term direct-current EEG (DC-EEG) to imply an ideal frequency response of the EEG with a minimum of 0 Hz. However, the term "DC" has at least two misleading connotations. First, the EEG events are, of course, never per definition 0 Hz. Second, and more importantly, the term DC EEG puts an a priori emphasis on the low-frequency part of the EEG, whereas currently available techniques do not compromise any simultaneous analyses carried out at fast or even ultrafast frequencies.

The terminology related to recording of the higher EEG frequencies includes descriptive terms, such as wideband or broadband EEG (for review see ref. and references therein), which typically refer to the higher end of the frequency band. The comparable non-technical (widesideband) or broadband, however, makes them inaccurate and ambiguous.

In order to circumvent the above problems we have recently coined the term full-band EEG (FUBE; see also ref. in this issue). This concept has recently been accepted by a steadily growing number of scientists, clinicians (cf) as well as manufacturers of EEG amplifiers, and it simply conveys the idea that the full, physiologically and clinically relevant EEG bandwidth is examined in any given recording session without any trade-off that would favor one frequency band at the expense of another.

TECHNICAL REQUIREMENTS AND PRACTICAL ASPECTS

Recording of FUBE EEG requires (see also Figure 1 for more details; see also ref.) for detection of the infraslow events requires a genuine DC-coupled amplifier with a sufficiently high input impedance and DC stability as well as a wide enough dynamic range (preferably > 100 mV or higher), whereas detection of the ultrafast frequencies requires a high enough sampling rate and a large data storage capacity. Several commercially suitable, DC-coupled amplifiers of this kind have recently become commercially available.

Detection of the infraslow events requires also a DC-stable electrode-skin interface (Figure 1). To achieve this, the electrodes must be non-polarizable (Ag/AgCl), and the chlorides is required in the gel for stable operation of the Ag/AgCl electrodes (see and Discussion therein). The reliable, sintered Ag/AgCl contact elements used in our work have proved to be both maintenance-free and very stable in recordings lasting up to several days. In addition, electrodes need to be well attached, and the skin-borne signals caused by movements and galvanic skin response (GSR; see ref.) should preferably be short-circuited by pretreatment of the epidermis at the recording site (various techniques are available for this purpose). Sufficient short-circuiting of the skin is so painful that we have successfully done that even with sleeping participants.

It may be occasionally necessary to accept slight compromises related to DC-stable electrode-skin interface in some clinically challenging applications (such as sick preterm). However, a non-ideal DC-stability of the electrode-skin interface can easily lead to significant artefacts. Hence the EEG must be well attached, and the difficulties of such modifications. For instance, disposable Ag/AgCl electrodes may give adequately stable recordings in calm patients, but their firm attachment to the skin is difficult and hence movement artefacts are much more common. Leaving out the complete elimination of skin-borne signals might give reasonably stable recordings in calm patients (see ref.) and some short-lasting events (such as SATs in early neonates, see later) might be recorded reasonably well for clinical purposes. However, recordings of longer responsiveness (such as infraslow oscillations, ISOs, during sleep) or phasic events accompanied with changes in the autonomic nervous system (such as arousal shifts, which may include GSRs) will no longer be reliable. Movement artefacts and slow baseline shifts will also be causes of major fraction due to the intact and mobile, transition field potentials under the electrodes.

The limitations of the FUBE technique are mostly similar to those of the conventional EEG. Lack of high-pass filtering in FUBE changes the visual appearance of slow
artifacts (e.g., eye and tongue movements), but their visual recognition in FbEEG recordings is easy with little experience. Median filters and/or spatial filters, for near-continuous removing of many artifacts are now readily available in pertinent analysis software packages. Skin-born potentials ("sweet artifacts") in, tum, do not cause problems in FbEEG recordings if they are evaluated by short-circuiting (see above). Whereas it is obvious that excessive movements of patients may compromise all kinds of EEG recordings, it is notable that recording of even the infraslow frequencies with the above settings is remarkably easy to learn and quick to perform.

CLINICAL APPLICATIONS OF FbEEG

Nevastat EEG

In our recent FbEEG recordings from preterm and full-term neonates, we found that the dominating frequency range of the total spectral power is much below (as low as 0.01-0.1 Hz) the conventional EEG frequency band (Figure 2). Most notably, FbEEG discloses spontaneous activity transients (SAT), which consist of very slow (up to several seconds) EEG waves with faster, nested activity (Vainhatalo et al., unpublished). It has been known for decades that slow frequencies are dominant in the neonatal EEG, but it is now obvious that the conventional EEG severely attenuates and distorts these slow signals. Further molecular analysis on post-mortem fetal human specimens (Vainhatalo et al., unpublished), combined with data from experimental studies in animals, suggest that SAT episodes probably represent endogenously driven, spontaneous activity, which is crucial in shaping neuronal connectivity at an early developmental stage (i.e., prenatal stage where sensory input has little or no role in cortical network activity). Thus, FbEEG recordings do not only unravel a novel and developmentally crucial type of activity in the preterm cortex, but these findings also call for a revised classification for the EEG of premature and full-term infants. By doing so, FbEEG will open a new window into preterm EEG monitoring and diagnoses.

Sleep EEG

In addition to the well-recognized and thoroughly studied oscillations at low delta range (0.5-1 Hz), slow (1-2 Hz), recording with FbEEG has recently revealed infraslow oscillations (ISOs: 0.01-0.2 Hz) during non-REM sleep. Interestingly, comparison of the ISOs to the changes in the amplitude of higher frequencies shows a robust temporal correlation (see Figure 3). An analogous link was also seen between ISO and physio-brain events, such as the K-complex or interlaminar epileptiform activity. ISOs recorded by FbEEG in humans may thus reflect slow cyclic modulation of cortical excitability under both physiological and pathophysiological conditions, a phenomenon similar to that seen in a number of studies on experimental animals and previously inferred on the basis of human data. Therefore, it seems highly plausible to propose that recording ISOs should become an integral part of the routine clinical EEG in patients with sleep disorders.

Furthermore, transient arousals during sleep are associated with a vertex-positive DC shift with an amplitude that may exceed 100 microvolts, and a duration of several tens of seconds (Figure 4). Vainhatalo et al., unpublished). The brain arousal mechanisms, and especially their clinically important EEG correlates have remained elusive and are still under heavy debate. Thus, it seems
Figure 4. Slow EEG shift associated with arousals during sleep. Initially positive DC shifts with large amplitude and long duration are repetitively seen during transient arousals in a several minutes long epoch (see the two lower traces, the bottom trace is with a higher gain of 0.5 µV/s, the second lowest represents the F3/EEG signal). An example of such event is shown on an expanded time scale in the upper two traces (superimposed with F3/EEG), and its slow component is completely eliminated by the conventional high-pass filter set 0.10 Hz (see the trace below it). (Unpublished observations by S. Vanhalst et al.)

Figure 5. Event-related potentials and cognitive studies

Most of the research on low-frequency EEG has focused on slow potentials that are associated with various kinds of cognitive tasks and states, such as contingent negative stimulation (contingent negative variation, CNV), motor movements (Bereitschaftspotential), and the orienting paradigm. Some attempts have been made to construct functional brain-computer interfaces based on deliberate induction of slow wave recorded potentials. All these potentials have a duration of up to several seconds, and often an amplitude in the order of only few microvolts, which means that their recording is technically challenging. As a result, the perception threshold and even the sensory evoked responses may possess a significant potential for clinical monitoring of brain function during, e.g., sleep.**

The routine clinical use of brain stem evoked potentials (activity measured at around 500-1000 Hz) indicates that it is possible to record non-invasive EEG activity with much higher frequencies than those of the conventional clinical EEG. Among the higher frequencies, the importance of gamma rhythms in a large variety of cognitive functions has been well established (for reviews, see**). More recently, studies on responses related to somatosensory stimulation or motor movements have reported complex bursts of activity associated with the ultra high frequency range (above 200 Hz).
Figure 6

High frequency oscillation (HFO) in response to median nerve stimulation. Amplitude of the frequency-filtered trace at 475-1000 Hz demonstrates a prominent peak of oscillations with maximal area at 14-20 ms after stimulation. Modified from ref. 19.

Hz: often called high frequency oscillations. HFO: Figure 6; for review, see ref. 9. These responses are sensitive to balance issues, 20-22 motor interference 23 or pharmacological manipulations, such as anesthetics or sedatives. 24,25 They are physiological properties that are distinct from conventional evoked responses. Furthermore, it has been recently shown that they are specifically (as opposed to conventional evoked responses) affected in dysplasia 26 and other disorders of cortical integrity. 26,27,28 Hence, there is currently much interest in the idea that they could offer a new avenue for brain monitoring and diagnostics.

Conclusion

Extensive resources have been invested into the development of a variety of neuromonitoring techniques such as IMHL, PET, and MEG. Hence, it is striking that the frequency response and many other core aspects of the routine EEG are not based on conventions that were set more than 50 years ago by trial and error in technical limitations. The above examples indicate that the frequency response of the routine EEG is far from adequate, and that its extension to cover the infraslow and ultrafast activity will open a wide range of applications in both basic science and in the clinic. Since the technical issues reviewed in this FEEG recording of brain activity can be readily solved in everyday routine practice 19, there are no technical nor practical arguments in favor of recording EEG with the conventional bandwidth of about 0.5-50 Hz.

In addition to the examples presented above, the scope of FEEG measurements is likely to strongly expand in the near future. For instance, very slow, high-amplitude waves of spreading depression 29 are frequently seen in invasive recordings of animal models of ischemia, trauma, and, possibly, during migraine attacks 30,31. It is likely that they can be measured with FEEG from the human scalp as well. Due to the extraordinary sleepiness of the field of clinical EEG, a significant, albeit purely practical, problem in the implementation of FEEG may be encountered in amplifying existing working routines. More and larger FEEG studies, and especially open-minded clinicians, are urgently needed to accurately determine the clinical diagnostic niche of both infraslow and ultrafast EEG activities. Considering the fact that suitable electrodes, amplifiers, and data acquisition software are readily available, FEEG is likely to become the standard benchmark for a wide range of applications in both basic science and in the clinic.

References

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