Minimum Technical Requirements for Performing Ambulatory EEG

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Invited Review

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Abstract

Ambulatory EEG (AEEG) devices offer portable, computer-assisted, multi-channel, digital EEG recording with or without video in a natural environment. The technology is similar to routine EEG and inpatient long-term video-EEG monitoring but is designed to be compact and wearable. Although computer-based technology is well-suited to digital recording, signal processing, and visual display, acquiring interpretable EEG outside of the hospital setting presents different technical challenges. Published guidelines have established technical standards for performing routine EEG and inpatient video-EEG monitoring, but technical standards for AEEG have been lacking. Therefore, this guideline provides minimal technical standards for the performance of AEEG which are essential to ensure the quality of studies for clinical and research practice. These minimum standards are expected to evolve over time with improved performance and advances in the current technology.

Introduction

Ambulatory EEG (AEEG) monitoring provides prolonged interictal and potentially ictal (i.e., during an epileptic seizure) EEG recordings in patients with paroxysmal neurological disorders. Because AEEG is most often recorded for several days, systematizing technical performance standards is necessary to ensure optimal recording quality and outcome data (Tatum WO, 2017). Sources of environmental "noise" may degrade the signals of interest (Chavez et al., 2018) and hamper accurate interpretation (Tatum 2013, Tatum 2017, Mathias & Bensalem-Owen 2019, McKay & Tatum 2019). The purpose of this technical guideline is to provide minimum standards for performance of AEEG.

AEEG is a form of diagnostic long-term EEG monitoring with several potential indications. These may include: 1) differentiating epileptic and nonepileptic events; 2) providing a longer interictal EEG sample when standard EEG is non-diagnostic; 3) classifying seizure types and epilepsy syndromes; 4) quantifying seizure frequency and duration; 4) identifying seizure triggers that occur outside the hospital setting; and 5) making decisions regarding adjustment of anti-seizure medications (Velis et al., 2007; ACNS, 2008; Schuele et al., 2021).

The American Clinical Neurophysiology Society (ACNS) has provided minimum technical standards for performing in-hospital EEG with respect to equipment, electrode placement, electrical safety, calibration, sensitivity, study duration, montages and digital recording (Acharya et al., 2016, Sinha et al., 2016, Halford et al., 2016; Kuratani et al., 2016), but none of these standards is specific to AEEG. The International Federation of Clinical Neurophysiology (IFCN) has developed clinical guidelines for EEG including AEEG, but without technical standards (Tatum et al., 2018). The evidence for establishing technical standards is limited to low level evidence (primarily level III and IV studies) and expert opinion (Ebersole and Leroy, 1983, Liporace et al., 1998, Schomer 2006, Faulkner et al., 2012a, Faulkner et al., 2012b). No single agreed-upon method exists for recording AEEG under all circumstances. The following standards are considered the minimum technical requirements for recording AEEG in adults and children in routine clinical practice but are expected to evolve over time.

Equipment

Essential components of an AEEG recording system include a lightweight amplifier in a portable, battery-operated system capable of recording at least 16 channels of EEG data with an additional channel for ECG and an event recording button. The recording system should be able to store the entirety of the collected data for the typical duration of AEEG recordings for subsequent review. The AEEG amplifiers should meet minimum technical requirements previously established by the ACNS (Sinha et al., 2016; ACNS, 2008) with input impedance greater than 10 megaohms and a Common Mode Rejection Ratio (CMRR) more than 90 dB to improve signal-to-noise ratio (Halford et al., 2016). Most AEEG systems have at least 12-bit analog-to-digital conversion (Michel 2015). A bit depth of 16 bits for analog-to-digital conversion is recommended, providing a 0.3 μV resolution at a maximum input range of ±10 mV. Most current externally powered non-ambulatory EEG systems have a higher acquisition bit depth, but AEEG typically uses a lower bit depth of signal resolution to minimize power consumption.

A minimum sampling rate of 256 Hz should be utilized. Crosstalk between EEG channels should be <1% (Casson et al., 2010). Instrument calibration should be performed routinely to ensure appropriate function of the amplifiers (Sinha et al., 2016, Seeck et al., 2017). Use of a video camera is an option with some AEEG systems. Optimal systems should record and store data continuously and in its entirety. AEEG equipment requires connectivity from the amplifier to a computer for data review, archiving and storage, typically by Bluetooth connection, to allow viewing by multiple readers. USB connections are also available in computers for data transfer.

The characteristics of most commercially available systems exceed the above recommendations. They include light weight (~0.5 kg) systems that can be worn at the waist or in a backpack with a higher number of EEG channels (32 or more) (Seneviratne et al., 2017, Manfredonia et al., 2016), higher input impedances and CMRR, and higher sampling rates. Modern AEEG units have the capability to record and store up to 96 hours of data using compact flash memory cards. Some AEEG systems do not store the entirety of the data and record only intermittent scheduled sections and triggered events.

Some newer video-AEEG (v-AEEG) systems can connect to computers using cellular, wireless, or Bluetooth connection for "home telemetry" (Brunnhuber et al., 2014), permitting real-time access for video quality review, impedance checks, trouble shooting, and to assist interpretation. Data acquisition and review require a persistent network connection between the recording device, a Cloud server, and a review workstation. The speed of data review is limited by the resolution of the recorded video, the network connection speed, and the stability of the network connection (Schuele et al., 2021). Maintaining a Cloud-based continuous v-AEEG monitoring system requires substantial technical support, and the clinical utility of such a system may be limited unless technical support personnel and/or EEG technologists are available to trouble-shoot technical problems remotely and/or enter the recording environment to adjust video-EEG recording systems and electrodes.

AEEG Sensors

Conventional EEG is typically recorded with surface disc electrodes secured with collodion. Silver-silver chloride and gold cups are available, with the former generating a lower electrode impedance. Electrode caps and dry electrodes for AEEG have the potential to reduce preparation time and maintenance (Yeung et al., 2015, Halford et al., 2016) but are not typically used for AEEG because of greater sensitivity to movement artifact and rapid signal deterioration over time.

The common digital reference electrode is usually placed in the FCz or CPz location to minimize common artifacts from movement, myogenic, and ocular sources (Acharya et al., 2016, Sinha et al., 2016, Seeck et al., 2017). The ACNS recommends a minimum of 16 recording electrodes for routine EEG to demonstrate most normal and abnormal patterns (Sinha et al., 2016), and this should be the minimum number of electrodes for AEEG. The International Federation of Clinical Neurophysiology (IFCN) recommends recording at least 25 electrodes for long-term EEG monitoring in adults and children to provide improved coverage of the anterior and inferior-basal regions of the temporal lobe, which

often include the voltage maxima from discharges propagating from the mesial temporal structures (Seeck et al., 2017, Tatum et al., 2018).

Additional AC channel inputs recording electromyogram (EMG) and electrooculogram (EOG) signals, although optional, may be useful in certain circumstances especially for identifying sleep/wake states (Sprenkeler et al., 2017). A single channel modified lead 2 ECG recording during AEEG is essential, as it is with standard EEG. Multimodal AEEG monitoring with DC channels that include oximetry, airflow respirometry, and band plethysmography may be customized for home sleep testing (Carpentier et al., 2014).

Video and Audio

Use of a video camera is an optional feature, available with many newer AEEG systems. Synchronized video with AEEG is helpful to characterize events and to identify artifacts that may mimic epileptiform activity and electrographic seizures. Recording video adds bulk, memory and power requirements, and cost to AEEG. Furthermore, there are limitations regarding field of view and mobility of the video equipment.

AEEG systems with video (ambulatory video EEG, AVEEG) should include high quality video cameras that are synchronized with the EEG recording to facilitate behavioral analysis. High-definition video recording (1080 x 1440 pixels/inch resolution, >30 frames/sec), monochrome or color, with an audio channel, is necessary. The cameras should have a large field of view (wide-angle lenses) to maximize the likelihood of capturing events from a stationary camera. Using a camera which can automatically switch to an infrared video recording mode in low-light situations is important for recording events in dark or dim light conditions. Maintaining proper distance from the camera (to remain in focus) and remaining centered in the field are the responsibility of the patient or caregiver and crucial to good quality video recording during AVEEG.

AVEEG is optimal and worthwhile for patients who have events frequently enough to be events likely to be recorded. The amount of data collected for AEEG without video is 1-2% of that in recordings with video, which makes the task of streaming AEEG data to the Cloud using a cellular network more manageable. Depending upon the ability to stream AEEG data to the Cloud in real time, patients may need to return to the EEG laboratory to download recordings on successive days to facilitate daily review and reporting. Alternatively, if the data quality is adequate, patients can return to the laboratory at the end of the recording period to return the equipment for downloading the AEEG. Live streaming of high-definition video can provide the ability to view the video as it is being recorded but requires a high-speed internet connection, which may not be available in all locations.

Safety

Performing EEG is a non-invasive and safe procedure (Tatum et al., 2018). Since AEEG is performed without the continuous presence of trained personnel, and with limited ability to intervene, unique patient safety issues merit consideration (Tatum, 2017). During AEEG recording outside the hospital setting, sleep deprivation, antiseizure medication taper, and hyperventilation are usually

avoided to limit the safety risk that could occur from seizure provocation. Similarly, sedation protocols to improve diagnostic yield are also avoided due to the risk of unanticipated complications. Devices that can trigger an alarm in emergencies are available at some centers (Brunhubber et al., 2014). Further, some AEEG services incorporate on-call support for risk assessment when safety issues or the need for trouble-shooting technical issues arise.

Electrical injury during standard EEG is rare. Cutaneous injuries and burns are rarely encountered during standard EEG recording when electrodes are safely maintained (Tyner & Knott, 1983; Stecker et al., 2006; Patterson et al., 2007; Netherton et al., 2007). If, however, the patient is connected to the AEEG device while it is being charged (and plugged into an AC power source), there is potential risk of electrical injury. Therefore, patient connection to the AEEG equipment should be avoided while the internal battery is being charged. As with any electrically powered device, exposure to water will damage the AEEG equipment, so showering, bathing, swimming or any other water exposure are prohibited during AEEG recording.

If reusable electrodes or electrode caps are used, all electrode sensors must be disinfected after each use to prevent transmission of infection (Sinha et al., 2016).

Performance in Practice

Set-up

During the set-up process for AEEG, technologists should teach patients and caregivers proper use of the equipment and how best to ensure that events are recorded**.** The setup may be hospital- or clinic-based or even performed at the patient's home. This requires travel time and portable equipment and adds expense (Kandler et al., 2017).

In accordance with standards established for recording clinical EEG, the initial set-up begins by obtaining demographic and clinical information, as with routine EEGs. Information regarding current types and frequency of events is especially important. Electrodes should be secured using collodion adhesive. Electrode impedances should be checked to ensure that scalp electrodes have impedances less than 10 kΩ. For AEEG recordings lasting more than a day, impedances need to be reassessed to maintain them below 10 kΩ (Seneviratne et al., 2013, ACNS, 2008). Calibration of the signal should be performed (Acharya, 2016a; Acharya et al., 2016b; Sinha et al., 2016; Nuwer et al., 1998, Seeck et al., 2017).

Use of the International 10–20 System of electrode placement combined with supplemental leads is recommended (ACNS, 2008). A "tap test" over each electrode may be performed by the technologist to validate the integrity of the recording system prior to home AEEG monitoring. A brief baseline EEG recording should be performed without the 60 Hz notch filter to assess the baseline quality of recording. Common activities (e.g., eye movement, chewing, talking, swallowing etc.) should be performed and documented during set-up to reproduce artifactual waveforms for post-recording

comparison and to facilitate accurate interpretation. Activating procedures are not routinely used and are patient-specific when performed during baseline AEEG recording.

AEEG quality may be poor in some children due to difficulty maintaining electrode integrity (Carlson et al., 2018). Restrictions are outlined to limit patients' movement during AEEG to improve recording quality. Depending on the intended duration of the recording, patients may also need instructions on battery charging or replacement. If the system has video recording capabilities, detailed instructions regarding setup of the video system should also be provided. Instruction for the push-button event activation and diary documentation should be reviewed.

Activity Log

A patient daily activity log or diary is a simple, practical way to monitor patients during AEEG. A written record is kept of the times and description of behavioral episodes that occur.

Patients and caregivers should be encouraged to document and detail the push button events in the diary. This information should include: 1) the date and time of event occurrence (which should correspond to the same date and time displayed on the AEEG monitor); 2) a detailed description of the event and how it compares to the patient's habitual events; 3) the presence or absence of any direct interaction with the patient (questions asked or commands given, and the responses); and 4) whether the patient's awareness of the event is maintained or impaired. Emphasis on avoiding over-vigilance of non-specific symptoms is emphasized during the baseline set-up.

Push-button activation

Push button activation confirms that a patient- or observer-specified event has occurred and is an essential component of AEEG. Testing the event button during set up ensures system integrity and provides education to the patient on how to use the system. Nevertheless, a significant minority of patients remain self-unaware of their events during seizures. These events can be marked by others using the push-button activation.

Push button activations can be supplemented with voice recording. Patient vocalization or verbalization (in addition to that of witnesses who can interact with the patient and describe the event) can help clarify the observed semiology. Push-button activations also prompt the reader to review that portion of AEEG for paroxysmal events.

Push button activation during AEEG may provide information about the electrographic onset of a seizure but may not indicate the precise electro-clinical temporal correlation unless video recording is performed (Shoeb et al., 2005). Event characterization can be augmented if during set-up the patient and observers are provided simple testing protocols that can be performed in the home environment.

Both the push-button activations and the activity log should be reviewed with the patient upon return. This is useful in clarifying details regarding marked events and helping to distinguish between intentional and unintentional push button activations.

Review

When AEEG recording is completed and the device is removed, data are downloaded and processed, and EEG is reviewed at a workstation monitor on site or remotely. Ideally, the entire EEG recorded should be available to the interpreter for review. All activities and behaviors are annotated in an activity viewing box. Requirements for review of AEEG are similar to those for routine EEG. Customizable reformatting of AEEG montages, digital filters, and channel sensitivities as for routine EEG should be available and used to display the recording (Sinha et al., 2016, Seeck et al., 2017). Typical filter settings should include a high-pass filter of 0.5 Hz and low pass filter of 70 Hz. Montage selectors allow data reorganization of the AEEG to clarify waveform visualization (Ochoa et al., 2008). A 60 Hz notch filter may be necessary during review because of ambient exposure to line noise during AEEG (Tatum, 2013). Viewing AEEG on a monitor should allow varying scrolling speeds. A standard horizontal scaling should be available for EEG review, in which one second occupies between 25 and 35 mm, with a minimum resolution of 128 data points/second on the screen for a 10-second page, requiring a horizontal resolution of at least 1,280 pixels. (Halford et al., 2016). There should be the ability to perform split screen review and an ability to compare the data at different times of recording using a variety of preprogrammed or customized montages, sensitivities, and filter settings.

Contemporary AEEG systems also offer software options (Gotman, 1999) which include artifact reduction, spike and seizure detection, and in some, compressed spectral array and other quantitative EEG measures (Furbass et al. 2015; Kelley et al., 2010; Sheuer et al., 2017). These have been adapted for AEEG from the same software used for inpatient video EEG monitoring. Quantitative EEG and spike and seizure detection software cannot run on the AEEG recorder in real time during data acquisition due to excessive processing and battery use demands and must be implemented after the recording is complete which can create logistical challenges and a delay in review. Automated seizure detection and quantitative EEG analysis have limited sensitivity for seizure detection, particularly for very brief or focal seizures (González Otárula et al., 2019). Therefore, the entire raw AEEG data should be available for the physician interpreter to ensure that clinically significant findings are not missed.

Archiving and Storage

AEEG should be archived and stored securely in compliance with HIPAA requirements. Local practices should be followed for data disposal, re-use, backup, archiving and storage. Video of all events captured on v-AEEG, interictal epileptiform activity, ictal EEG, and other concerning waveforms should be archived and stored for a minimum of 7 years, and preferably longer (ACNS, 2008; Sinha et al., 2016; Halford et al., 2016; Kuratani et al., 2016). Along with hospital supported storage options, various interfaces offer AEEG viewing, archiving, and secure transfer for data sharing. Twenty-four hours of AEEG recording requires an average of 8-30 GB of internal memory (mostly for video), depending on the video resolution recorded. On-board flash memory cards of size 64 GB or larger can provide adequate storage for several days of recording. Manufacturers should provide a method to export de-identified files of AEEG recordings in nonproprietary, publicly available EEG data formats (e.g., European Data Format) (Nuwer et al., 1998).

Conclusions and Recommendations

AEEG systems are high-tech devices that record EEG outside the hospital setting. No single best device or method exists for optimal technical AEEG recording under all circumstances and settings. This guideline should be considered a minimum standard for the performance of AEEG for clinical purposes. The strength of the conclusions for this guideline for the use of AEEG would benefit from higher levels of evidence, in addition to expert consensus. Developments and forms of AEEG monitoring are evolving, including the increasing availability of simultaneous video recording and the potential for real-time monitoring and review of data. Greater sophistication and technological advances will increase the quality and utility of AEEG studies in the diagnosis and management of patients with paroxysmal disorders.

DISCLAIMER

This Guideline is provided as an educational service of the American Clinical Neurophysiology Society (ACNS). It is based on an assessment of current scientific and clinical information. It is not intended to include all possible proper methods of care for a unique problem or all legitimate criteria for choosing to use a specific procedure. Neither is it intended to exclude any reasonable alternative methods. ACNS recognizes that specific patient care decisions are the prerogative of the patient and the physician caring for the patient, based on all the circumstances involved. The clinical context section is made available in order to place the evidence-based guidelines into perspective with current practice habits and challenges. Formal practice recommendations are not intended to replace clinical judgment. This Guideline will be revised as science, evidence, and technology evolve.

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