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Review

Review on the current long-term, limited lead electroencephalograms

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ABSTRACT

In the last century, 10–20 lead EEG recordings became the gold standard of surface EEG recordings, and the 10–20 system provided comparability between international studies. With the emergence of advanced EEG sensors, that may be able to record and process signals in much more compact units, this additional sensor technology now opens up opportunities to revisit current ambulatory EEG recording practices and specific patient populations, and even electrodes that are embedded into the head surface.

Here, we aim to provide an overview of current limited sensor long-term EEG systems. We performed a literature review using Pubmed as a database and included the relevant articles.

The review identified several systems for recording long-term ambulatory EEGs. In general, EEGs recorded with these modalities can be acquired in ambulatory and home settings, achieve good sensitivity with low false detection rates, are used for automatic seizure detection as well as seizure forecasting, and are well tolerated by patients, but each of them has advantages and disadvantages. Subcutaneous, subgaleal, and subscalp electrodes are minimally invasive and provide stable signals that can record ultra–long-term EEG and are in general less noisy than scalp EEG, but they have limited spatial coverage and require anesthesia, a surgical procedure and a trained surgeon to be placed. Behind and in the ear electrodes are discrete, unobtrusive with a good sensitivity mainly for temporal seizures but might miss extratemporal seizures, recordings could be obscured by muscle artifacts and bilateral ictal patterns might be difficult to register. Finally, recording systems using electrodes in a headband can be easily and quickly placed by the patient or caregiver, but have less spatial coverage and are more prone to movement because electrodes are not attached.

Overall, limited EEG recording systems offer a promising opportunity to potentially record targeted EEG with focused indications for prolonged periods, but further validation work is needed.

1. Introduction

Epilepsy is a common neurological disorder with an incidence of approximately 40–70/100,000 per year in adults, defined by the ILAE as an enduring predisposition to generate epileptic seizures and by the neurobiological, cognitive, psychological, and social consequences of this condition [1,2]. Despite adequate antiseizure medication (ASM) selection and dosage, about one-third of patients with epilepsy will continue to have more than one seizure per month, but seizure occurrence is often random. The difficulty in predicting seizures is a major burden for patients with epilepsy, and their families, with a huge impact on quality of life (QOL) [3,4]. Until recently, seizure monitoring mainly relied on patientś and families' subjective recall of the events, but studies have revealed that patients report approximately only half of their seizures; and even fewer during sleep [5,6]. For this reason, portable sensors, and in particular those recording electroencephalograms (EEGs), are an important tool in epilepsy, as they aid in confirming the diagnosis, determining the epileptic syndrome, and, during long-term EEG recordings, accurately quantifying seizures and determining the epileptogenic focus [7]. Nonetheless, patient video-EEG is uncomfortable, expensive due to the high technical and personnel demand required, and has a lower yield as most systems do not record in the patients environment [8]. A single 20-minute routine EEG shows abnormalities in 30–50 % of patients with epilepsy, and studies have concluded that up to 10 % of patients with epilepsy do not present with interictal epileptiform activity, despite repeated EEGs [9,10]. Hence, further work regarding updated sensors that may be able to record prolonged EEGs, and improved bio-signal processing and analysis is urgently needed (see Table 1).

This review focuses on long-term EEG systems with limited leads,

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Table 1
Summary of the reviewed studies.

First Author, year	Device type/EEG system	Setting	N	Aim	Performance/Results
Carvalho, 2020 [11]	Neury: behind the ear device, two bipolar EEG channels	Hospital	38 patients with the suspicion of continuous spike-and-wave of sleep	Quantify the spike index with a full 10–20 montage and with Neury and validate a wearable EEG logger to perform repeated spike index quantifications	Accurate spike index quantification when compared to a standard 10–20 EEG and feasible in clinical settings with excellent patient tolerability
Frankel, 2021 [18]	Epilog: wireless, single-channel EEG sensor, placed below the hairline. Each patient wore four Epilog sensors	Hospital	40 adults	Determine which seizure types can be recorded from the scalp, determine epileptologists' ability to identify electrographic seizures from a single-channel, and from Epilog	Epileptologists correctly classified seizure activity in 84 % of the single-channel EEG and 71 % of the Epilog events, incorrectly labeling seizure activity as non-ictal in 29 % of Epilog events
Frankel, 2021 [24]	Epilog: wireless, single channel EEG sensor. Each patient wore four Epilog sensors, behind the ear and on the forehead	Hospital	20 adults	Demonstrate that epileptologists can accurately detect focal- seizures in REMI montage and that automated seizure detection algorithms can guide epileptologists	The automated algorithm identified electrographic seizure activity with a mean sensitivity of 100 % and specificity of 70 % and focal onset seizures with a mean sensitivity of 90 %.
Bacher, 2021 [25]	Six to eight subgaleal implanted electrodes	Hospital	21 patients with drug- resistant focal epilepsy	Validate a continuous EEG detection paradigm using a subcutaneous EEG recording channel	The seizure detection algorithm across 21 patients achieved 93 % accuracy, 91 % specificity, and 97 % sensitivity
Viana, 2021[14]	Three contact electrodes (2-channel bipolar EEG) subcutaneously implanted	Ambulatory/ Home during 230 days	1 patient with refractory epilepsy	Report the longest subcutaneous EEG recording focusing on usability and comparing it to patient diaries	There was agreement between seizure days but seizure clusters were not documented. It was well tolerated and accepted by the patient
Mckenzie, 2017 [19]	SBS2: Smart phone brain scanner −2 consists of an Android tablet wirelessly connected to EasyCap, a 14-electrode headset	Hospital, lower middle-income country	205 patients with epilepsy or suspected seizures of any age	Assess the capacity of SBS2, comparing the detection of electrophysiological abnormalities as recorded by the smartphone-based versus standard EEG among patients with epilepsy	Recorded epileptiform abnormalities in 14 % of SBS2 and 25 % of standard EEG. SBS2 had a 39.2 % sensitivity and 94,8% specificity to detect epileptiform discharges
Bruno, 2020 [37]	Epilog	Hospital	12 patients with epilepsy	Investigate to what extent available wearable devices are non-intrusive, comfortable, and stable on the body	Patients reported that the device was comfortable to be worn for a long time and easy to master, but the evaluation was lower in comfort during sleep and ease of manipulation
Kjaer, 2017[26]	Actiwave: three electrodes near Fp1, F7, Tp2 connected to a portable EEG recorder	Hospital and home	6 children with absence epilepsy	Evaluate Actiwave in an ambulatory setting and test the performance of the automatic detection algorithm	Automated algorithm detected 98.4 % of all paroxysms with only 0,23 false detections per hour. Some patients were not comfortable wearing it in public places
Gu, 2017[27]	Four electrodes behind the ear	Hospital	12 patients with refractory focal epilepsy	Prove the feasibility of automatic seizure detection with unobtrusive EEG electrodes placed behind the ear.	The automatic seizure detection algorithm behind the ear achieved a mean sensitivity of 94.5 % and false detection rate of 0.52 per hour
López-Larraz, 2023[12]	Four electrodes, one head-band with smart textiles (Garmet EEG) and one with metal electrodes (Dry EEG)	Experimental	In the first study 6 healthy volunteers, in the second one 10 different healthy volunteers	Characterize the first sensor layer implemented using only materials from the textile industry measuring EEG activity over the forehead of healthy participants	Garmet EEG was more frequently affected by artifacts, but both registered similar EEG signals regarding morphology and amplitude in rest states
Nasseri, 2020 [38]	Epitel Epilog to record EEG, a bipolar EEG channel from two electrodes	Inpatient and home settings	21 patients with epilepsy	Measure device signal quality and assess patients with epilepsy preferences with wearables	Data was classified as good in 21.4 %. The mean Likert scale result was 1.5 for easy to manipulate, 2.25 for usable, and 3.50 for would use for seizure prediction
Zibrandtsen, 2017[20]	Ear EEG device with four recording electrodes in an earpiece, one device on each ear	Hospital	15 patients with suspected temporal lobe epilepsy	Examine the ability of ear EEG to characterize ictal and interictal events in epileptic patients, compared to scalp EEG	There were no differences in specificity or sensitivity for seizure detection
Macea, 2023	Sensor Dot, two EEG channels with dry electrode patches	Hospital and at home for up to 8 months	16 patients with focal refractory epilepsy	Investigate the diagnostic yield of automated detection using sensor Dot in admitted patients and ambulatory ones	With the seizure detection algorithm the inpatient group achieved an overall sensitivity of 52 % and the outpatient group achieved a sensitivity of 23 %
Pacia, 2022[21]	A single, 6-contact subdural strip electrode array placed on the subgaleal space	Hospital	21 epileptic patients	Investigate the reliability and viability of subgaleal EEG for seizure identification	Epileptologists accurately identified 98 % of seizures, with a sensitivity of 98 % and specificity of 99 %
Remvig, 2022 [33]	Subcutaneous EEG analyzed with Episight analyzer software	Home	8 people with epilepsy and 12 healthy subjects	Evaluate the performance of subcutaneous EEG-based automatic detection algorithm	The algorithm achieved a sensitivity of 86 %, with a false detection rate of 2.4 per 24 h. The reduction in the

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Table 1 (*continued*)

First Author, year	Device type/EEG system	Setting	N	Aim	Performance/Results
					amount of data was 99.6 % in the epilepsy dataset
Japaridze, 2022 [34]	Headband on the forehead, recording a bipolar EEG channel corresponding to F7-Fp1	In hospital	102 patients with suspicion of absence seizures	Measure the accuracy of an automated absence detection algorithm and assess the patient́s responsiveness	The automated absence detection algorithm had an average sensitivity per patient of 78.8 %
Mascia, 2023 [13]	Parylene-C tattoo dry EEG electrodes in a 10–10 standard system	Experimental	Single subject in resting state	Compare EEG tattoo to the commercial system MUSE	The tattoo system was able to differentiate between eyes open and closed conditions and it did not differ from MUSE
Kamousi, 2019 [22]	Ceribell system: 10 electrodes in a stretchable headband that records 8 channels	Laboratory and ICU	Healthy subjects and patients with altered mental status	Compare the quality of EEG signals Ceribell and the signals recorded with conventional clinical EEG recordings.	The correlation between Ceribell and the conventional EEG was similar to the correlation between the two conventional systems.
Titgemeyer, 2019[23]	Emotiv EPOC headset with 16 channels	Hospital	22 patients with epilepsy	Compare commercially available device data with conventional EEG	Emotiv had a sensitivity for all epileptiform activity of 39 % and a specificity of 85 % and conventional EEG had a sensitivity of 56 % and specificity of 88 %
You, 2020[28]	Behind the ear electrodes	Hospital	12 patients with epilepsy	Develop an automatic seizure detection algorithm trained by unsupervised learning and evaluate it with behind-the-ear electrodes	The algorithm achieved a sensitivity of 96.3 % and false alarm rate of 0.14 per hour
You, 2022[29]	Behind the ear electrodes	Hospital	16 patients with epilepsy	Develop a personalized deep-learning algorithm for seizure monitoring with behind-the-ear electrodes	The personalized seizure detection algorithm achieved a mean sensitivity of 94,2% and a false alarm rate of 0,29 per hour
Vandecasteele, 2020[30]	Four behind-the-ear electrodes	Hospital	54 epileptic patients	Determine if recognition of ictal patterns is possible with behind-the-ear EEG and develop a seizure detection algorithm with these data	Visual recognition of ictal patterns is possible with behind-the-ear EEG. Patient-specific seizure algorithm reached a sensitivity of 69.1 % and 0.5 false positives /24 h
Swinnen, 2021 [31]	Four behind-the-ear electrodes	Hospital	12 patients with typical absence seizures	Used behind-the-ear channels to detect absences and develop a patient-specific seizure detection algorithm	The semiautomatic detection algorithm achieved a sensitivity of 83 %, with a time to review 24 h EEG of 5–10 min
Stirling, 2021 [35]	Subscalp EEG, two channels from both brain hemispheres	Ambulatory	5 patients with refractory epilepsy	Record and compare interictal and ictal activity with a subscalp system and conventional EEG, and illustrate the potential for seizure forecasting	Seizure forecasting was performed in one patient who spent 26 % in a high-risk state with 83 % of seizures occurring in this high-risk state
Weisdorf, 2018 [15]	Subcutaneous electrodes, two bipolar channels	Hospital	4 patients with probable or definite temporal lobe epilepsy	Describe the similarity between subcutaneous and scalp EEG including epilepsy and sleep patterns as well as artifacts	High similarity between subcutaneous electrodes and nearby temporal scalp electrodes
Weisdorf, 2019 [16]	Subcutaneous electrodes, two bipolar channels	Home	Nine patients with temporal or frontal temporal epilepsy	Explore the feasibility of subcutaneous EEG for home monitoring, clinical implications, safety, and compliance	Monitoring with subcutaneous EEG is possible for up to 3 months and in general well tolerated
Viana, 2021[17]	Subcutaneous EEG, two-channel bipolar EEG	Home	14 patients with epilepsy, 12 healthy subjects	Study the quality and consistency of subcutaneous EEG signal	Frequency band powers were highly stable and electrode impedances remained low
Viana 2022[36]	Subcutaneous EEG, two-channel bipolar EEG	Home	6 epileptic patients	Determine if patient-specific seizure forecasting is possible with ultra-long-term subcutaneous EEG	Three patient-specific forecasting architectures achieved a sensitivity from 64 to 80 % and time in warning from 10.9 % to 44.4 %

that could provide more accurate diagnostic information and seizure and spike burden assessment, as well as future biomarker assessment, allowing clinicians to better diagnose epilepsy and tailor treatment, thus optimizing seizure control. In the future, the combination of seizure diary and neurophysiological data may be able to better monitor outcomes, and potentially alert, or even predict, when an upcoming seizure is going to occur, ultimately improving QOL of patients with epilepsy.

1.1. Literature search methods

In June and July 2023, we performed a PubMed search using semi-structured strings (“Long-term AND limited lead EEG”, “Subcutaneous electroencephalographic monitoring”, “Long term Electroencephalogram seizure detection devices”, “Electroencephalogram tattoo”, “Limited lead electroencephalogram for seizure detection”, “Subcutaneous electroencephalogram for seizure detection”, “Subgaleal electroencephalogram for seizure detection”, “Mobile electroencephalogram for seizure detection”, “Noninvasive mobile electroencephalogram”, “Epihunter”, “SEER electroencephalogram”, “Byteflies”, “Epitel”, “Portable electroencephalogram for seizure detection” and “Wearable electroencephalogram for seizure detection”). We restricted our search to articles written in English or Spanish and to studies performed on human subjects older than 28 days of age. We only included articles in which the electroencephalogram was used for seizure or seizure mimics detection, in which a long-term (i.e. 24 h or longer), limited lead extracranial EEG was used. Intracranial EEG or studies during which EEG was used as a tool for monitoring evoked potentials, consciousness, drowsiness, anesthesia, or metabolic encephalopathy were excluded. The initial search returned 663 papers, additionally, 2 papers were identified from relevant articles known to the authors and from references included in other studies. After screening for relevance and excluding repeated studies and review articles, we included 28 articles in this literature review.

1.2. Interictal EEG/background assessment

Neury is a wearable device that recorded from 2 bipolar EEG channels for 24 h in patients with continuous spike-wave of sleep and demonstrated accurate spike index quantification when compared to conventional 10–20 EEG [11]. It reduced the time needed for recording preparation, improved portability, increased freedom to move, minimized the weight, and was well tolerated which could increase patients ́ acceptance and consequently adherence.

An EEG sensor layer was designed in which the electrodes are embedded into smart textiles, threads, and fabrics, and the system is placed over the forehead of healthy participants [12]. The authors developed two different headbands with electrodes in positions F7, Fp1, Fp2, and F8, one made with smart textiles (Garmet EEG) and the other integrated standard metal electrodes and coaxial cables (Dry EEG). Each one had four electrodes, reference and ground electrodes, and connectors at the back to attach to the amplifier. First, they studied the impedance and signal transmission in 6 healthy participants. Subsequently, they evaluated spontaneous and evoked EEG activity patterns in 10 healthy participants measuring the activity sequentially with each headband [12]. Garmet EEG showed higher impedances, and the signal was more frequently affected by artifacts, but both registered similar EEG signals regarding morphology and amplitude in rest states. The authors concluded that Garmet EEG could imply lower manufacturing costs and less pollution and could be applied to other home-based systems, for example for monitoring sleep [12].

Parylene-C tattoo electrodes are unobtrusively and could monitor brain signals, so a group validated dry electrodes placed according to the 10–10 standard system and a modified headband in a single subject in a resting state and they compared it to the commercial system MUSE[13]. The tattoo system was able to differentiate between eyes open and closed conditions and it did not differ from MUSE [13].

1.3. Seizure burden evaluation/detection

Three contact electrodes (resulting in 2-channel bipolar EEG) were placed over the left temporal region, subcutaneously in a 35-year-old patient with focal epilepsy for 230 days [14]. EEG was recorded in an ambulatory, everyday life setting, with good adherence (86.8 % adherence, 20.8 h/day), but there were some periods with device disconnection due to personal hygiene, or accidental disconnections related to sleep, exercise, or malfunction of the recorder. The patient reported 22 seizures, and the subcutaneous EEG documented 32 seizures. There was overall agreement between seizure days but seizure clusters were not documented [14]. Discrepancies between seizure sensors and patient diaries have been previously documented, and these were, likely at least in part, ascribed to loss of awareness during the event, forgetfulness, and events occurring at night. Results highlight the urgent need and importance of devices that accurately identify patients ́ seizures [5,6,14]. Amongst the limitations mentioned are limited spatial sampling, visual review of the subcutaneous EEG, and a high false positive event detection rate (n: 4768, one hour)[14].

Another group aimed to describe the similarity between subcutaneous and scalp EEG including epilepsy and sleep patterns, as well as artifacts [15]. Hence, they implanted three leads over the suspected seizure focus and a small housing in 4 patients with probable or definite mesial temporal lobe epilepsy, recording two bipolar channels. Seven to eleven days after implantation probands were admitted to the epilepsy monitoring unit and recording was done simultaneously with conventional scalp EEG. They found high similarity between scalp and subcutaneous recordings in time and time–frequency domains, as well as for physiological events and spike morphology, but often with a smaller amplitude in subcutaneous recordings [15]. These authors emphasized the importance of carefully selecting the implantation location of the subcutaneous electrodes [15].

A subcutaneous EEG device was placed on 9 patients with temporal or frontal temporal lobe epilepsy, and at least one seizure per month, to explore home monitoring, clinical implications, safety, and compliance [16]. The implant had 3 leads, parallel to the temporal lobe, recording two bipolar channels, and an external logging device for power supply and data transfer. Eight patients completed at least 9 weeks of monitoring and obtained recordings 73 % of the time. One participant left the study after 30 days because the implant was uncomfortable. Most participants had soreness at the implantation site, two had occasional headaches and two had minor skin irritation, but overall, participants reported minimal impact on daily routines [16]. The authors concluded that monitoring with subcutaneous EEG is possible for up to 3 months and is in general well tolerated [16].

Another subcutaneous device was placed in 14 patients with epilepsy and 12 healthy subjects to study the quality and consistency of subcutaneous EEG signals [17]. The implant consists of a three-contact wire and a small ceramic housing implanted unilaterally over the presumed seizure focus or the right central region in healthy subjects. The recordings lasted from 23 to 231 days, with adherence 75 % of the time, without significant electrode migration. The authors documented that frequency band powers were highly stable, with clear differences between day and night time and electrode impedances remained low [17].

Epilog is a wireless, single-channel EEG sensor, that was placed below the hairline in 40 adults during their stay in the epilepsy monitoring unit, and each patient wore four Epilog sensors [18]. The sensor location was decided with the epileptologists ́ guidance based on seizure semiology, imaging, and EEG. The authors then extracted 75 seizures from 22 of the 40 adults and compared the epileptologists' interpretation of the Epilog recording and a recording from a single EEG channel close to Epilog [18]. Epileptologists correctly classified seizure activity in 84 % of the single-channel EEG and 71 % of the Epilog events, incorrectly labeling seizure activity as inter-ictal in 16 % of single-channel EEGs and 29 % of Epilog events [18]. Epileptologists were better at classifying focal seizures in single-channel EEG and generalized seizures in Epilog. Approximately 80 % of all seizures were visible at each of the 4 Epilog locations, but the ictal activity was visible in at least one electrode for each seizure event, concluding that if the Epilog sensor is correctly placed it would record the majority of seizures [18].

The Smartphone Brain Scanner (SBS2) consists of an android tablet wirelessly connected to EasyCap, a 14-electrode headset to register epileptiform abnormalities compared to conventional EEG [19]. The authors recorded the standard 10–20 EEG and EEG with SBS2 simultaneously in 205 patients with epilepsy or with suspected seizures of any age in Bhutan, and EEGs were interpreted by neurologists, using the 10–20 EEG as the gold standard. Epileptiform abnormalities occurred in 14 % of SBS2 and 25 % of standard EEG. SBS2 had a 39.2 % sensitivity and 94.8 % specificity to detect epileptiform discharges, and 31 % of the focal and 82 % of the generalized abnormalities were identified [19]. The authors consider that SBS2, with some modifications, could be useful in resource-limited settings where standard EEG is not available. Furthermore, it may be deployed in an at-home setting, with special utility when generalized epilepsy is suspected.

Some authors tested a device with four recording electrodes inside an earpiece placed in the outer portion of the external acoustic meatus in 15 patients with suspected temporal lobe epilepsy with one or more events per week [20]. The authors recorded with an earpiece placed on each ear and a simultaneous 10–20 scalp EEG in an epilepsy monitoring unit, and two board- certified neurophysiologists reviewed the recordings. They found a good correlation between ear electrodes and scalp EEG, especially towards the midline, with good detection of seizure onset, with no differences in sensitivity or specificity for seizure detection [20].

A group investigated the reliability of a single, 6-contact subdural strip electrode array placed into the subgaleal space, close to the midline for seizure identification and epilepsy management in 21 epileptic patients undergoing intracranial EEG [21]. The tracings were reviewed by three epileptologists as no seizure or seizure, and the labels were compared to the intracranial EEG recordings, achieving concordance among all three reviewers in 91.3 %. The subgaleal electrodes remained stable for as long as 13 days, and epileptologist's review identified 98 % of seizures, with a sensitivity of 98 % and specificity of 99 %. Hence, subgaleal EEG electrodes were deemed reliable for identifying focal onset seizures in epilepsy patients [21].

Ceribell is a rapid response EEG system that consists of 10 electrodes in a stretchable headband that records 8 channels, and it automatically uploads data to a cloud server [22]. In healthy patients they recorded in a laboratory with Ceribell and two conventional EEG systems simultaneously for approximately 37 min, performing different activities [22]. The correlation between Ceribell and the conventional EEG was similar to the correlation between the two conventional systems. The group then analyzed 22 patients with altered mental status and suspicion of seizures in an ICU, first recording with Ceribell and then with the conventional EEG, obtaining information that was concordant to a large extent.

Emotiv EPOC was compared to a conventional EEG in 22 adults during their stay in the epileptology ward, recording simultaneously for approximately 30 min [23]. Emotiv EPOC is a headset with a modified combination of the 10–20 system containing 16 electrodes connected via Bluetooth to a tablet. The recordings were evaluated by experienced epileptologists and regarding all epileptiform activity Emotiv had a sensitivity of 39 % and a specificity of 85 % and conventional EEG had a sensitivity of 56 % and specificity of 88 %[23]. The focal seizure pattern was marked as pathological in both EEG systems but 13 % of the abnormalities in conventional EEG were not present in Emotiv due to artifacts, and 63 % of pathologies were detected with both [23].

1.4. Automatic seizure detection

Four Epilog sensors were placed bilaterally behind the ear and on the forehead, below the hairline, approximately at F7/F8 and T5/T6 in adults during EMU stays [24]. The data collected by the Epilog sensors was converted to the REMI 10-channel montage and uploaded into a Persyst 14b server with mobile access to be reviewed by three board-certified epileptologists. The epileptologists reviewed records from a) 10 subjects who had focal onset electrographic seizures and b) 10 subjects who had no seizures or epileptiform activity, as well as algorithm-determined seizure detection start/stop annotated EEG from the same a) and b) subjects [24]. Detection of focal onset seizures by epileptologists achieved a sensitivity of 61 %, precision of 80 %, and false detection rate of 0.002 per hour. With annotations from the automated detection algorithm, sensitivity improved to 68 % and false detection rate to 0.005 per hour. The automated algorithm identified electrographic seizure activity with a mean sensitivity of 100 % and specificity of 70 % and focal onset seizures with a mean sensitivity of 90 % and a mean false alarm ratio of 0.087 per hour [24].

A group of authors implanted 6 to 8 subgaleal electrodes on 21 patients undergoing intracranial EEG recordings due to focal refractory epilepsy obtaining 5–14 days of recordings [25]. They developed, trained, and evaluated a seizure detection algorithm for each patient that achieved 93 % accuracy, 91 % specificity, and 97 % sensitivity [25]. Specificity and accuracy were reduced in patients with extra-temporal onsets or that involved multiple lobes, and hence subgaleal electrodes were deemed to have sufficient accuracy to be used as a long-term monitoring device [25]. As in similar studies, accuracy measurements may have ultimately been compromised by placement location in this setting.

Actiwave is a small portable EEG recorder with three electrodes, one placed near Fp1(reference), one near F7 (active), and one near TP7 (active) in six children with absence epilepsy [26]. The authors first obtained a conventional 10–20 EEG for 30 min and then left with the Actiwave that registered for 24 h on four occasions. Parents were also asked to report clinical events. They developed an automatic paroxysm algorithm based on the optimal setup that detected 98.4 % of all paroxysmal events with only 0.23 false detections per hour, and with a positive predictive value of 87.1 %[26]. They documented that parents observed 4.7 % of the possible events. Of note, some patients reported discomfort wearing the EEG recorder and electrodes in public places.

Four electrodes were placed behind the ear in 12 patients with refractory epilepsy admitted for long-term video EEG for pre-surgical evaluation, and therefore the 10–20 system was simultaneously recorded [27]. Ten patients had temporal epilepsy and two had extratemporal epilepsy. The authors were able to record 47 seizures, including 41 detected from scalp EEG, with a mean sensitivity of the automatic seizure detection algorithm of 100 % and false detection rate of 1.14 per hour, and 38 from behind the ear, with a mean sensitivity of 94.5 % and false detection rate of 0.52 per hour [27]. Electrooculography artifacts were not visible in behind-the-ear recordings, and this may have influenced the higher false detection rate from scalp EEG, as repetitive blinks may have been classified as a seizure by the algorithm. The study concluded that behind-the-ear EEG is useful in patients with temporal lobe epilepsy and probably in patients with extratemporal lobe epilepsy as well [27].

A deep learning method applied the concept of anomaly detection to overcome the imbalance between ictal and interictal activity and trained the algorithm to detect ictal events [28]. The authors included EEG data from 12 epileptic patients monitored in an epilepsy monitoring unit with intracranial electrodes at the suspected seizure onset zone and behind-the-ear electrodes with cross-head channels. The information was reviewed by two epileptologists. These researchers used the data from 6 patients as a training group, and the remaining 6 as the test group. They recorded 27 ictal events in six patients and the algorithm achieved a sensitivity of 96.3 % and a false alarm rate of 0.14 per hour [28].

The same group developed a personalized deep learning-based algorithm for automatic seizure detection using data from behind-the-ear EEG electrodes and also proposed a method to calibrate the anomaly score for each patient [29]. The authors included EEG data from 16 epileptic patients (temporal and extratemporal epilepsy) in an epilepsy unit monitored with intracranial electrodes placed on the suspected seizure onset zone and cross-head behind the ear channels. For each patient, they used data from two days, one for calibration and the other one as test data. The personalized seizure detection algorithm achieved a mean sensitivity of 94.2 % and a false alarm rate of 0.29 per hour [29]. Thus far, this system has been tested in hospitalized patients, and roll-out into the ambulatory setting is anticipated.

Four electrodes were placed behind the ear in 54 epileptic patients, mainly with temporal epilepsy, monitored with standard video EEG in a hospital setting, and the authors determined that ictal patterns can be visually recognized using only behind-the-ear EEG channels [30]. The group recorded 182 seizures arising mainly from the (frontal-)temporal lobe. The sensitivity was higher for focal to bilateral tonic-clonic seizures which achieved a sensitivity of 100 % and for seizures arising from the frontotemporal lobe, with a sensitivity of 85 %. Frontoparietal seizures had a sensitivity of 0 % (they recorded 2 frontoparietal seizures) [30]. They then developed and trained a patient-independent seizure detection algorithm that reached a sensitivity of 64.1 % and 2.8 false positives/24 h and a patient-specific seizure detection algorithm that reached a sensitivity of 69.1 % and 0.49 false positives /24 h[30]. In this study, muscle artifacts may have obscured behind the ear EEG tracings. video may have been helpful in seizures with subtle ictal patterns and bilateral ictal patterns may be difficult to recognize due to the differential amplification of relatively symmetric signals [30].

One group registered information from 12 patients with typical absence seizures admitted for epilepsy monitoring with conventional EEG and four behind-the-ear electrodes connected to Sensor Dot, a small device attached to the upper back using a patch [31]. They propose a semiautomatic seizure detection algorithm, the algorithm first selected suspected absences, which were then presented to six epileptologists to determine if it was a seizure, to reduce the time needed to review the register. The semiautomatic detection algorithm achieved a sensitivity of 83 % and a precision of 89 %, with a time to review 24 h of EEG data that came down from 1 to 2 h to 5–10 min [31].

The Sensor Dot was also tried in adult patients with refractory epilepsy and at least one focal impaired awareness seizure per month over six months [32]. The 16 inpatient subjects were admitted for presurgical evaluation and had simultaneous conventional scalp EEG recording and the Sensor Dot placed ipsilateral to the suspected seizure focus, which was replaced every 24 h due to limited memory storage [31]. The 16 outpatients used Sensor Dot at home, for a minimum of 16 h per day, and placed the device ipsilateral to the suspected seizure focus or in the most affected hemisphere if the epilepsy was multifocal, with monthly follow-ups [32]. The inpatient group used Sensor Dot for at least one day and considered seizures detected by the scalp EEG as the gold standard. The related seizure detection algorithm achieved an overall sensitivity of 52 % (higher for temporal lobe seizures) and a mean of 7.1 false detections per hour. The outpatient group used Sensor Dot for a median of 74 days, considered seizures reported by patients as the gold standard, and the algorithm achieved a sensitivity of 23 % (again higher for the temporal lobe seizures) and 7.7 false detections per hour. The authors attribute the low sensitivity to the quality of the patches, recommending lower impedance and higher biocompatibility, and also advise further patient education. Ultimately training algorithms with patient-specific EEG patterns were possible future detection improvement opportunities [32].

One group of authors designed a study to evaluate the performance of a subcutaneous EEG automatic seizure detection algorithm [33]. They included two datasets recorded with a minimally invasive subcutaneous EEG, eight corresponding to patients with temporal lobe epilepsy, and twelve healthy controls. In patients with epilepsy, the three contact electrodes (two bipolar EEG channels) were placed over to the suspected epileptic focus and in healthy subjects from behind the ear towards the vertex [33]. The automatic seizure detection algorithm detected all focal to bilateral tonic-clonic seizures, achieving a sensitivity of 86 %, with a false detection rate of 2.4 per 24 h. Using the algorithm allowed for a reduction in the amount of data to be reviewed by 99.6 %[33]. The authors suggest that this algorithm can be used in a semiautomatic way to reduce the time invested in EEG analysis [33].

Epihunter is a wearable headband EEG device, with dry electrodes, connected to a smartphone, coupled with an automated absence detection algorithm that also assesses the patient́s responsiveness to an alarm via smartphone [34]. The authors included 102 patients with suspected absence seizures, older than 3 years, and they placed the headband on the forehead with an elastic band, recording a bipolar EEG channel corresponding to F7-Fp1. The automated absence detection algorithm had an average sensitivity per patient of 78.8 % and a median sensitivity per patient of 92.9 %, with an average false detection rate in all 102 patients of 0.5 per hour [34]. The majority of patients did not have any false alarms. Behavior was tested in 36 seizures, and during 30 out of 36 seizures, patients were unresponsive [34].

1.5. *Seizure Forecasting*

Epi-Minder is a minimally invasive sub-scalp device that continuously recorded EEG in five patients with refractory epilepsy, registering two channels from both brain hemispheres [35]. Data from sub-scalp was captured with a system placed behind the ear and transferred wirelessly to a mobile phone, all participants wore it for at least 8 months. The electrodes were placed over the pericranium, with a location chosen to optimize registering epileptiform activity [35]. They compared these data with a conventional EEG recording and 4 extra scalp electrodes placed as close as possible to the subscalp electrodes after 1, 4, and 24 weeks following implantation [35]. The surgical procedure was well tolerated and no significant complications occurred. Seizures were successfully identified with the subscalp electrodes as confirmed by the concomitant conventional EEG. Seizure forecasting was performed for one patient who spent 26 % in a high-risk state, 11 % in a medium-risk, and 63 % of the time in a low-risk state, with 83 % of seizures occurring in the high-risk state [35]. They concluded that a high prediction performance can be achieved with an event-based seizure forecaster, but a larger cohort is needed [35].

A group of researchers assessed if patient-specific seizure forecasting is possible with ultra-long-term subcutaneous EEG [36]. They included six patients with drug-resistant focal epilepsy, who were implanted with a three-contact lead wire, yielding two bipolar EEG channels, placed over the suspect seizure focus monitoring for 46 to 230 days. Electrographic seizures were identified by an epileptologist with experience in subcutaneous EEG and verified by a neurophysiologist. They used three different patient-specific forecasting architectures achieving significant forecasting performances in three to five of six patients, with sensitivity from 64 to 80 % and time in warning ranging from 10, 9 to 44,4% concluding that seizure forecast is possible with subcutaneous EEG [36].

1.6. *Patients' acceptability*

Epilog patients' acceptability was assessed in twelve epilepsy patients during their hospitalization in the epilepsy monitoring unit [37]. The authors reported that when Epilog was attached to the upper forehead it tended to fall off at night, but when placed behind the ear it was very stable. Patients̈ evaluation with the Technology Acceptance Model Fast Form reported that the device was comfortable for a long time, usable, and easy to master, but the evaluation was lower in comfort during sleep and ease of manipulation; the mean score was 3.0 ± 1.3, and therefore the use was considered effortless [37].

The subcutaneous EEG reported by Viana et al was well tolerated and accepted, although this group noted headaches during the first three weeks, but also found high adherence, presumably also due to placement under the skin usually requiring less maintenance, without serious adverse effects and was able to record during more than seven months, in a real-life setting [14].

The Neury device had excellent tolerability with no interference with daily activities [11].

The Garmet EEG headband designed by López-Larraz et al was used for 42 to 48 min, and the degree of comfort was reported by healthy participants as high, for the whole system and the sensors, although recording durations were shorter than with many other systems. Participants did not report the headband as bothersome and the perception of stability was positive [12].

A group evaluated the response of patients with epilepsy to four commercially available wearable devices, including Epitel Epilog [38]. The device was attached to the forehead of 21 patients, and it recorded a bipolar EEG channel from two electrodes obtaining 21.4 % of data classified as good, 33.3 % classified as acceptable, and 45.3 % were marginal. Regarding patients' surveys the mean Likert scale result (1: strongly agree, 7: strongly disagree) was 1.50 for easy to manipulate, 2.25 for usable, 2 for long-term comfort, 1.75 for comfort during sleep, and 3.50 for would use for seizure prediction [38].

Thirteen of the fifteen patients who tried the earpiece tested by Zibrandtsen et al. described some level of discomfort, due to soreness in the cartilage or outer ear, where it was placed, leading to discontinuation in three patients [20].

Patients̈ wearing the Sensor Dot reported as the most frequent adverse effects skin irritation, itch, and patch imprinting, some of which were worse during the summer. Patients reported that the comfort was tolerable, but also wanted days without the Sensor Dot, mainly during weekends and festivities [32]. The quality of life questionnaire did not change significantly after using Sensor Dot [32].

2. Conclusions

There is an urgent need to offer patients with epilepsy and their caregivers a more reliable alternative to seizure diaries to quantify

Table 2
Main advantages and disadvantages of the summarized long-term, limited lead EEG systems (conventional 10–20 EEG included for comparison).

EEG monitoring modality	Main advantages	Main disadvantages
Conventional 10–20 EEG	Gold standard Accurate estimation of seizure burden Excellent temporal resolution Good spatial coverage Detects seizures from all lobes	Possible skin injury Need for the electrodes to be repositioned by a technician Electrodes and wires are uncomfortable and highly visible Obtrusive Signal could be degraded with time Time-consuming to review Need to be in the hospital or clinic Expensive Bulky recording devices Not suitable for daily life monitoring
Subgaleal EEG	Reliable for identifying focal onset seizures Minimally invasive Electrode recordings remained stable Accurate	Requires anesthesia, a surgical procedure, and a trained surgeon Lower sensitivity for extra-temporal onsets and seizures that involved multiple lobes
Subcutaneous EEG	Minimally invasive The signal is highly stable Can record ultra-long-term EEG Allows increased mobility Discrete device Muscle artifacts are smaller than in scalp EEG Good adherence	Limited spatial coverage Requires anesthesia, a surgical procedure, and a trained surgeon Soreness in the implantation site, headaches, and minor skin irritation It can be contaminated with muscle artifacts The placement position must be well-considered Device disconnection due to personal hygiene, sleep, exercise, or malfunction of the recorder
Subscalp EEG	Minimally invasive Discrete device Recorded signal comparable to conventional scalp EEG but less noisy Not affected by movement artifacts Can record ultra-long-term EEG Detects focal seizure activity	Requires anesthesia, a surgical procedure, and a trained surgeon Susceptible to muscle activity
Behind the ear EEG	Recorded signal comparable to scalp EEG Discrete Wearable Unobtrusive Good sensitivity mainly in temporal and frontal temporal seizures Electrooculography artifacts were not visible	Extratemporal seizures might be missed since electrodes are closer to the temporal lobe Muscle artifacts might distort the entire signal and miss seizures Bilateral ictal patterns are difficult to register with crosshead channels due to the differential amplification of symmetric signals Patients reported skin irritation, itch, and patch imprinting
In the ear EEG	Discrete Wearable Unobtrusive	Need for individualized design Hearing loss Discomfort due to soreness in the cartilage
Tattoo EEG	Comfortable Light-weighted Portable	Was evaluated in interictal states Tested on a few subjects
Headband EEG	Can be mounted by untrained personnel Quickly placed If battery powered has no 60 Hz noise Accurate detection of epileptiform abnormalities	Less spatial coverage Prone to movement since electrodes are not fixed to the scalp
Single channel EEG	Reduced time for preparation Improved portability Increased freedom to move Minimum weight Well tolerated	Uncomfortable during sleep Some patients reported discomfort wearing the EEG recorder and electrodes in public

seizures, as this could improve overall epilepsy management and aid in drug trials. The conventional 10–20 EEG is considered the gold standard, but it has several limitations such as possible skin injury, the need for the electrodes to be repositioned by a technician, high cost, electrodes and wires being uncomfortable and highly visible, and worsening recording quality over time without lead repair. Long-term EEG systems could be especially useful for patients with infrequent events that need to be better characterized, with persistent events despite several changes in antiseizure medication, to quantify seizures in patients with events in which there is loss of awareness and in patients where, due to behavioral or other aspects, a long-term hospitalization in an epilepsy monitoring unit is not possible. There are now several alternatives to conventional EEG for long-term monitoring with limited leads, such as subscalp, subcutaneous, behind and in the ear, single channel, and headbands, and each of those options has advantages and disadvantages (Table 2). They offer several advantages such as being used in ambulatory and home settings due to their minimal invasiveness, some are easily placed by caregivers, achieve good sensitivity with low false detection rates, are used for automatic seizure detection as well as seizure forecasting, and are well tolerated by patients. For a separate review of website information and articles on selected wireless systems, including 10–20 system EEG devices, please refer to a survey of these systems [39].

The implementation of these devices into clinical care is in progress, and several of the outlined devices are seeking or have obtained FDA approval. Furthermore, CPT billing codes for 8 lead EEGs may enable a potential pathway, for clinical care implantation and revenue of long-term limited leads in the future. It is also conceivable that pending information on added value, CPT codes may be revised to permit EEGs with even fewer leads, as some seizure types may be able to be monitored or assessed with less than 8 lead EEGs.

These long-term recordings, while tracking circadian patterns, create a new challenge, as their evaluation is time-consuming. The offered solutions are seizure detection algorithms, as the ones mentioned here, but many algorithms need to further improve their sensitivity and lower their false detection rates. The EEG detection algorithms may improve if they are trained with larger data sets and with patient-specific data, and if they are integrated with additional clinical, diary, or neurophysiological and biological signals. In the meantime, automatic detection algorithms could be used in a semi-automatic way in which they select the suspected events and those are reviewed by a trained neurologist or epileptologist to improve accuracy, albeit lowering the time needed for review. Also, deep learning and artificial intelligence algorithms with patient personalization have been studied with promising results. The combination of seizure diary and neurophysiological data with automatic detection algorithms may be able to better monitor outcomes, and potentially alert, or even predict, when an upcoming seizure is going to occur, ultimately improving QOL of patients with epilepsy.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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