

Wearable EEG: what is it, why is it needed and what does it entail?

Alexander J. Casson, Shelagh Smith, John S. Duncan and Esther Rodriguez-Villegas

Abstract—This paper presents a review of wearable EEG technology: the evolution of ambulatory EEG units from the bulky, limited lifetime devices available today to small devices present only on the head that can record the EEG for days, weeks or months at a time. The EEG requirements, application areas and research challenges are highlighted. A survey of neurologists is also carried out clearly indicating the medical desire for such devices.

I. INTRODUCTION

The electroencephalogram, or EEG, is a classic method for measuring a person's *brainwaves*. Electrodes are placed on the scalp and detect the micro-Volt sized signals that result outside the head due to the synchronised neuronal action within the brain. Current monitoring is generally either inpatient: in the tertiary care centre with time locked video and the patient typically restricted to a bed by wires connecting the electrodes and recording unit; or ambulatory: here the recorder is portable and in principle the subject can go about their normal daily life.

In practice, however, this is rarely the case. It is quite common for people undergoing ambulatory monitoring to take time off work and stay at home rather than be seen in public with such a device. Wearable EEG is the evolution of ambulatory EEG units from the bulky, limited lifetime devices available today to small devices present only on the head that can record the EEG for days, weeks or months at a time. This evolution is illustrated at a high level in Fig. 1.

The development of these devices, while challenging, is timely, and at this conference there is an entire special session dedicated to *truly wearable EEG*. This paper aims to provide a review and overview of wearable EEG technology, its uses and requirements, and the desire to have such systems in place. We will focus mainly on epilepsy and the medical applications of wearable EEG as this is the historical background of the EEG, our area of expertise and a core motivating area in itself, but will also discuss other application areas.

As part of our review we have carried out a survey of the neurologists at the National Hospital for Neurology and Neurosurgery and the National Society for Epilepsy in the UK for their views on wearable EEG as a key user group. This shows that it is thought wearable EEG will be a key future tool.

The authors are with Imperial College London: {acasson, e.rodriquez}@imperial.ac.uk, and the National Hospital for Neurology and Neurosurgery: shelagh.smith@epilepsynse.org.uk, j.duncan@ion.ucl.ac.uk.



Fig. 1. The evolution of AEEG to wearable EEG. AEEG image courtesy of the National Society for Epilepsy.

TABLE I

SUMMARISED STANDARDS FOR DIGITAL EEG RECORDING FROM [2].

| | |
|---|---|
| Channels: ≥ 24 , preferably 32. | Inter-channel crosstalk $< 1\%$. |
| At least 12 bit analogue to digital conversion with a minimum resolution of $0.5 \mu V$. | 70 Hz, 40 dB per decade, anti-aliasing low pass filter. |
| Sampling rate: ≥ 200 Hz, preferably higher. | Additional noise not less than $1.5 \mu V_{pp}$ or $0.5 \mu V$ RMS. |
| High pass filtering at ≤ 0.16 Hz. | CMRR at amplifier input ≥ 110 dB. |
| 50/60 Hz notch filter available but not routinely used. | Referential montage to allow later <i>re-montaging</i> . |
| Electrode impedances < 5 k Ω . | Pre-amp impedances > 100 M Ω . |

II. EEG TECHNOLOGY

A. The EEG

Many excellent texts (such as [1]) are available on EEG technology and the typical signals produced and so only brief mention is given here to outline the specifications required for high quality wearable systems.

Typical signals detected on the scalp are in the range 20–150 μV over a 0.5–60 Hz bandwidth [1]. The signals vary both temporally and spatially and so multiple channels are used with electrode positions usually determined using the international 10-20 standard. Equipment recommendations from the International Federation of Clinical Neurophysiology are given in [2] and summarized in Table I.

Present ambulatory systems typically have at least 16 channels and can operate for around a day without recharging. Wireless systems offer around 8 EEG channels and last for 12 hours.

B. Future trends

The trend in EEG units is undoubtedly for higher sampling frequencies and more recording channels. Although [2] proposes 200 Hz as a reasonable minimum sampling frequency it is not uncommon for inpatient monitors to now offer sampling frequencies of 1 kHz or more. Also, while recording as few as four EEG channels has been shown to be clinically useful [3], and is typically used in augmented cognition applications (see Section III-C), modern inpatient systems for epilepsy diagnosis may offer 256 channels. Furthermore, it has been shown that to avoid spatial aliasing (signals appearing in one location when in fact they occur in another, purely due to how the electrodes are setup) towards 600 channels are needed [4].

Whilst it is debatable whether such high resolution systems are necessary for all patients and diagnostic issues, truly successful wearable EEG solutions should not stand in the way of this trend from a technological viewpoint. Wireless transmission of the data, while power intensive, will also be a key part of wearable EEG to minimise the cumbersomeness of the system (removing wires from the electrodes to the recording unit). It also facilitates possible integration into body area networks which are currently of large research interest.

III. APPLICATION AREAS

A. Epilepsy

Epilepsy is a well known and high incidence neurological disorder characterised by debilitating seizures that significantly affect the sufferer's quality of life. It affects approximately 1% of the population [5] and in 2004 the cost of the disease in Europe was over €15 billion [6].

However, despite this large prevalence and the disease's consequences, misdiagnosis is a significant issue. It is estimated that 13–20% of patients present diagnostic problems [7] and 25% of diagnosed epilepsy sufferers do not actually have the condition [8]. Although to avoid misdiagnosis the EEG should never be used alone, it is a key diagnostic tool for answering the questions: is epileptiform discharge present?; what type of epilepsy is present?; and what is its locus within the brain?

A standard EEG test lasts between 20 and 30 minutes and so is generally restricted to recording interictal activity (activity that occurs between seizures). Synchronous video monitoring is often also used. Longer term monitoring, with an aim of recording ictal activity is required in cases which present diagnostic or management difficulty [9].

Long term inpatient monitoring may be undertaken continuously for several days, significantly increasing the likelihood of seizures, or rare interictal activity, being recorded. However, the extra data produced can take a significant amount of time to analyse and the method comes with significant monetary and resource overheads. As a result it is not universally available [10]. It also removes the patient from their natural environment which may have been a causative factor in the suspected seizure disorder due to the particular stimuli present.

Ambulatory monitoring overcomes some of the limitations of inpatient monitoring with 24 hours of ambulatory monitoring being more than 50% cheaper than 24 hours of inpatient monitoring [10]. Overall it is estimated that AEEG is clinically useful in 75% of patients, and abnormalities are found in 12–25% of AEEGs for which an inpatient EEG was normal or non-diagnostic [10]. Whilst outpatient AEEG systems offer several benefits over long term inpatient monitoring, several limitations are present:

- 1) There are issues in ensuring that the electrodes remain securely attached for the duration of the testing and also in the social acceptability of wearing head mounted electrodes in public.
- 2) Systems can weigh up to 1 kg, limiting their portability.
- 3) Each channel recorded requires a wired connection from the patient's head to the recording unit and the compliance of these wires can limit patient movement.
- 4) Long term recordings generate large amounts of data for storage or transmission, approximately 1 GB every 24 hours. This requires a significant amount of power.
- 5) The data is time consuming for a neurologist to analyse, taking approximately two hours per 24 hour recording [11].

It is these issues that wearable EEG aims to overcome, extending current AEEGs to give a longer temporal sample that includes all stages of sleep and wakefulness and increasing the likelihood of recording typical seizures.

B. Sleep studies

Sleep disorders affect more than 70 million people in the US. The impacts of this are again huge: 20% of road accidents involving serious injury are sleep related and the annual cost of sleep disorders in the US is hundreds of billions of dollars [12]. Again, despite this, diagnosis is difficult and resource limited. In the UK, the overall waiting time from referral to sleep study can be up to three years [13].

Diagnosis typically uses PSG (polysomnography) which monitors multiple body functions such brain activity (EEG), heart rhythm (ECG), and breathing function during sleep. The requirements for wearable EEG for sleep studies are of course slightly different to those for epilepsy studies. Principally the duration of operation will be shorter, 12 hours at a time is likely sufficient, but if anything the devices have to be even less cumbersome. The patient ideally has a good night's sleep while wearing all of this monitoring equipment! Thus, ideally the device and its interconnections should be even smaller.

C. Brain computer interfaces and augmented cognition

Although the EEG has its roots in medical instrumentation EEG signals are not only indicative of abnormal health states. This fact is used in Brain Computer Interfaces (BCI) (see [14] for example).

The basic mode of operation is that a person's brain exhibits measurable changes in electrical activity when responding to stimuli or preparing for physical exertion. These changes can be detected and used, for example, to direct a

cursor or control a robot arm. As a result these applications could revolutionize the way in which people use computers

The natural continuation of BCIs, where a human influences the operation of a computer based on their thoughts is to close the loop: a computer monitors a person via an EEG and uses this to provide feedback, affecting the user's environment. This is a research concept known as augmented cognition which has arisen at the intersection of cognitive science, neuroscience, and engineering [15].

Classic uses would determine whether a person is: asleep, awake, bored, tired, stressed, or angry. This has uses in preventing people from falling sleep from the wheel as well as in computer-assistance technologies that will help pilots and others who face high stress situations.

Many of these methods are still at the research stage, but in addition to the success of the signal processing algorithms the success of the field and level of end user acceptance will strongly depend on the physical unit: the EEG system itself. It is ideally untethered from cumbersome wires and must be small, discrete and comfortable whilst also offering good battery performance. All of this puts future BCIs into the realm of wearable EEGs.

IV. WEARABLE EEG QUESTIONNAIRE

To illustrate the medical need and desire for wearable EEG we carried out a survey of 17 neurologists at the National Hospital for Neurology and Neurosurgery and the National Society for Epilepsy in the UK. The results are summarised in Table II.

The vast majority of respondents thought that current ambulatory recordings are useful over traditional inpatient recordings and also that wearable EEG would be a major improvement in EEG practice both for them and their patients. This clearly illustrates the desire for wearable EEG. All but two respondents also thought that ambulatory recordings will be more common in the future, and so this desire is likely only to increase with time.

Opinion, however, was more divided over the amount of data produced and the ability of signal processing algorithms to automatically reduce it. Despite many years of software availability further work is perhaps required on, or at least on the perception of, automated detection methods.

We also asked about some of the other applications of wearable EEG. Most people thought that it would be of use for sleep studies, but again opinion was divided on the other application areas. The medical usage of wearable EEG was thought to be more significant than the non-medical usage. This said, of course, our study population, being doctors, isn't necessarily representative of the users of augmented cognition and BCI systems and so may underestimate its importance. It is known that DARPA has shown a large amount of interest in augmented cognition and its potential applications [15].

Overall our results illustrate the medical desire for wearable EEG systems and it is likely that if they can be satisfactorily developed they will play a large part in future medical care.

V. REQUIREMENTS

Finally, we overview the two research areas core to making make wearable EEG a reality: new electrode technologies and lower power consumption.

A. Novel electrodes

Regardless of the connection method used, in an uncontrolled environment such as ambulatory monitoring it is possible for an electrode to come loose, preventing the EEG from being recorded. Methods are needed to overcome this significant limitation to make long term systems practical. The authors envision three possible solutions to this problem.

Firstly, one of the advantages of a wireless system is that it provides real-time access to the EEG being recorded. It would thus be possible to monitor patients remotely for a few minutes a day to check the quality of the signals. If electrode connection issues are found the patient can be directed to the local primary care unit (the GP's office in the UK) to have them reattached. This removes the need for the patient to return the tertiary care unit where the EEG is typically applied. Whilst this method is relatively resource intensive it is a simple solution which can be implemented immediately.

The second solution, and one in which significant progress has been made (see [16] for example), is in the use of dry electrodes. These electrodes require no special preparation of the subject, are simply placed on the scalp and can be easily held in place by a hat, readily accepted in social situations. Undoubtedly these electrodes have a big future, but there is still the issue of keeping the electrodes in place over a long period of time: a hat cannot be worn 24 hours a day, seven days a week.

Instead, the final solution may be a semi-implanted approach. This is not invasive electrodes within the skull, instead it is possible to envision electrodes placed subcutaneously or subdermally below the scalp, essentially not externally visible and intrinsically held in place. Such a system may provide an EEG analog of the Reveal Heart Monitor [17]. This is an implantable monitor which records 42 minutes of ECG in response to an automated detection. The device is implanted in an out-patient procedure and allows monitoring for 18 months. Of course the ECG situation is simpler as the signals are larger, easier to record and fewer channels are involved, but the principle is the same. These would likely provide the longest term solution, but significantly more work is required.

B. Lower power consumption

The power constraints for wearable EEG are summarised well in [18]. If the overall device is assumed to have a volume of 1 cm³ and half of this space is reserved for a battery of energy density of 200 Wh/l, 100 mWh of energy is stored. For operation over 30 days the average power consumption must be less than 140 μ W.

A front-end system consuming 25 μ W per channel is presented in [19]. A full power trade-off study is presented in [20], but at 200 Hz, 12 bit sampling, 300 bytes per second per channel of data is produced. For a 5 nJ/bit transmitter

TABLE II
RESULTS FROM THE WEARABLE EEG SURVEY CARRIED OUT.

| Question | Yes | No | Don't know | Not answered |
|--|--|----|------------|--------------|
| Are current ambulatory recordings diagnostically useful over traditional inpatient recordings? | 12 | 0 | 3 | 2 |
| Would you consider it a major improvement in your EEG practice if wearable EEG devices were available? | 13 | 1 | 2 | 1 |
| Do you think that your patients would consider it a major improvement their EEG experience if wearable EEG devices were available? | 12 | 0 | 3 | 2 |
| In the future do you anticipate ambulatory recordings being: | More common: 15; Used about the same: 1; Not answered: 1 | | | |
| Is the amount of EEG information produced by monitoring for weeks or months to capture rare events too much to be useful in practice? | 5 | 5 | 7 | 0 |
| Would you trust automated detection or data reduction software to reduce the amount of data presented to you? | 6 | 4 | 7 | 0 |
| Would you trust the automated diagnosis of disorders based upon detection software? | 1 | 10 | 4 | 2 |
| Do you think wearable EEGs would be useful for sleep studies in allowing more natural, unrestricted sleep than current sleep EEG units do? | 14 | 1 | 1 | 1 |
| Are you interested in the other potential applications of wearable EEGs, such as controlling computer games or receiving feedback based upon your current awareness level? | 8 | 4 | 4 | 1 |
| Do you think that wearable EEGs will be of more use to this sort of application area rather than in medical applications? | 2 | 7 | 7 | 1 |

transmitting each channel consumes approximately 12 μW . With these figures only 3 channel systems are possible.

To realise high quality wearable EEG systems significantly better performance is required on all fronts and this represents a major challenge. An alternative method is the application of online data reduction (see [21]) and the authors believe that this will be key to realising systems.

Finally, we make brief mention of power scavenging techniques where power is harvested from the ambient environment of the user, for example from body heat or movement [22]. It is believed that such techniques may harvest up to 100 μW significantly relaxing the power constraints. The drawback of this is that the power source is non-constant, and may have regulatory issues. Nevertheless work is progressing to make such systems feasible for when these issues are overcome.

VI. CONCLUSION

Wearable EEG devices face a number of research challenges. However, the devices have a wide range of applications and can improve and extend current practices. We have demonstrated that there is a clear medical desire for the introduction of such devices.

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