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Home-Video-EEG-Telemetry (HVET): **A review of the development of in-home video-EEG recordings**

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Summary

Video-EEG monitoring is an essential tool in epileptology, conventionally carried out in a hospital Epilepsy Monitoring Unit (EMU). Due to high costs and long waiting times for hospital admission, coupled with technological advances, several centres have developed and implemented video-EEG monitoring in the patient's home (home video-EEG telemetry, HVET). Here, we review the history and current status of three general approaches to HVT: (1) supervised HVT, which entails setting up video-EEG in the patient's home with daily visiting technologist support; (2) mobile HVET (also termed ambulatory video-EEG), which entails attaching electrodes in a healthcare facility, supplying the patient and carers with the hardware and instructions, and then asking the patient and carer to set up recording at home without technologist support; and (3) cloud-based HVET, which adds to either of the previous models continuous streaming of video-EEG from the home to the healthcare provider, with the option to review data in near real time, troubleshoot hardware remotely and interact remotely with the patient. Our experience shows that HVET can be highly cost-effective and is well-received by patients. We note limitations related to long-term electrode attachment and correct camera placing while the patient is unsupervised at home, and concerns related to regulations regarding data privacy for cloud services. We believe that HVET opens significant new opportunities for research, especially in the field of understanding the many influences in seizure occurrence. We speculate that in the future HVET may merge into innovative new multisensor approaches to continuously monitoring people with epilepsy.

Keywords

Epilepsy, video EEG, EMU, Home Video EEG telemetry (HVET), remote monitoring,

Key points

- Many patients admitted to Epilepsy monitoring units (EMU) can be assessed with home video EEG telemetry (HVET)
- Currently 3 types of HVET recording can be distinguished: supervised HVET, ambulatory HVET, and cloud based HVET
- In the near future, brief HVET recordings may be extended by wearable devices for seizure monitoring to increase patient autonomy and optimized treatment

Introduction

Epilepsy monitoring units (EMU) are the gold standard for evaluation of epilepsy in specialist centres worldwide. Due to high costs and long waiting lists, non-hospital based approaches have been developed, which we termed 'Home Video EEG Telemetry' (HVET). This approach is cheaper and easily scalable, allows elucidation of environmental factors shaping seizure manifestations often not detectable in hospital (see supplementary Figure S1) and allows for new ways of collaboration and research.

Three strands of development of HVET can be identified: The first strand is modelled on inpatient video-EEG telemetry (VT) recordings, being essentially an inpatient EMU moved to the patient's home, which we termed **supervised HVET**^{1,2}. The second strand of development is an evolution of ambulatory EEG, in which the patient takes EEG equipment and a camera back home for several days. Those recordings were referred to as ambulatory video-EEG³ or **mobile HVET**. The third strand, termed **cloud-based HVET**, emerged as a development of supervised HVET at King's (providing two cameras, more mobility for the patient and online streaming for supervision from the hospital); and independently in Australia, launched with a main purpose to create a cloud-based platform for managing data from implantable and wearable devices; the HVET service was launched as a first proof of concept for the cloud-based EEG tools, but soon became the main effort, due to the high demand.

We see two important drivers: cost, and scalability. In the UK, the HVET provider receives the same tariff as for inpatient VT, but HVET is significantly cheaper to provide. In the USA, specialist providers spearheaded the development of HVET and were able to provide a wide geographical reach, greatly scaling the availability of VT^{4,5}.

Two key enablers have been the emergence of purpose-designed ultra-portable hardware, and simple evolution of secure electrode attachment to the scalp. Equipment setup has diminished to a few instructions for laptops or tablets which are fully integrated with ultra-portable video-EEG systems, designed for use at home, with remote access and data transmitted from the home setting. Retaining good quality EEG signal in the home, with minimal maintenance, was a key development: In the King's approach, all electrodes covered with tape which protected the conducting paste from drying and further securing the electrode, sustaining electrode integrity for up to 4 days. The Evelina London Children's hospital adopted a non-collodion based electrode application approach, durable for 2-3 days⁶ which does not require a technologist to remove the electrodes. We think that this development

is particularly important as collodion is not available in all countries. In the Australian model, custom anchoring and stress relieving of the electrode system is used, which enables comfortable robust connections over the monitoring period without the need for bandaging.

Current service models for HVET

a) Indication

At King's College Hospital, 20% of referrals for VT are for presurgical evaluation. In the majority, antiepileptic drug (AED) reduction is required, which has risks and in our opinion is not safe outside a hospital. The majority (80%) of referrals for VT are for diagnostic reasons; this has become the remit for HVET.

b) Different clinical service models

Supervised HVET (figure 1) as provided by King's College Hospital follows the principle of EMU recordings, transferred to the patient's home. The electrode placement can take place in hospital or in the home; the latter is preferable for children and patients with learning difficulties. The technologist and equipment are transported to the patient's home. The quality of video and EEG show no significant difference from hospital ^{1, 2}. Carers are instructed to perform ictal assessment using a small ictal assessment card (see supplementary figure S2). We have not systematically evaluated home based ictal assessments, but anecdotally have seen assessments carried out very effectively. The effectiveness of ictal assessments performed by carers remains an important unknown, and warrants further study. Video-EEG data are downloaded during an on-site daily visit by the technologist. If seizures or events have occurred, they will be reviewed by the technologist, patient and carer or family to ensure all seizure types are captured (see supplementary tables 1 and 2). Although not yet available in this system, integrated and automated seizure alarms and seizure detections could enhance efficiency in the future. Troubleshooting issues, such as recording problems and adjusting the camera position, are solved during daily visits.

In the **mobile HVET** model (figure 2), patients are seen at the hospital or office where electrodes are placed on the patient's head. After the patients, carers or family have been instructed how to use the equipment, they are sent home. The diagnostic yield showed no significant difference to inpatient recordings ^{7, 8} (see also supplementary Tables 3-6). Patients and carers not infrequently struggle when positioning the camera or changing equipment batteries, which in the supervised HVET model is taken care of by the visiting technologist ⁸. As technologists do not have to leave the hospital and the

hospital does not provide transport, this model has found widespread adoption^{5, 9, 10}. The patient data can only be reviewed, pruned and reported when the patient has returned the equipment. In some service models the video-EEG data are made available in the cloud for an offsite reader panel^{5, 9} and in some models the recording device status may be continuously tracked remotely using a secure VPN between the hospital base and the patient's home.

HVET practice is being revolutionized by Cloud computing solutions designed for clinical EEG. Here, an EEG Cloud is defined as an internet-addressable service that accepts a stream of EEG and video from the internet for storage and is able to provide a stream of EEG and video to a client on the internet upon request. The EEG cloud can receive data in real-time from an EEG recorder placed in the patient's home, either using the patient's home network or cellular communication technology. In the USA, new CPT codes for 2020 describing requirements for long-term EEG assume continuous or intermittent monitoring during the examination and explicitly state this can be provided remotely and for up to 12 patients simultaneously by a single technologist. One **cloud based HVET** model (figure 3) has been trialed at King's College Hospital in partnership with a commercial provider of hardware and cloud services^{11, 12}, which allows supervision via cloud streaming of video-EEG. Technologists do not have to leave the hospital. The quality of the EEG and video recording can be monitored continuously over the cloud, allowing some remote trouble-shooting eg. camera positioning. Allowing for more patient mobility, two cameras have been deployed successfully, but the patient or carer still needs to be contacted to adjust the camera position in the home. Cloud based access allows for remote communication with clinicians, using real-time video-calling, and provides an easy opportunity for a second opinion and an earlier termination of the recording if the relevant data has been captured. In another cloud-based HVET service offered in Australia, patients are set up at a clinic by an expert technologist and sent home. For quality control both the video and EEG data can be accessed remotely through a VPN via 4G connection. Following disconnection, the pruned data are made available in the cloud for reporting by the neurophysiologist. The referring clinician will also be able to access relevant data online via a clinician viewer.

c) Paediatric patients and patients with learning difficulty (LD)

In patients with LD with or with challenging behavior, the change of environment between the familiar home and unfamiliar hospital environments can be difficult, leading to unsatisfactory video-EEG recording in hospital. HVET in the patient's home is likely to be preferable. If children are admitted to a hospital often one parent is needed for support, which is a significant disruption of family life. The ambulatory video EEG model is often preferred in children as it is difficult for parents to confine

children in one room. As the frequency of events in question is usually high, the risk of not recording all seizures on camera can be taken.

d) Yield, impact, costs and economics

HVET recordings in the USA were found to be almost 70% cheaper than inpatient VT. Patients who had undergone inpatient studies were found more likely to undergo subsequent additional inpatient testing, further contributing to an increase in long term costs. The same study also demonstrated that the time from physician referral to performance of the study was significantly shorter for HVET versus inpatient VT ¹³. Due to an identical national tariff for inpatient VT and HVET in the UK National Health Service, the development of home recording was supported and found in the case of supervised recordings to be 30% cheaper than the inpatient recordings. In addition, at King's College Hospital, 3 inpatient VT beds were no longer required, and were converted to neurosurgical beds, allowing an extra 460 elective surgical cases to be treated ¹⁴. The Australian service led to an 80% cost improvement.

e) HVT and research

As the seizure recording takes place in the patient's personal surrounding, environmental factors shaping seizure manifestations, including trigger factors, circadian rhythms and aspects related to social and psychological factors might come into the focus of research (supplementary figure S1). For example, we found that non epileptic seizures had a significantly shorter duration at home compared to the hospital setting (mean 320s at home versus mean 868s in hospital, unpublished data from King's College Hospital). The cloud environment enables collaboration, curation, and new research, such as the development of machine tools ¹⁵.

f) Current challenges and limitations

It is beyond the scope of this paper to review the regulatory problems clinicians have been facing to develop HVET recordings in various countries. Due to long travel times for technologists, supervised HVET recordings are often impractical to set up in rural areas. Patients and carers or families not infrequently struggle with setting up the recording in unsupervised ambulatory monitoring ^{7, 8, 16} and data may be lost. The integration of hospital based services with non-hospital based services remains a fruitful ground for collaboration and innovation. Synergies of combining both and achieving a higher diagnostic yield have been demonstrated ¹⁷.

With the current electrode technology that is available HVET recordings are limited to several days, often enough to obtain conclusive data to make a diagnosis. Repeat recordings may be required, but drug withdrawal in HVT, which is routine in the EMU, has not yet been attempted due to safety concerns.

Long term HVET monitoring for the evaluation of treatment with EEG and non EEG based sensors are on the horizon. Dry electrodes, which are easy to apply and are therefore promising in the lab are not yet suitable for overnight studies. In optimal conditions, dry electrodes can produce signals similar to adherent gelled “wet” electrodes. However, all dry electrodes are much more susceptible to movement artefacts than adherent gelled electrodes, and dry electrodes require sustained pressure over the electrode to maintain skin contact. This pressure would inevitably be intolerable over long periods of recording, especially during sleep. Nonetheless, gelled adherent electrodes require careful maintenance to retain good signals, and are also not easy to tolerate for the patient. Future technological innovation may allow dry electrodes to be more suitable for long-term at home recordings.

The signal quality obtained from an adherent gelled electrode will deteriorate over time. During inpatient VT, staff will keep electrode signal quality under regular review, and take steps to restore optimum signal quality, such as re-gelling or re-attaching the electrode. In the supervised HVET model, a technologist will travel to the patient’s home and will be able to take similar steps to restore good signal quality. In the mobile HVET model, 26 of 9965 HVET EEGs (0.3%) were unusable because of persistent EEG artefact¹⁸. We are not aware of data regarding the extent to which HVET EEG is compromised by loss of satisfactory signals (from eg. artifacts, high electrode impedance or electrode detachment) and how this compares with inpatient VT, although HVET inevitably poses greater challenges for maintaining good signals.

Correct video camera positioning may be suboptimal in unsupervised services. Nonetheless, in the supervised HVET model, a technologist can ensure optimal initial camera setup and review it during regular visits. Patients and carers can be contacted by telephone or video conference during mobile and cloud-based HVET, to be advised about optimal camera positioning. Data from supervised HVET at King’s showed no aspects of video obtained at home to be inferior to video in the EMU¹ (see also supplementary tables 1 and 2). Data from a large sample of 9965 mobile HVET recordings compared to a smaller sample of 436 EMU recordings showed that a similar proportion of adults achieved either an epileptiform EEG or a pushbutton event on video (61.7% for HVET, 54.4% for EMU) whereas a smaller proportion of children achieved these outcomes during HVET (72.5%, vs. 86.3% for EMU)¹⁸. Furthermore, a recent unpublished audit of mobile HVET provided by Alliance Family of Companies

showed that patients were fully visible on camera as confirmed every two hours during >98% of checks in 2994 consecutive patients evaluated during Q1 2020.

Future: From Diagnosis to monitoring, understanding seizure ecology and enhancing patient autonomy

The current development efforts in the Melbourne team are focused on completely removing the burden of HVET monitoring. The team have an aim to create systems that can capture gold-standard diagnostic data in a way that does not impact on normal life. No impact, means that the systems must be comfortable, invisible, and have no compliance issues. This will result in people being able to work, and children to be able to go to school. Furthermore, it will enable monitoring over longer periods which will improve our understanding of epilepsy and seizures on a patient specific basis. Linking such systems to the cloud, with machine learning capabilities to interpret data, will no doubt greatly empower people living with epilepsy. For example, many efforts are in progress to develop fast and resource-efficient methods to automatically detect seizures in real-time EEG¹⁹ and video²⁰ using machine learning.

During inpatient EMU admission, despite several days of monitoring, typical events are obtained in only about half of admissions^{21, 22} dependent on a range of factors including diagnosis, admission indication and medication burden²³. Further readmission may contribute to diagnosis in about half of EMU readmissions²⁴, but still in some patients typical events are not captured. However, monitoring at home is not constrained by the need to make the monitoring bed available for subsequent admissions; in principle, monitoring at home could continue for as long as needed to capture an index event. Extended monitoring periods of weeks or months are limited primarily by the difficulty of maintaining EEG recording over such a period. It seems unlikely that EEG technician time would be available to regularly re-attach electrodes, and highly unlikely that the monitored patient would be willing to endure scalp electrodes for more than two weeks.

Video alone may be of high value for the diagnosis of epilepsy and psychogenic non-epileptic attacks. For example, comparing video alone of epileptic seizures and psychogenic non-epileptic attacks, video obtained in an inpatient EMU had diagnostic accuracy >90%²⁵. Furthermore, video obtained at home by carers and family members has a high similarity (in terms of semiological features) to formal inpatient EMU video in the same patients²⁶. We speculate that a valuable extension of HVET would be to continue video recording alone at home (ie. without simultaneous EEG) for as long as required, in order to obtain typical events. Intense efforts are underway in several centres to develop low-cost long-term video monitoring systems for epilepsy, using readily-available technology developed for the

video games industry²⁷. It is highly likely that the duration of video would be substantially reduced by recording only when triggered by characteristic motion²⁸ or that AI-driven decision-support systems would be needed, to target expert review of lengthy video to segments likely to contain seizures.

Extended long-term diagnostic monitoring at home has conceptual similarities to systems in development for continuous monitoring for people with epilepsy, that combine wearable sensors (such as a smartwatch), continuous data streaming, online analytics, and feedback to patients, carers and clinicians (eg.^{29,30}). Such continuous monitoring systems may be enhanced by novel technology to continuously record EEG using ultra-miniaturised sub-scalp EEG systems³¹. Continuous monitoring addresses several potential needs for people with epilepsy, including creating an objective and automated seizure diary, with the potential to overcome concerns about patient-reported diary inaccuracy^{32,33} and creating a seizure alarm for carers. Furthermore, continuous monitoring of EEG opens the possibility of seizure forecasting³², which may be immensely valuable. Furthermore, continuous monitoring could be readily coupled with systems to provide treatment reminders and prompt self-management, as well as the potential to interact with electronic health records and facilitate appropriate contact with professionals, thereby greatly enhancing patient autonomy.

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Legends

Figure 1

Here, we illustrate and describe the approach to supervised HVET initially implemented at King's College Hospital. (A) The patient is either connected in the hospital or at home. A technician conducts a daily visit to check recording, conduct seizure review with patient or family and return 24hrs data to the hospital for daily review and analysis. Clinicians use an iPad with Face-Time encryption for patient interviews while at home. (B) Recording equipment in the hospital department prior to transport. (C) The recording equipment is transported by hospital van and driver and assembled in the patient's home. Inset: the technician carries a button-press alarm system for technician security in case of emergency as part of the hospital's 'lone worker policy'.

Figure 2

Here, we illustrate and describe the approach to mobile HVET as implemented by Alliance Family of Companies. The patient is connected in the hospital. The camera, which is separate from head-box which includes recorder, is taken home by the patient. Video (shown in A) and EEG (shown in B) are acquired separately and synchronised when equipment (shown in C) is returned to the hospital. Equipment is light and flexible and can be used in-doors and out. No daily visits by technician are needed and the recording is unsupervised.

Figure 3

Here, we illustrate and describe the approach to cloud-based HVET currently implemented at King's College Hospital. (A) Patient being set up in the hospital and initial data upload to the cloud service from the hospital. (B) Patient ready to take equipment home. (C) Patient reconnects recording to cloud through home Wi-Fi and enables data upload from home. (D) Simultaneous monitoring, reviewing, pruning and reporting and archiving from the hospital via the cloud service.

Supplementary Figure S1 (see supplementary materials)

Seizures arise in the context of many influences, which may be observable using HVET. We term these interacting influences 'the ecology of seizures'. These influences of the patient's natural environment on seizure occurrences may not be detectable in a hospital Epilepsy Monitoring Unit.

Supplementary Figure S2 (see supplementary materials)

Ictal assessment card given to carers after ictal assessment training (upper panel front of the card; lower panel back of the card).

We confirm that we have read the Journal's position on issues involved in ethical publication and affirm that this report is consistent with those guidelines.

Franz Brunnhuber

Jeremy Slater

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Mark Richardson

Our disclosure:

Franz Brunnhuber: no conflict of interest

Jeremy Slater: JS is employed as the Chief Medical Officer of the Alliance Family of Companies. AFC's primary service offering for patients is in-home video EEG monitoring.

Devi Amin: no conflict of interest

Sushma Goyal: no conflict of interest

Gardar Thorvardsson: GD is CEO of 4. Kvikna Medical ehf, which offers Stratus EEG, a cloud-based EEG acquisition, review and patient management service.

Dean R Freestone: DRF is CEO of Seer Medical, which offers at-home video-EEG services.

Mark Richardson: no conflict of interest

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