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Proof of concept evaluation of the electroencephalophone as a discriminator between wakefulness and general anaesthesia

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Editor's key points

- Anaesthetic monitors commonly produce an auditory output, which anaesthetists are adept at interpreting.
- The EEG waveform is complex, and changes in complex ways with changes in anaesthetic depth.
- The authors have developed a system that produces an auditory output from the transformed EEG.
- They tested the ability of anaesthetists to differentiate outputs associated with consciousness and unconsciousness.

Background. Depth of anaesthesia (DOA) monitors based on the electroencephalogram (EEG) are commonly used in anaesthetic practice. Their technology relies on mathematical analysis of the EEG waveform, generally resulting in a number which corresponds to anaesthetic depth. We have created a novel method of interpreting the EEG, which retains its underlying complexity. This method consists of turning the EEG into a sound: the electroencephalophone (EEP).

Methods. In a pilot study, we recorded awake and anaesthetized EEGs from six patients. We transformed each EEG into an audio signal using a ring buffer with a write frequency of 1 kHz and a read frequency of 48 kHz, thus elevating all output frequencies by a factor of 48. In essence, the listener hears the previous 12 s of EEG data compressed into 250 ms, updated every 250 ms. From these data, we generated a bank of 5 s audio clips, which were then used to train and test a sample of 23 anaesthetists.

Results. After training, 21 of the 23 anaesthetists were able to use the EEP to correctly identify the conscious state of >5 of 10 randomly selected patients ($P<0.001$). The median score was 8 out of 10, with an inter-quartile range of 7–9.

Conclusions. The EEP shows promise as a DOA monitor. However, extensive validation would be required in a variety of clinical settings before it could be accepted into mainstream clinical practice.

Keywords: consciousness monitors; electroencephalography; monitoring, intraoperative

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Electroencephalographic depth of anaesthesia (DOA) monitors are commonly used in anaesthesia, but have not been conclusively shown to eliminate or even reduce the incidence of anaesthetic awareness.[1 2] There are a number of reasons why such devices might misclassify a patient's conscious state, one of which is the electronic algorithm used to process the raw electroencephalogram (EEG) into a number intended to correlate with anaesthetic depth.[3] Research efforts have focused on refining such algorithms or inventing new ones, but the reality is that no major conceptual advance in the technology of EEG-based DOA monitors has occurred in over a decade. Here, we outline a novel method of interpreting the single channel spontaneous frontal surface EEG, which shows promise in functioning as a DOA monitor: the electroencephalophone (EEP). Outputting the electroencephalographic waveform as a sound bypasses the need for complex mathematical manipulation of the EEG, since the human ear is uniquely suited to processing intricate analogue signals in raw form.[4]

The primary aim of the study was to assess the feasibility of transforming the spontaneous EEG into a sound. Secondary aims were to optimize the sound for detecting that an anaesthetic has been administered, and to prove the concept that the EEP can function as a DOA monitor, by testing the null hypothesis that a subject using the EEP would perform no better than random chance in determining the conscious state of a given patient.

Methods

Ethics approval and patient population

We obtained approval for the study from the West of Scotland Research Ethics Committee (REC no. GN11AN376; R&D

no. 11/WS/0101). Written informed consent was obtained from each patient.

Six adult patients, undergoing elective orthopaedic surgery, without paralysis, of ASA grade I–II, were enrolled in this pilot study. Exclusion criteria were previous neurological diagnosis (e.g. epilepsy), or surgery where access to the forehead was limited by positioning or drapes (e.g. prone or deckchair positions).

After data collection and transformation into the EEP, 23 anaesthetists took part in an online module where they listened to the audio recordings. The ethics committee waived the requirement for written consent for this activity.

Study protocol

After cleaning with an alcohol wipe, three standard electrocardiogram (ECG) electrodes were attached to each patient. The positive electrode was attached to the forehead (Fp2), the negative electrode to the right zygoma and the ground electrode to the left zygoma. The electrodes were attached by short cables to a preamplifier and data acquisition (DAQ) board (USB-DUX-sigma, Incite Technology Ltd, Stirling, UK) which fed into a laptop computer. The DAQ board also provided electrical isolation of the patient. A real-time display of EEG confirmed an adequate electrode placement. The patients did not receive premedication. Before administering anaesthesia, patients were asked to lie still for 5 min so that a baseline reading could be obtained. Anaesthesia was induced with propofol titrated to effect, and fentanyl 1.5 mg kg^{-1}. The airway was maintained with a laryngeal mask airway, and anaesthesia was maintained with sevoflurane 1.5–2 in 50% oxygen with spontaneous ventilation in a circle system. Further opiates were administered at the discretion of the attending anaesthetist.

Event marking on the laptop computer was used for the baseline period, at induction of anaesthesia, whenever a disturbance resulted in artifact, and at the point where end-tidal sevoflurane consistently read 80% of predicted MAC for age. Five minutes after this point, recording was discontinued. The clinical and MAC-guided determination of adequate anaesthesia was subsequently supported by off-line analysis of the EEG using the relative beta ratio (BetaRatio), an EEG parameter which has been previously validated.[5–7]

EEG signal processing

We amplified the EEG with a standard two stage instrumentation amplifier: first by a factor of 10, then the direct current filtered signal by a factor of 50, which gave an overall gain of 500. The signal was then digitized with a sampling rate of 1 kHz and resolution of 24 bits (Fig. 1). To avoid aliasing the signal was low-pass filtered. After digitization, the 50 Hz mains signal was removed, frequencies $<$10 and $>$200 Hz were eliminated, and automatic gain control employed so that the output from all samples would have the same audio volume. The central difficulty in making the EEG audible is that its frequency range is too low for the human ear. After some experimentation, we decided to play the EEG faster and at the same time repeat it cyclically. This was done by means of a ring buffer. The EEG was written to the buffer at a rate of 1 kHz, but read from the buffer at a rate of 48 kHz, thus multiplying all frequencies in the EEG by 48. The buffer size was 12 000 ms and was read every 250 ms meaning that, in essence, the listener hears the

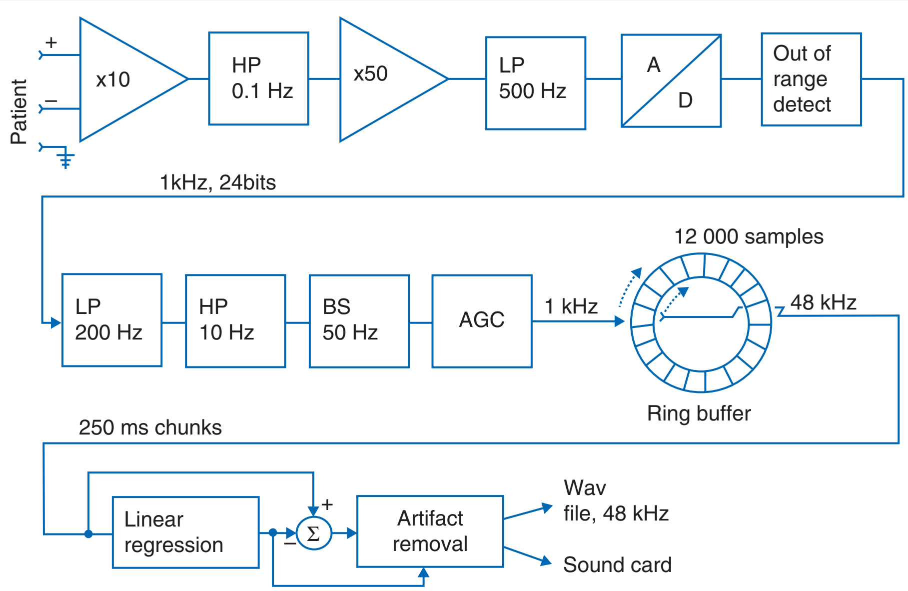

Fig 1 Schematic flow diagram to show generation of EEP from raw EEG. HP, high-pass filter; LP, low-pass filter; A/D, analogue-to-digital converter; BS, band-stop filter; AGC, automatic gain control.