BUILDING TRUST IN NEONATAL BRAIN MONITORING: EVALUATING A NEW ELECTRODE (aCUP-E) FOR aEEG

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Continuous neonatal brain monitoring using aEEG depends strongly on electrode performance. Existing electrodes may suffer from adhesion problems, impedance instability, and signal degradation during prolonged recordings. This study evaluates a novel neonatal electrode (aCUP-E) specifically designed for long-term aEEG monitoring. Twenty newborns underwent simultaneous recordings using commercial and aCUP-E electrodes. Compared with commercial electrodes, aCUP-E achieved 86.2% versus 65.3% optimal recording time, demonstrated improved survival over 24 hours, lower impedance variability, and comparable signal acquisition according to Bland-Altman analysis. These findings support that new electrodes such the aCUP-E could improve and broaden the use of aEEG as a reliable tool for prolonged neonatal neuromonitoring.

INTRODUCTION

Prematurity presents a major clinical challenge in neonatology, with approximately 15 million infants born prematurely worldwide each year, corresponding to more than one in ten births. In this population, central nervous system immaturity and the increased risk of hypoxic-ischaemic events, hemorrhages, infections, and metabolic disorders make early neurological monitoring an essential component of neonatal intensive care [1].

Amplitude-integrated electroencephalography (aEEG) is widely used for continuous bedside monitoring of neonatal brain activity in intensive care units [2]. Unlike conventional electroencephalography (EEG), aEEG provides a simplified and compressed representation of brain electrical activity, allowing neonatologists to assess background activity, detect relevant changes over time, and identify cyclic variations related to quiet sleep at specific gestational ages. However, the reliability of aEEG strongly depends on the quality of the acquired signal and the stability of the recording system, particularly during prolonged monitoring.

aEEG is derived from the processed EEG signal, displayed on a compressed time scale and a semilogarithmic voltage axis. The signal is typically band-pass filtered between 2 and 15 Hz to attenuate very low-frequency drift and high-frequency noise [3]–[5]. Clinical aEEG commonly uses a limited bipolar montage such as C3–P3 and C4–P4 for the left and right hemispheres, together with a midline reference electrode [6] This configuration enables continuous bilateral brain monitoring using a simple system suitable for neonatal units.

Fig. 1 illustrates the bilateral aEEG traces and the corresponding electrode impedance information used in a term of this study. In Fig. 1a, the processed signals are shown in blue, their upper and lower margins in red, while the four individual electrode impedance values in are displayed in Fig. 1b. Impedance monitoring provides information on electrode–skin contact quality and is therefore relevant for assessing recording reliability.

Although aEEG is increasingly used for continuous neonatal brain monitoring, its reliability remains strongly dependent on electrode performance. Recordings performed in neonatal intensive care units may be affected by environmental electrical noise, physiological artifacts, patient movement, and variations in electrode-skin contact. Incubators, cardiorespiratory monitors, ventilators, infusion pumps, phototherapy

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systems, and other devices located close to the patient may introduce interference that compromises recording quality [7],[8]. In addition, respiratory, cardiac, muscular, and movement-related activity can overlap with the cerebral signal and hinder interpretation [9].

From an engineering perspective, the electrode-skin interface is a critical component of the signal acquisition chain. Electrode impedance depends on adhesion, contact pressure, gel condition, and skin properties and may therefore change over time [10]. High or unbalanced impedances may increase susceptibility to electrical interference, whereas temporal fluctuations may indicate unstable electrode-skin contact and lead to movement-related artifacts or transient signal loss.

Previous studies have evaluated several electrode technologies for neonatal EEG monitoring, but important limitations remain. Ters *et al*. found similar recording quality with hydrogel and gold-cup electrodes, although gold-cup electrodes required more frequent replacement, and hydrogel electrodes still relied on fixed adhesive and gel interfaces during prolonged monitoring [11]. Cordeiro *et al*. selected wet-gel electrodes because of their ease of application, stable impedance, and non-invasive use; however, their performance evaluation focused mainly on initial applicability and did not assess long-term impedance variability or electrode survival [12]. More recently, Asayesh *et al*. demonstrated the technical feasibility of neonatal EEG recording using a dry-electrode cap, avoiding the need for conductive gel. However, the dry system was more susceptible to movement-related artifacts than the gel-based cap, particularly during respiration-like movements [13],[14].

Therefore, although these technologies are clinically practical, evidence remains limited regarding sustained adhesion, gel maintenance, temporal impedance stability, replacement requirements, and recording continuity over time. Few studies have simultaneously assessed optimal recording time, impedance variability, electrode survival, and signal agreement under the same

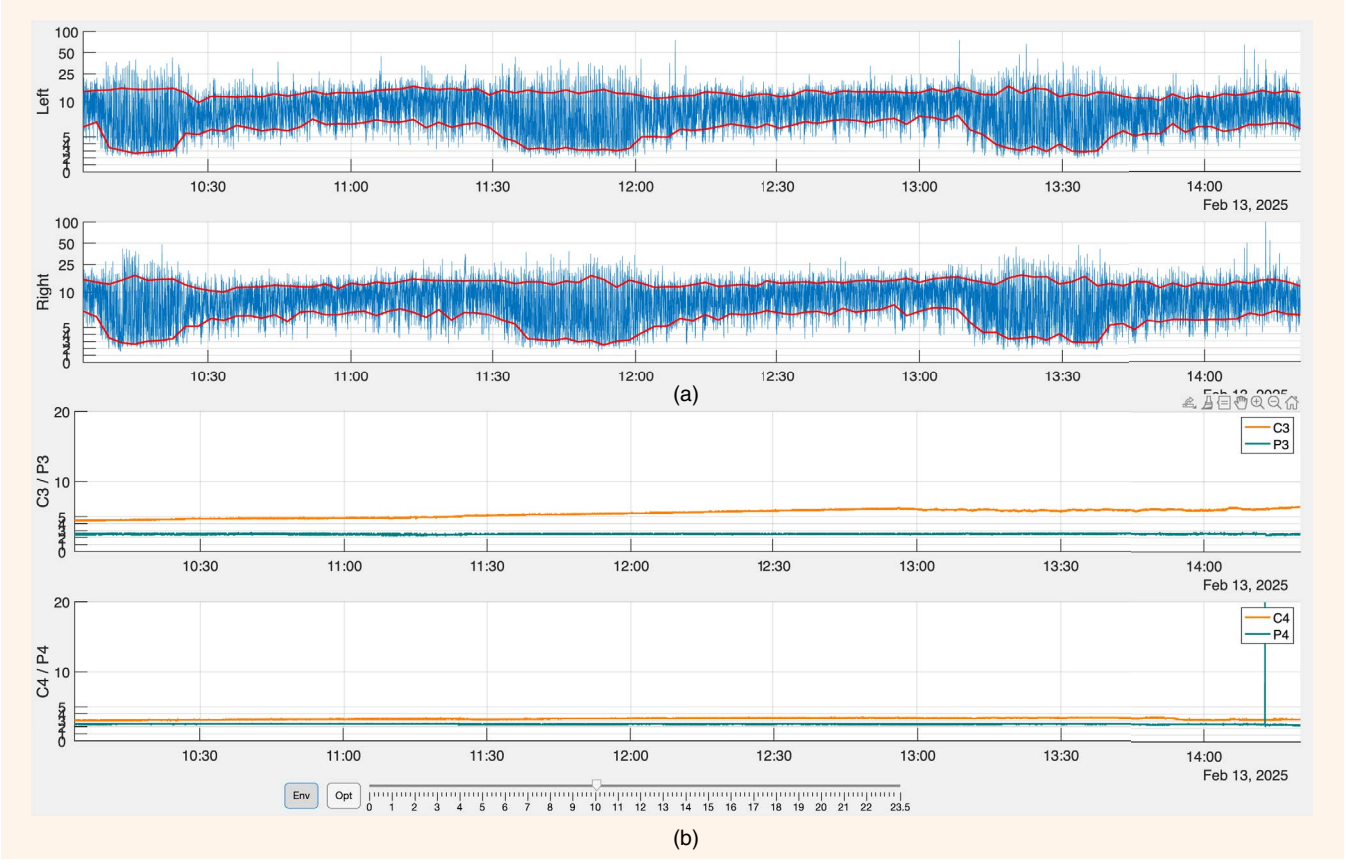


Fig. 1. MATLAB interface reproducing the aEEG monitor display in a term neonate. (a) The aEEG signal is represented in blue, and the upper and lower margins of the aEEG band are represented in red. The upper plots correspond to the left and right hemispheres. (b) The lower plots display the four individual electrode impedance values. In contrast, the clinical monitor displays the mean impedance value.

clinical conditions. The present study addresses this gap through a paired comparison of aCUP-E and commercial electrodes during prolonged neonatal aEEG monitoring.

aCUP-E: AN ELECTRODE DESIGNED FOR PROLONGED NEONATAL MONITORING

In this context, the NeuroÈpia group at Southern Catalonia Biomedical Research Institute (IRB CatSud) developed aCUP-E, an electrode specifically designed to improve adhesion, impedance stability, and recording continuity during prolonged neonatal aEEG monitoring.

aCUP-E has a flexible and translucent design adapted to the neonatal scalp. Its transparency enables inspection of the underlying skin, while its adhesive interface is designed to maintain electrode-skin contact during prolonged recordings. The electrode housing also allows electroconductive gel to be added or replaced without removing the electrode, reducing the need for repeated removal and repositioning. An important consideration given the risk of electrode-related pressure injuries and skin damage during neonatal EEG monitoring [15]. Its short connection cable facilitates newborn handling and kangaroo mother care.

The device evaluated in this study corresponds to the second version of aCUP-E, developed from an earlier prototype previously assessed in neonatal aEEG recordings [16]. The design was modified to improve adhesion, reduce electrode–skin impedance, and minimize motion artifacts during prolonged monitoring by lowering its profile and reducing friction with bed sheets.

The present study aimed to compare the performance of aCUP-E and commercial liquid-gel electrodes during simultaneous 24-hour neonatal aEEG recordings. Performance was evaluated according to four clinically and technically relevant criteria: optimal recording time, temporal impedance variability, electrode survival, and agreement of the acquired aEEG measurements. We hypothesised that aCUP-E would improve recording continuity and impedance stability while maintaining measurements comparable to those obtained with the commercial electrodes.

STUDY DESIGN AND PARTICIPANTS

A clinical study was conducted at the University Hospital Sant Joan of Reus, Spain (HUSJR) to evaluate the performance of aCUP-E during prolonged aEEG monitoring. The study was approved by the Ethics Committee (CEIm) reference number 032/2021 and was authorized by the Spanish Agency of Drugs and Medical Devices (AEMPS), reference number 918/21/EC-R.

The study included 20 aEEG recordings from newborns admitted to the Neonatal Intensive Care Unit at HUSJR. The cohort included 11 term and 9 preterm newborns, with postmenstrual ages ranging from 32 to 41 weeks. Only newborns without evidence of neurological injury were included in the analysis. Each recording had a minimum duration of 24 hours and included simultaneous monitoring with both the commercial liquid-gel electrodes and aCUP-E electrodes. Cases with excessive artifacts, incomplete recordings or technical problems that prevented a reliable analysis of the data were excluded.

ELECTRODE CONFIGURATION AND SIGNAL ACQUISITION

A five-electrode bipolar configuration was used in accordance with the international 10–20 system [17]. Commercial electrodes (Neuroline 720, Ambu) were placed on one hemisphere and aCUP-E electrodes on the contralateral hemisphere, with side assignment alternated between subjects. The midline reference electrode was also an aCUP-E electrode. This setup, illustrated in Fig. 2, allowed bilateral aEEG recording and

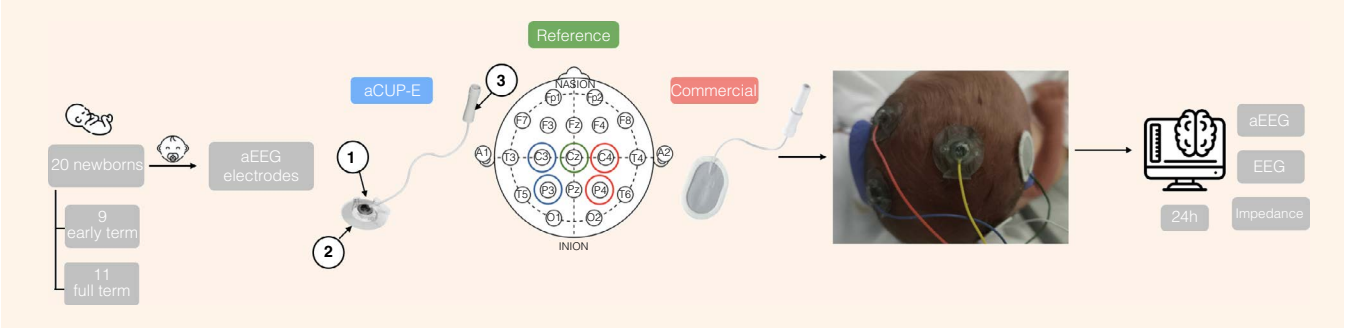


Fig. 2. Clinical study design, showing the electrode configuration and principal components.

enabled a direct comparison between the aCUP-E and commercial electrodes under simultaneous recording conditions. The main components included the housing that allows for safe gel injection or replacement; the adhesive interface for delicate neonatal skin; and the connector and wire compatible with standard EEG/aEEG recording systems [16].

Scalp preparation was performed according to standard clinical procedure to optimize impedance and adhesion. The commercial electrodes incorporated conductive gel, whereas aCUP-E required electroconductive gel to be applied after the electrode has been adhered to the scalp. The gel could be replaced every 12 to 24 hours without removing the electrode. The skin beneath and around the electrodes was visually inspected during monitoring for signs of erythema, irritation, or skin injury.

Signals were recorded for at least 24 hours using the Olympic Brainz Monitor (OBM) from Natus Medical, which allows real-time visualization of aEEG, raw EEG signal and electrode impedance. The recorded data were exported in European Data Format (EDF) and subsequently processed using Python and MATLAB.

PERFORMANCE EVALUATION CRITERIA

The performance of aCUP-E was evaluated against commercial electrodes using the four predefined criteria: optimal recording time, signal agreement between electrode types, electrode survival, and temporal impedance variability. Together, these criteria assessed signal quality, electrode-skin contact stability, and recording continuity during prolonged neonatal aEEG monitoring

OPTIMAL AND NON-OPTIMAL RECORDING SEGMENTS

Recording segments were automatically classified as optimal or non-optimal using an algorithm based on predefined signal-quality criteria. This classification was performed to identify recording periods suitable for reliable comparison between types and clinically interpretable aEEG analysis.

Two predefined signal-quality criteria, based on neonatal EEG characteristics and the previously described signal-processing methodology, were used to identify non-optimal segments [7]. First, EEG activity with an amplitude greater than 150 µV and a duration longer than two seconds were considerered unlikely to correspond to physiological brain activity. Second, segments with an aEEG bandwidth lower than 2 µV were classified as non-optimal, as this pattern is commonly associated with technical issues such as saline bridging rather than genuine cerebral activity [16].

Segments meeting either of these conditions were classified as non-optimal. All remaining segments were classified as optimal accordingly and were used to quantify the proportion of recording time providing reliable signal acquisition.

SIGNAL AGREEMENT BETWEEN ELECTRODES

Agreement between electrode types was assessed to determine whether aEEG measurements obtained with the aCUP-E were comparable to those obtained with commercial reference electrodes. Correlation analysis quantified the association between measurements, and the Bland-Alman method evaluated agreement and systematic bias [18],[19]. Both analyses were performed separately for the lower and upper margin of the aEEG margins.

For each recording, a two-hour interval was manually selected from the segments previously classified as optimal by the algorithm. The selected interval was required to show adequate signal quality in both channels and low, stable impedance values, as stable electrode contact and impedance are essential for reliable neonatal aEEG recordings and to minimize technical artifacts [8]. This procedure allowed the two electrode technologies to be compared under equivalent recording conditions.

ELECTRODE SURVIVAL

Electrode survival was defined as the period during which the electrode maintained adequate recording conditions. An electrode was considered to have failed when its impedance exceeded 20 kΩ for at least 15 consecutive minutes. This duration threshold was applied to exclude short and transient impedance increases due to short disconnections for newborn handling from the survival analysis. Kaplan–Meier curves were used to estimate electrode survival over time, and the Tarone–Ware test was used to compare survival distribution of the two electrode types [20].

IMPEDANCE VARIABILITY

Impedance variability was used as an indicator of the temporal stability of the electrode-skin interface.

Unlike absolute impedance, which represents the contact condition at a specific time point, impedance variability reflects how consistently that contact is maintained throughout the recordings. Low and stable electrode–skin impedance is essential for reliable long-term acquisition of electrophysiological signal [21]. Large fluctuations may indicate changes in adhesion, gel distribution, contact pressure, or patient movements and may increase the occurrence of artifacts and transient signal loss.

Impedance signals were processed using a 1-minute moving average to reduce noise and minimize irrelevant short-term variations. For each recording, impedance values were divided into 30-minute segments with a 50% overlap. The mean and standard deviation were calculated for each segment, and the mean of the segments level standard deviation was then obtained for each subject. This approach enabled impedance stability to be compared between electrode types using information from the recording period.

RESULTS OF THE ELECTRODE PERFORMANCE EVALUATION

OPTIMAL RECORDING TIME

The proportion of recording time automatically classified as optimal was calculated for *Neuroline 720* commercial electrodes and aCUP-E. This outcome provided a quantitative measure of the time during which each electrode-maintained signal conditions considered suitable for aEEG interpretation.

Fig. 3 shows the optimal brain activity time recorded by each electrode, illustrating that the aCUP-E achieved a higher mean percentage of optimal recoding time than commercial electrodes, with values of 86.2% and 65.3%, respectively. This represents an absolute difference of 20.9 percentage points. Although variability was observed between individual recordings, the difference was particularly pronounced in cases 5, 8, and 14.

SIGNAL AGREEMENT BETWEEN ELECTRODE TYPES

Correlation and Bland–Altman analyses were used to compare the signal recorded with aCUP-E and commercial electrodes. For each recording, a two hour interval was selected from the segments previously classified as optimal. These segments showed adequate signal quality in both channels and stable impedance values.

Fig. 4 compares both electrode types for the lower and upper aEEG margins. Margin values were normalized by the average value to eliminate bias due to small different distance between electrodes and asymmetry in the location of electrodes between hemispheres. The

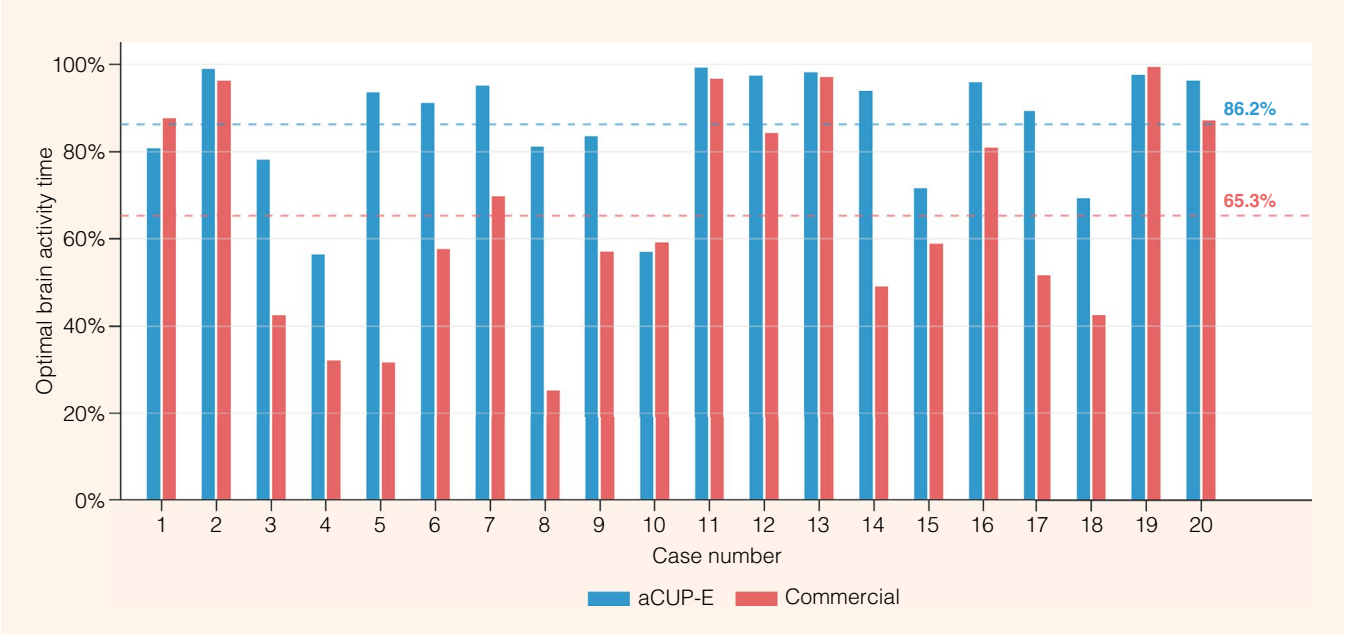


Fig. 3. Percentage of recording time classified as optimal signal for each electrode type across the 20 cases. Each pair of bars represents the percentage of recording time classified as optimal signal for each case. Dashed lines indicate the mean for each electrode type.

upper panels correspond to the lower margin, and the lower panels correspond to the upper margin. In each row (Fig. 4a and Fig. 4b), the left panel shows the relationship between paired measurements obtained with aCUP-E and the commercial electrode, and the right panel shows the corresponding Bland-Altman analysis. Each points represents a pair of measurements obtained during the selected recording interval. In the Bland-Altman plots, the x-axis represents the mean of the paired measurements, and the y-axis represents their difference.

For the lower margin, the correlation analysis showed a clear positive relationship between electrodes types, with an r^2 value of 0.83. In the corresponding

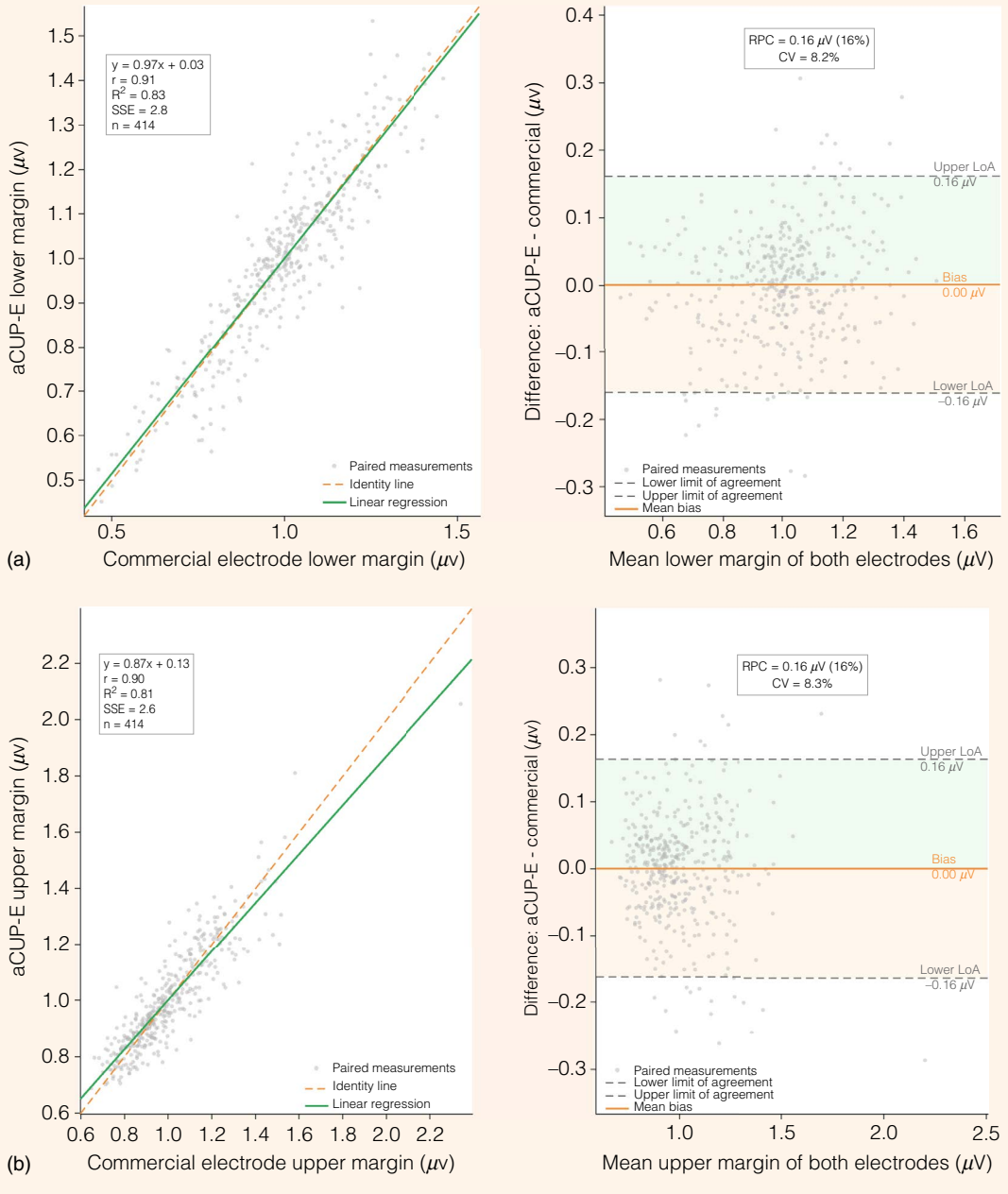


Fig. 4. Correlation and Bland–Altman plots for margin values in optimally recorded 2h segments across all cases. RPC indicates the reproducibility coefficient and CV the coefficient of variation. (a) Lower aEEG margin agreement between electrode types; (b) Upper aEEG margin agreement between electrode types.

Bland-Altman analysis, most differences were centred close to zero and remain within the limits of agreement. This RPC was 16% and the CV was 8.2%.

For the upper margin, the measurements showed greater dispersion, with an R^2 value of 0.81. The corresponding Bland-Altman analysis showed similar variability, with an RPC of 16% and a CV of 8.3%. Nevertheless, the differences remained centred around zero, indicating no clear systematic bias between electrode types.

Overall, aCUP-E provided measurements comparable to those obtained with commercial electrodes during optimal recording periods. The relationship between measurements was slightly stronger for the lower aEEG margin.

ELECTRODE SURVIVAL RESULTS

Kaplan-Meier analysis was used to determine the duration for which each electrode type maintained adequate recording conditions during the 24-hour monitoring period. As shown in Fig. 5, aCUP-E maintained a higher survival probability throughout the recording. The survival curves for the aCUP-E curve remained above those of the commercial electrodes, indicating a lower probability of electrode failure over time. Commercial electrodes showed a more pronounced decrease in survival probability, particularly during the first hours of monitoring, whereas the aCUP-E showed a slower decrease and greater temporal stability.

At the end of the 24-hour monitoring period, the estimated survival probability was approximately 81% for aCUP-E and 40% for commercial electrodes. At the central positions, survival was approximately 85% and 45%, respectively, whereas at the parietal positions they were approximately 77% and 36%. The Tarone–Ware test showed statistically significant differences overall ($p = 4.5 \times 10^{-5}$), centrally (p=0.0039), and parietally (p=0.0042).

IMPEDANCE STABILITY OVER TIME

Fig. 6 compares the temporal variability in impedance between the aCUP-E and commercial electrodes using the moving standard deviation method described above. Fig. 6a presents the results by electrode type and recoding position, distinguishing between central and parietal electrodes. Fig. 6b presents the overall paired comparison between electrode types after averaging both positions for each subject. Lower values indicate lower impedance variability and, therefore, greater stability of the electrode-skin contact.

aCUP-E electrodes showed significantly lower temporal impedance variability than the commercial electrodes, indicating a more stable electrode-skin interface throughout the recordings. Median variability was lower with aCUP-E at both the central and parietal positions, with values of 0.12 versus 0.58 kΩ and 0.44 versus 1.02 kΩ, respectively. The same pattern was observed in the overall paired comparison, with median values of 0.28 for the aCUP-E and 0.88 kΩ for the commercial electrodes.

The differences were statistically significant overall ($p = 2.6 \times 10^{-5}$), centrally (p = 0.0007) and parietally (p = 0.0024). These results support grater temporal stability of the electrode-skin contact with aCUP-E during prolonged recordings. Throughout the monitoring period, no erythema, irritation, or skin injury was observed during routine visual inspection of the skin beneath and around the electrodes.

DISCUSSION OF THE ELECTRODE PERFORMANCE

The main findings of this study were that neonatal-specific electrodes, such as the aCUP-E, can increase the proportion of optimal recording time (by 21%) compared with commercial electrodes, improve the probability of maintaining adequate recording conditions over 24 hours, and reduce temporal impedance variability, while the signal was comparable to commercial electrodes during optimal recording periods. Together, these findings indicate that aCUP-E improves recording

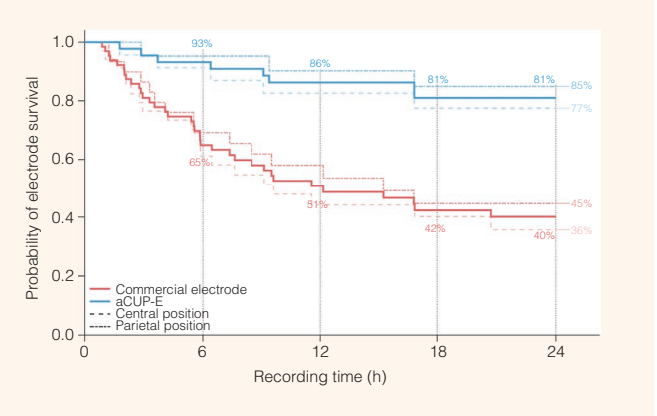


Fig. 5. Electrode survival over recording time. Kaplan–Meier curves showing time to electrode failure during 24-h monitoring. Electrode failure was defined as impedance >20 kΩ for at least 15 consecutive minutes. Blue curves represent aCUP-E and red curves represents commercial electrodes, solid and dashed lines indicate central and parietal positions, respectively.

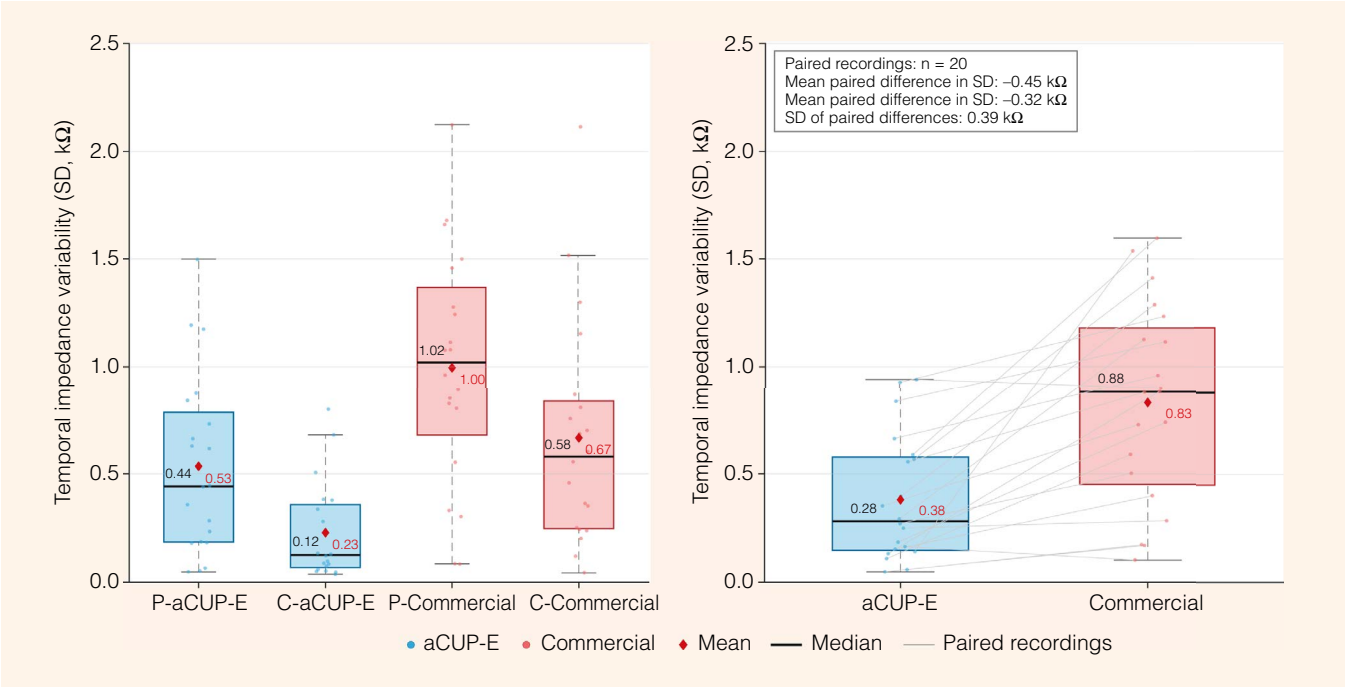


Fig. 6. (a) Temporal variability in impedance, expressed as the standard deviation (SD) of impedance calculated from consecutive 30-minute recording segments, comparing electrode type and recording position. Lower SD values indicate a more stable electrode-skin interface during prolonged monitoring. (b) Overall paired comparison after averaging the values from both recording positions for each subject. Black horizontal lines indicate the median, red diamonds the mean, coloured dots individual recordings, and grey lines paired measurements.

continuity and electrode–skin contact stability without compromising signal comparability.

The greater proportion of optimal recording time achieved with the aCUP-E indicates that these electrodes maintained signal conditions suitable for aEEG interpretation for a larger part of the monitoring period. This is particularly relevant because prolonged recordings with stable signal quality are essential for reliable neonatal monitoring [2],[22]. In addition, the Bland–Altman analysis showed no evidence of systematic bias between electrode types during the selected optimal intervals, supporting the comparability of the aEEG measurements obtained with the two electrode types.

The proportion of optimal recoding time was also higher than that reported for the previous aCUP-E prototype. In the earlier study, 72.45% of recording time and 56.43% of commercial electrode classified as optimal, compared with 86.2% and 65.3%, respectively, in the present study [16]. However, this comparison is descriptive because the studies involved different recordings and were not designed as a direct head-to-head evaluation. Therefore, the observed improvement cannot be attributed exclusively to the electrode design modifications.

Previous studies have similarly identified electrode longevity, impedance stability, and skin safety as key factors in prolonged neonatal EEG monitoring [11],[12]. Consistent with these findings, aCUP-E showed a higher survival probability and lower temporal impedance variability than the commercial electrodes. These findings suggest that the electrode-skin interface remained more stable throughout monitoring [10]. Greater contact stability may reduce transient signal disturbances and the need for electrode repositioning, gel replenishment, or replacement during prolonged recordings [8]. Overall, these findings support the potential of aCUP-E as a non-invasive electrode for prolonged neonatal cerebral monitoring.

Despite these advantages, more studies on aCUP-E with performance beyond 24 hours, and comparison with additional neonatal electrode technologies would including, skin tolerance, application time and cost per patient, may be needed before broader clinical implementation [7],[12].

This study has several limitations. The sample size was relatively small, and all recordings were obtained at a single medical center. Although signal-quality classification was performed automatically using

predefined thresholds, one optimal two-hour interval per recording was manually selected for the agreement analysis, which may introduce observer-dependent variability [23],[24]. Finally, the automatic classification algorithm was not independently validated against a fully expert-labelled dataset. Future studies should validate both the algorithm and electrode performance in larger multicentre cohorts [23],[24].

ACKNOWLEDGMENT

This research was funded by the 'la Caixa' Foundation (contract LCF/TR/CC22/52500009), by Instituto de Salud Carlos III (ISCIII) (Grant DTS24/00069) and co-funded by the European Union, and from Agència de Gestió d'Ajuts Universitaris i de Recerca (AGAUR) Producte project (2025 PROD 00204). Open Access funding provided by Universitat Rovira i Virgili within the CRUI CARE Agreement.

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