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BRAIN-COMPUTER INTERFACE COMMUNICATION FOR A LOCKED IN CHILD WITH EPILEPTIC ENCEPHALOPATHY

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ABSTRACT: There are many technologies being developed to assist individuals with severe disability. Devices based on human machine interface have been used to restore or replace lost movement and communication. Unfortunately, these technologies have not yet been extensively explored in children with severe disability. This paper describes a case study of a 16 year old patient in a locked-in state with virtually no communication. She is unable to move her body and is non-verbal. BCI potential was assessed using the mindBEAGLE system which utilizes auditory and vibro-tactile modalities to evoke a response. Long-term monitoring on clinical EEG characterized the neurophysiology of the patient including nearly continuous generalized discharges. The best classification accuracy for auditory and vibrotactile BCI was 40%. Higher accuracy (54%) was achieved using the motor imagery modality. Clinical neurophysiology measures can inform or to some extend predict the success of BCI performance of different modalities contributing to the user-centered design in BCI development.

INTRODUCTION

Being able to communicate is an essential right and need of every human being. Imagine being aware of your environment, seeing, hearing and feeling everything around you, but being unable to move or speak to express yourself. Such Lock-in Syndrome (LIS) describes patients who are conscious and aware but severely paralyzed with complete immobility and loss of verbal communication. It can be caused by acute injuries (e.g., brainstem stroke, which is the most frequent cause of LIS) to chronic causes (e.g., amyotrophic lateral sclerosis; ALS)[1] that render the motor system non-functional[2].

LIS can be divided into incomplete (some voluntary movement in addition to eye movement), classic (preserved vertical eye movement and blinking) or complete (no voluntary movement). LIS involves loss of all voluntary muscle control other than sometimes restricted lateral or vertical eye movements. As a result, most communication attempts utilize eye movement [3] for communication control. For example, eye-gaze computers can be controlled by the user's eye movement and be interpreted by a second person given the user has good control of eye movements. This kind of communication requires the help of a second person who needs to be willing and capable of following time-consuming procedures.

Brain computer interface (BCI) systems based on sensorimotor rhythms and evoked potentials have been developed and used to provide such quadriplegic patients with potential options for communication and control independent of any movement input[4]. BCIs have been used by LIS patients to communicate[5,6] and even used to navigate a computer[7]. BCIs are also used to control devices that have permitted patients with spinal cord injury to regain movement[8] and control a wheelchair[9]. Virtually all of this progress has occurred in adults.

EEG based BCI can use different modalities to evoke a response, such as event-related potentials (ERP). The most common ones are visual, auditory and vibro-tactile. Investigation of different modalities of BCI in a single LIS patient found that the vibro-tactile modality was more effective for communication than visual and auditory modalities[10]. Similarly, Guger et al. [11] reported that 2/3 LIS patients reached a classification of 100% using vibro-tactile modality.

Such non-invasive BCI systems typically rely on EEG. However, some patients with acquired brain injuries and other conditions that may benefit from BCI may also have abnormal EEG. Epileptic encephalopathies may include frequent pathological generalized discharges that are not seizures but may impair cognition and awareness[12]. It is unknown if available EEG-based BI paradigms can still work in the presence of such overlying EEG patterns.

The aim of this paper is to report a case study of exploring different BCI modalities and associated event related potentials (ERP) and event-related desynchronization(ERD) used to establish communication in a child with LIS and epileptic

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encephalopathy and explore how this clinical neurophysiology influences BCI performance.

MATERIALS AND METHODS

Participant

This is a single case study of a 16 year old female in complete locked-in state following post-operative brainstem hemorrhage 3 years prior to the study date. Shortly after a complicated operation to remove a large brainstem tumor, she incurred a life-threatening hemorrhage resulting in central brainstem herniation and bilateral injury to pontomedullary regions. She suffered a cardiac arrest and secondary hypoxic-ischemic injury of the deep grey matter (thalamus and putamen) without evidence of cortical or other areas of injury.

Although there were no clinical seizures, several EEG were completed in the first 3 months following the injury. These demonstrated intermittent slowing but no epileptiform discharges and age-appropriate posterior-dominant rhythms were often present.

At 13 years old, the child was clinically left in a state of complete quadriplegia aside from some very delayed small finger movements on the right side on command, no reliable eye movements but grossly intact visual fields to confrontation, grossly intact hearing based on isolated responses to sounds and possible responses to commands based on parental interpretation.
She required tracheostomy but not mechanical ventilation and was entirely gastrostomy dependent for nutrition.
After years of trying different communication systems including eye gaze devices without success, the patient's family approached the University of Calgary Pediatric Brain Computer Interface Laboratory. Three years after her injury she and her family were provided the opportunity to attempt several different modalities of BCI.

BCI Assessment

EEG voltage signals were acquired from the scalp using the g.USBamp EEG system (g.tec medical engineering GmbH, Austria), with either 8 or 16 active gel-based electrodes located according to the preset international 10-20 system. The system aligned the event EEG with event marker, band-pass filtered (0.1-30 Hz) and digitized the signal at 256 Hz and wirelessly transmitted the signal to a laptop for processing. A linear discriminant analysis was applied.

A commercially available EEG-based BCI consciousness assessment and communication system called mindBEAGLE (g.tec medical engineering GmbH, Austria) was used to perform the following tasks:

Auditory ERP: This paradigm was based on the auditory evoked P300 which involved identification of a target auditory stimulus when they are presented randomly mixed with non-target stimuli (oddball paradigm). The auditory paradigm consisted of frequent low tones (87.5%) and infrequent high tones (12.5%). The patient was asked to close her eyes to minimize distractions, and to silently count the number of times she heard the infrequent, target stimulus. Classification accuracy reported by the mindBEAGLE was used as an outcome.
Two sessions, two trials per session, were completed with two days.
Vibrotactile ERP with two tactors (VT2): two vibro-tactile stimulators were placed on each of the patient's left and right wrists. The patient was instructed to count the rare (12.5%) stimuli presented to one wrist to elicited P300. Classification accuracy reported by the mindBEAGLE was used as an outcome. Three trials (two trials on the first session and one trial on the second session) were completed with two days.

Vibrotactile ERP with three tactors (VT3): in addition to the two vibro-tactile stimulators that were placed on each of patient's left and right wrists, a third tactor was placed on the patients left lower leg as a distractor. Classification accuracy reported by the mindBEAGLE was used as an outcome. Three trials (two trials on the first session and one trial on the second session) were completed with two days.

Motor Imagery (MI): this modality utilizes sensorimotor rhythm modulation using hand motor imagery. The patient was instructed to imagine moving her right or left hand chosen randomly for 4s. The instructions came in random interval 0.5-2s to avoid adaptation. In total, the patient completed two runs of 30 imagined movements per run for each hand. Classification accuracy reported by the mindBEAGLE was used as an outcome. Three trials were completed on a single session.
Auditory, vibrotactile and MI tests were conducted with 15 min break between each paradigm. When the patient is tired, indicated by closing her eyes and not opening them for long time, the session was ended. For all tasks, data is extracted from -100 to 600 ms, around the simulation. The data is baseline corrected and averaged. A paired t-test was applied to measure significance difference between targets and non-targets, where the green shaded area indicates $p<0.05$[13].

For auditory and vibrotactile trials, the data is classified with a linear discriminant analysis (LDA) to distinguish target from non-target stimuli. This results in a classification accuracy ranging from 0 to 100 %. For MI, the data is used to train a common-spatial pattern (CSP) algorithm that weights each electrode based on discrimination accuracy. The data from the window 3-5 seconds is used to train the CSP algorithm followed by estimating a variance of a 1.5 sec window which is used to train LDA classifier. This results in a classification

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accuracy ranging from 0 to 100 % with a chance accuracy level of 50 % (2-classes are discriminated)[13].

Studies took place in the recently established Pediatric BCI Laboratory at the Alberta Children's Hospital. Protocols have been approved by the institutional research ethics board.

Clinical Neurophysiology

Ambulatory EEG Recording: Ambulatory Trex EEG was recorded for 21 hours using 19 electrodes connected to Xltek brain monitor (Natus Neuro, Middleton, USA). The sampling frequency for the EEG recording was 256Hz.
Brainstem Auditory Evoked Potential (BAEP): BAEPs were evoked bilaterally using left and right monoaural rarefaction mixed frequency clinic stimulation at 11.1Hz and were recorded with surface electrodes (Cz-A1/A2).

Somatosensory Evoked Potential (SSEP): The SSEPS were obtained by electrical stimulation of the left and right median nerves at the wrist (10.5mA, 2.5Hz) and posterior tibial nerve at the ankle (13.2mA, 2.9Hz).

*Visual Evoked Potential (VEP)***:** VEPs were obtained by full-field monocular LED stimulation of the left and right eyes.

RESULTS

The patient and her parents attended 3 Sessions with each lasting 90-120 minutes. Tolerability appeared favorable though feedback from the patient was obviously limited. Fatigue was suggested by parental report at variable timing during the sessions. State changes were otherwise challenging to determine based solely on clinical observation.

Clinical Neurophysiology

Ambulatory EEG Recording: The majority of the ambulatory EEG recording (~90%) consisted of generalized periodic discharges (GPD) at approximately 1Hz frequency which increased during sleep states (figure 1). These discharges often assumed a triphasic wave appearance.

BAEP: There were well defined and reproducible waves I, III and V on the left with no discernible peaks on the right. Absolute latency of peak II was normal, but the interpeak I-III latency was slightly over 2.5 SD above the mean. The interpeak III-V latency was normal, with a delayed absolute latency of peak V.

SSEP: A robust twitch was reported during the study for both upper limbs. Reproducible peaks were recorded at the erb's point and the corticomedullary junction with normal latencies (left Erbs 8.6ms, right Erbs 9.7). However, no discernible peaks were obtained cortically for the upper extremity. A robust twitch was noted in the right lower extremity, with a reproducible peak at the popliteal fossa (latency 8.9ms), however, no cortical peak was seen. No twitch was reports with simulation of the left lower extremity, even with the stimulation intensities over 20mA. No reproducible peaks were obtained at the popliteal fossa or cortically.

VEP: P1 waves recorded from Oz, O1 and O2 were present. Normal conduction latencies (90ms) were recorded in the visual pathways bilaterally.

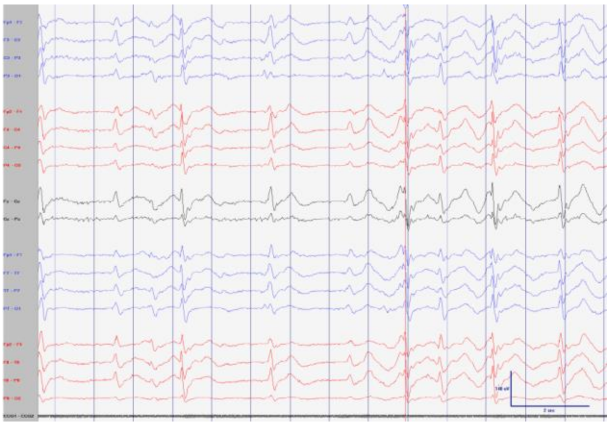

Figure 1: Generalized Periodic Discharge (GPD) in the shape of triphasic waves

BCI Assessment

Auditory P300: Both the target and non-target stimulus produced an average P300 with peak amplitude 8.75 µV, 7.68µV, 8.90µV and 8.77µV at CP1, CP2z , CPz and Pz, respectively (Figure 2).. The median accuracy for the best trial on the first day was 10%. On the second day at the same electrode locations, the P300 responses were 16.5uV and 10.8uV, respectively with the median accuracy improved to 40%.

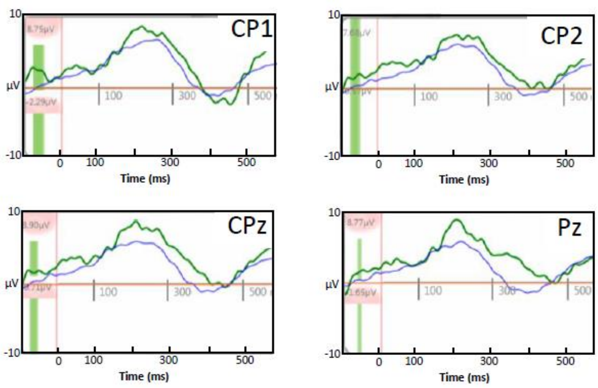

Figure 2: Auditory Evoked Potentials. P300 waveforms from selected electrodes (CP1, CP2, CPz, Pz) evoked by target (green) and non-target (blue) auditory stimulation. The vertical red line indicates when the cue

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is present to the patient. The green shades indicate the time when the target and non-target waves are significantly different.

VT2 P300: The first VT 2 trial resulted in 0% median accuracy. The second and third VT2 trials resulted in 35% and 40% median accuracy, respectively. For the trial with 40% accuracy, the peak amplitude were 3.33μV, 9.35μV, 8.77μV and 5.48μV FCz, CP1, Cz, and C4, respectively, in response to target vibro-tactile stimulus (Figure 3).

VT3 P300: All VT 3 trials resulted 0% median accuracy.

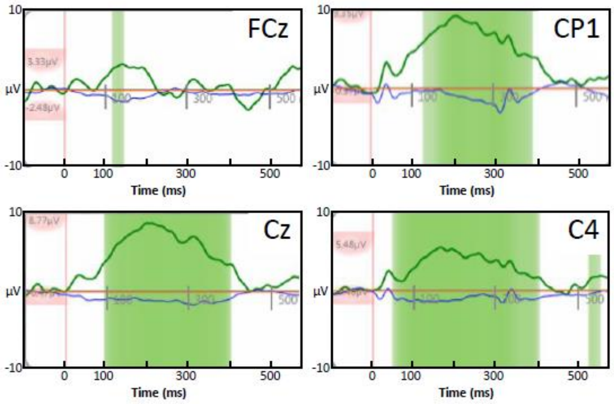

Figure 3: Vibro-tactile Evoked Potentials (VT2). P300 waveforms from selected electrodes (FCz, CP1, Cz, C4) evoked by target (green) and non-target (blue) vibro-tactile stimulation. The vertical red line indicates when the cue is present to the patient. The green shades indicate the time when the target and non-target waves are significantly different.

Motor Imagery: The first trial resulted in a median accuracy of 46.3%, which improved to 54.3% accuracy in after two trials (Figure 4).

DISCUSSION

While earlier results have shown that LIS patients can use BCI based on motor imagery[14], auditory P300 [15] and vibro-tactile P300[16], this case study extends the potential use of such BCI systems for a child with LIS. With this patient, communication using any modality was not possible due to the low classification accuracy. This in part may have related to comorbid epileptic encephalopathy, suggesting that baseline clinical neurophysiology may be important in advancing BCI applications in such clinical populations.

Our unsatisfactory BCI performance may partly be explained by the clinical neurophysiology that was observed. The presence of EEG-patterns consistent with epileptic encephalopathy may indicate more severe global cerebral dysfunction.

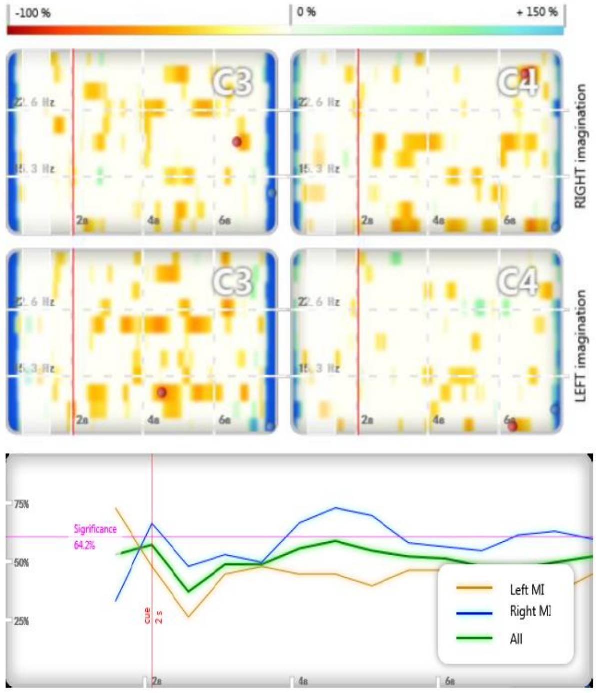

Figure 4: Motor Imagery (MI) evoked event related desynchronization and accuracy. The top 4 graphs show EEG desynchronization map for the right (top) and left (bottom) imagination. The vertical red line indicates when the cue is present to the patient. The bottom plot shows accuracy for left MI (yellow), right MI (blue) and all combined (green). The horizontal purple line indicates 64.2% accuracy which is the threshold for significance.

However, many other pediatric conditions that feature such frequent, generalized discharges are not uniformly associated with severe impairment of cognition or consciousness. For example, epileptic encephalopathies like continuous spike-and-wave discharges in sleep (CSWS), electrical status epilepticus I sleep (ESES) and Landau-Kleffner syndrome (LKS) can be seen in fully conscious, ambulatory children who might appear normal aside from slow effects on learning and development over time. In other words, young brains can sometimes be highly functional “beneath” such grossly abnormal EEG recordings. Such patterns are also potentially treatable with anticonvulsant medications or steroids[17,18], suggesting a potentially modifiable factor that could improve BCI performance in such subjects.

The BAEP test also indicated abnormal auditory activation which may have affected BCI performance based on auditory evoked potentials. An earphone with identical right and left output may be used to overcome unbalanced auditory evoked potential.

The abnormal SSEP of upper and lower extremities and lack of cortical responses suggest abnormal conduction above the cervicomodullary junction, consistent with the known injuries in this patient. The lack of twitches also indicates peripheral nerve conduction defect. As a result, BCI performance based on both VT2 and VT3 was likely limited due to interruption of the signal at cervicomodullary junction. This suggests SSEP results can inform better placement of vibrators for BCI based on vibro-tactile stimulation.

The above results emphasize the importance of user-centered design in BCI development. While some studies find that the visual modality to be superior to other[19], Kaufmann and colleagues[10] found out that vibro-tactile based BCI resulted in the highest classification accuracy. Furthermore, the accuracies achieved in healthy participants do not necessarily transfer too LIS patients[10].

Unique ethical consideration must be taken into account when working with adolescent patients lacking autonomy and communication. As in the case of complete locked-in syndrome, consent to participate is determined by the child's parent or guardian. Under such sensitive circumstance, it is important to maintain balance between offering hope for improved communication and realistic expectations among families.

CONCLUSION

This case study explored different BCI modalities that were used to establish communication in a child with LIS and epileptic encephalopathy. Our unsatisfactory assessment of BCI performance was partly explained by the clinical neurophysiology that was observe. Most patients have one or more clinical neurophysiology done following their injury. The data from these tests should be used to refine the classifier used in BCI as well as to choose the best BCI modality for better BCI performance.

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