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Field Deployable EEG Monitor for Nerve Agent Casualties

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***Abstract*— Early recognition and aggressive management of seizure activity is important in the treatment of patients with nerve agent exposure. However, these patients can experience non-convulsive seizures that are difficult to identify without EEG monitoring. In this paper, we discuss the development and testing of a low-cost, field-deployable device that records and displays patient EEG trends over time. The device is optimized for early levels of care for military and mass casualty patients until they can be relocated to medical facilities with more comprehensive monitoring. The device also records pulse oximetry and acceleration information, and patient data are available for later analysis and improvement of treatment protocols.**

I. Introduction

THE goal of this project is to create a small, portable system for monitoring EEG for non-convulsive seizures in patients with nerve agent exposure, head trauma, and other emergencies involving loss of consciousness. The device is intended for military field use and mass casualty situations during which patients are initially treated and transported to higher levels of care. Under conditions of nerve agent toxicity and possible partial paralysis, patient seizures can be difficult to assess based on physical symptoms alone. The system discussed here provides the ability to record EEG from a small set of electrodes applied below the hairline and display the output from an embedded algorithm designed to detect EEG patterns associated with generalized seizure activity and ongoing status epilepticus. Early recognition and aggressive treatment of brain seizure activity during the initial management of these patients has been shown to improve clinical outcomes. [1][2]

Our initial approach was to create a small forehead patch (Fig. 1) with simple LED displays. A forehead electrode montage would only be able to detect very large, generalized EEG events. However, for emergency use, the low-cost patch concept has several advantages over more traditional bench top and belt-worn EEG instruments, including:

- a simple and fast application procedure by field medics with limited EEG training,
- the ability to simultaneously assess large numbers of casualties at a site,
- the ability to continuously monitor patients throughout stabilization and relocation to a treatment facility, and
- the ability to keep the devices in compact cases and field kits for emergencies.

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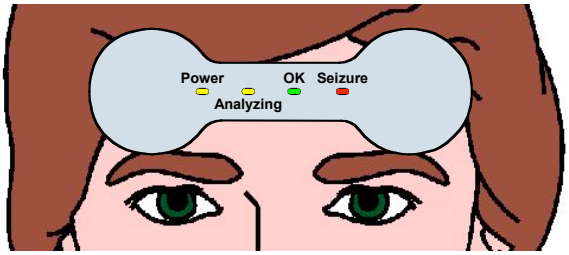

Fig. 1. Initial patch design concept.

As the design evolved in collaboration with military chemical agent researchers, neurologists, and paramedics, the electrode configuration, data displays, and form factor were modified.

Standard configurations of 32 to 256 electrodes are normally used for electroencephalography, and clinicians always want as many electrodes as possible to maximize sensitivity to localized EEG events. Under the insistence of clinical collaborators, we expanded our recording montage to include four electrodes along the hairline on the forehead and two behind the ears for more complete monitoring. Similar montages have been shown capable of detecting generalized seizure activity [3], and this configuration is still simple enough for field use.

Nerve agent induced seizures manifest not only as simple, discrete ictal events, but also as recurring cycles of epileptiform discharges that gradually wax and wane. In this regard, knowing instantaneous patient status is not as important as knowing trends over time. Therefore, we expanded our initial red/green LED display concept to a graphical display of trends of recurring EEG activity. This history would allow emergency responders to determine if secondary pharmacological interventions are positively affecting recurrent activity in the patient's EEG.

During transport, neurological patients are commonly secured in a head brace for immobilization until they reach a treatment facility, and these head braces typically include straps across the patient's forehead. Thus, we changed our initial design to move the display from the forehead to a small module connected via a short cable (Fig. 2).

Hypoxia is a possible cause of neurological complications in nerve agent exposure victims that can be difficult to detect during transportation. We therefore added a pulse-oximeter to the forehead electrode array along with the associated data displays. The pulse detection is also useful to identify and reject ECG contamination of the EEG signals.

To identify and help reject movement-related artifacts, a 3D accelerometer was added to the electrode assembly, and flash memory was also added to record all system signals for later review and analysis.

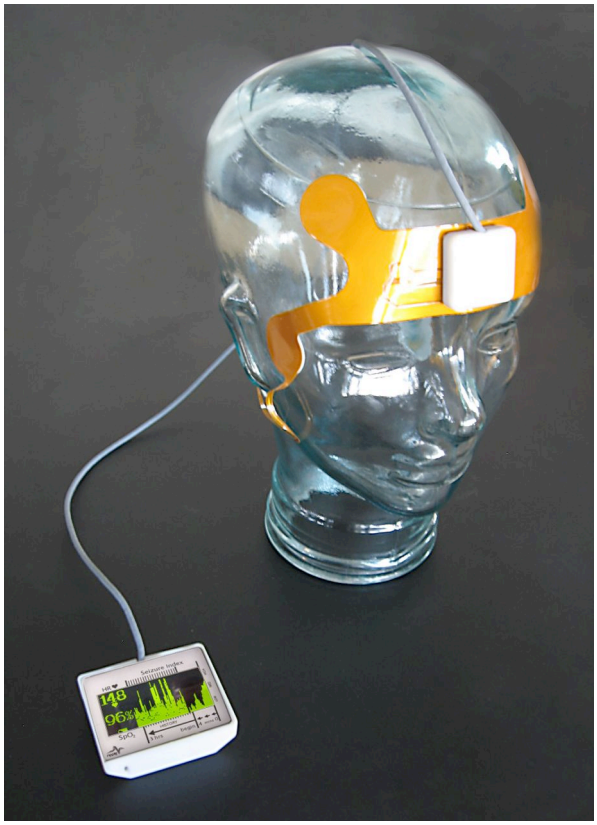

Fig. 2. Refined concept used for prototype development and testing.

II. Electronics Design

The electronics for the EEG monitor are distributed between a small enclosure mounted to the forehead electrode array, and the enclosure for the batteries and display. The head assembly electronics include ESD protection and EMI filtering circuits for the electrode leads, a 16-channel neural signal amplifier ASIC (similar to the design described in [4]), pulse oximetry LED driver and photodiode amplifier, and a DSPic brand microcontroller with integrated ADC. The differential inputs of the amplifier are configured to record all 15 possible pairs of the six electrodes. A large subject ground electrode is integrated into the front of the forehead array and the entire outer layer of the electrode assembly is a shield that is connected to subject ground.

The display enclosure includes a graphical OLED display, a removable MicroSD memory card, and four AA primary cells. A thin, shielded cable connects power and digital data between the two assemblies. The modular design allows different display and battery options for different future applications with the same compact headstage electronics.

III. EEG Processing Algorithm

The seizure processing developed for this device employs Waveform Train Decomposition (WTD), and details of the algorithm are being prepared for a separate publication [5]. In WTD (Fig. 3), multichannel EEG is segmented into short epochs of six to ten seconds, and recurrent waveforms present in the EEG are extracted. These components are quantified according to (1) their tendency to form periodic series, and (2) the total energy of the EEG they comprise. These data are expressed as a recurrence index that is plotted over separate ranges of six minutes and three hours. These trends can be used by medics in assessing the effects of treatments on patient EEG during early care.

IV. Results

The EEG recording capabilities of the device were validated in healthy subjects for resistance to artifacts from electromagnetic interference, and saturation from motion artifacts and myoelectric signals from facial muscles. A protocol was approved by the University of Utah Institutional Review Board and the US Army Office of Human Subject Protection to record EEG with prototype devices in six healthy subjects. Once the device was applied, subjects were instructed to blink, squint, clench their jaws, shake their heads, stand up, sit down, use a cell phone, walk, lie down, and nap. EEG data were downloaded following each trial and assessed off-line.

With the shielded electrode configuration, power line signal (60 Hz) artifacts in a variety of office and hospital

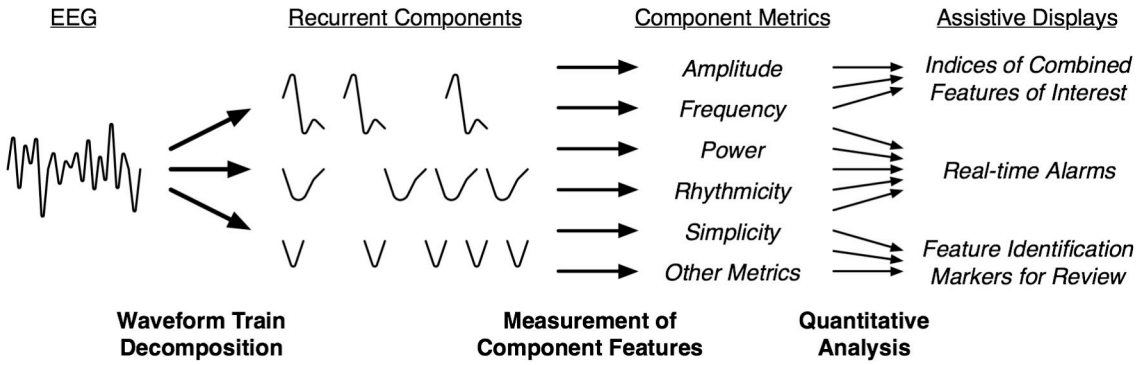

Fig. 3. General outline of the Waveform Train Decomposition (WTD) approach. Multi-channel EEG data are decomposed into linearly separable, recurrent components. Basic metrics can be applied to these components and combined to form higher-level metrics and displays based on expert knowledge, training data, or empirically-derived indices.

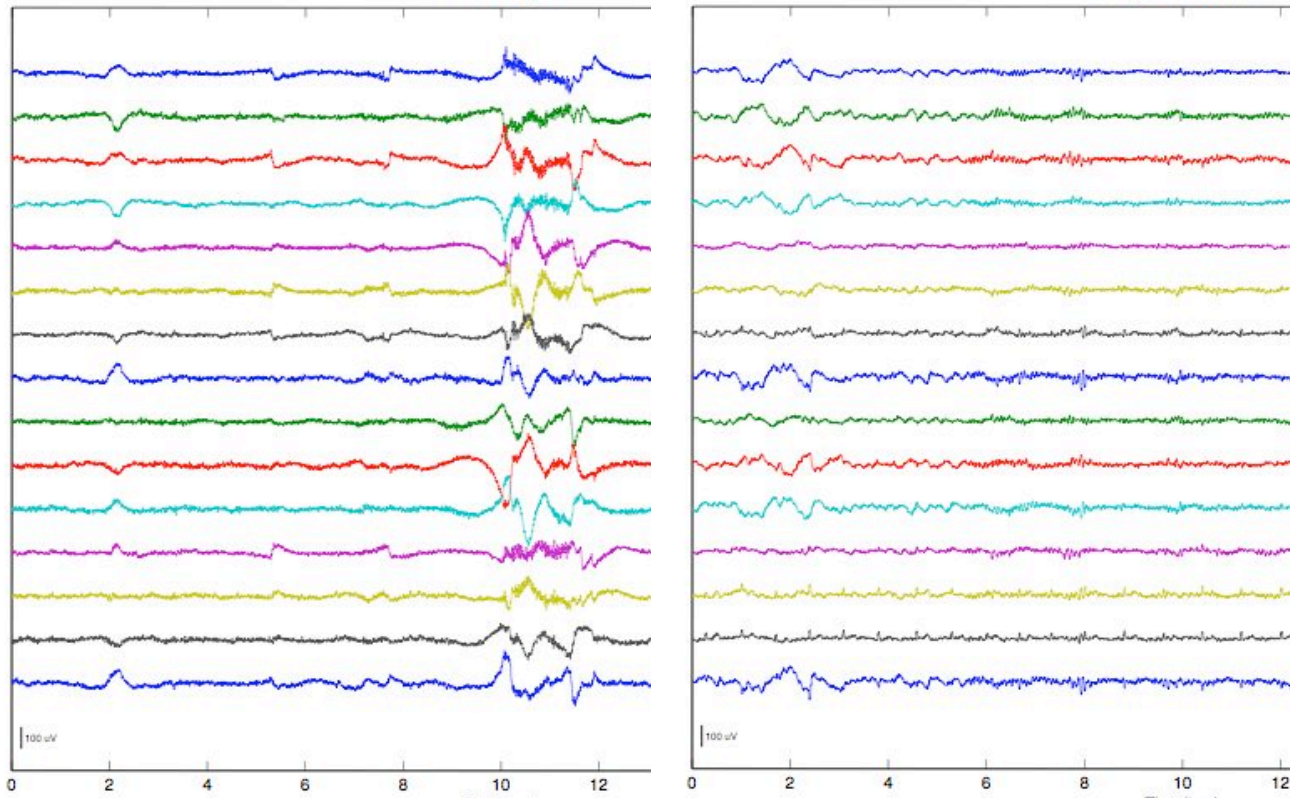

Fig. 4. Recorded EEG data for all 15 differential channel pairs during awake eye blink and motion artifacts (Left), and during sleep activity (Right). Note the 100μV scale bar at the bottom left of each figure, the horizontal axis is in units of seconds. The linear dynamic range of each pair is ± 2 mV; note that the motion and eye blink artifacts are well within the dynamic ranges of the channels.

environments were typically less than $10\,\mu V_{P\text{-}P}$. Notch filters were not used to further remove line noise due to the ability of the WTD processing to reject minor components in these frequency bands. Measured signal-to-noise ratios were similar to commercial portable EEG systems ($<1\,\mu V_{RMS}$).

As expected, EMG and motion artifacts were prominent in the recordings; however, these artifact signals did not saturate the bioamplifier. As seen in the left panel of Fig. 4, the artifact signals recorded during muscle activity (e.g. jaw clench) are well within the linear dynamic range of the system (± 2 mV).

Recorded data were also reviewed by Neurology staff at the University of Utah. Data recorded during napping exhibits sleep spindle activity consistent with Stage 2 sleep cycles. In the right panel of Fig. 4, symmetrical, bilateral patterns are shown on each channel of recorded data. This evidence of sleep spindle activity suggests it is possible to record and observe clinically relevant EEG events using the prototype system.

V. Future Work

The pilot clinical study revealed that the electrode array will require modification to accommodate patients of smaller sizes. We have also received subsequent feedback from clinical collaborators that nerve agent exposure patients may perspire profusely, which may preclude the use of adhesive-type surface electrodes. To accommodate both issues, the electrode is being changed to an elastic headband structure. The WTD algorithms have been validated with offline clinical and animal data, and further validation under online test conditions are needed prior to its regulatory clearance for clinical use.

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