Electromyography-based seizure detector: Preliminary results comparing a generalized tonic–clonic seizure detection algorithm to video-EEG recordings

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**SUMMARY**

**Objective:** Automatic detection of generalized tonic–clonic seizures (GTCS) will facilitate patient monitoring and early intervention to prevent comorbidities, recurrent seizures, or death. Brain Sentinel (San Antonio, Texas, USA) developed a seizure-detection algorithm evaluating surface electromyography (sEMG) signals during GTCS. This study aims to validate the seizure-detection algorithm using inpatient video–electroencephalography (EEG) monitoring.

**Methods:** sEMG was recorded unilaterally from the biceps/triceps muscles in 33 patients (17 white/16 male) with a mean age of 40 (range 14–64) years who were admitted for video-EEG monitoring. Maximum voluntary biceps contraction was measured in each patient to set up the baseline physiologic muscle threshold. The raw EMG signal was recorded using conventional amplifiers, sampling at 1,024 Hz and filtered with a 60 Hz noise detection algorithm before it was processed with three band-pass filters at pass frequencies of 3–40, 130–240, and 300–400 Hz. A seizure-detection algorithm utilizing Hotelling’s T-squared power analysis of compound muscle action potentials was used to identify GTCS and correlated with video-EEG recordings.

**Results:** In 1,399 h of continuous recording, there were 196 epileptic seizures (21 GTCS, 96 myoclonic, 28 tonic, 12 absence, and 42 focal seizures with or without loss of awareness) and 4 nonepileptic spells. During retrospective, offline evaluation of sEMG from the biceps alone, the algorithm detected 20 GTCS (95%) in 11 patients, averaging within 20 s of electroclinical onset of generalized tonic activity, as identified by video-EEG monitoring. Only one false-positive detection occurred during the postictal period following a GTCS, but false alarms were not triggered by other seizure types or spells.

**Significance:** Brain Sentinel’s seizure detection algorithm demonstrated excellent sensitivity and specificity for identifying GTCS recorded in an epilepsy monitoring unit. Further studies are needed in larger patient groups, including children, especially in the outpatient setting.

**KEY WORDS:** Seizure detection devices, Sensitivity and specificity, Surface-electromyography, Video-electroencephalography, Generalized tonic–clonic seizures.

Seizure-detection devices promise to reduce morbidity and mortality associated with epilepsy, and to improve the quality of life for people with epilepsy and their families. They can warn family members or caregivers of witnessed seizures, particularly occurring in sleep, thereby enabling them to monitor the patient’s safety or even intervene with first aid or abortive therapies. Of all seizure types, generalized tonic–clonic seizures (GTCS) are most com-
monly associated with an increased risk of morbidity and mortality in people with chronic epilepsy.\(^1,2\) GTCS are associated with injuries, ranging from subdural hematomas to spine or bone fractures, as well as aspiration pneumonia, drowning, or burns. More importantly, sudden unexpected death of epilepsy (SUDEP) is the most common cause of early death in people with epilepsy and is closely associated with GTCS.\(^3,4\) Seizure-detection devices need to reliably recognize GTCS to improve their quality of life.

Surface electromyography (sEMG) recordings of compound muscle action potentials during exercise demonstrate particular activation patterns.\(^5\) The recruitment of muscle fibers occurs in particular frequencies, which then can be analyzed statistically.\(^6\) During GTCS, muscles contract in a more sustained manner than during most exercises, with synchronous contraction of facial, truncal, and antagonistic extremity muscles. Recently, one European group recording from the deltoid or biceps muscles, demonstrated the reliability of sEMG in the detection of GTCS.\(^7\)–\(^12\) The group developed an algorithm that utilized the zero-crossing method for evaluating frequency changes in combination with root mean-square analyses of compound muscle action potential amplitudes. The zero-crossing method has been designed to identify the tonic phase of GTCS,\(^8,9\) and using a process of exclusion, can effectively differentiate GTCS from psychogenic nonepileptic spells.\(^11\)

Brain Sentinel (San Antonio, TX, U.S.A.) developed an algorithm to analyze sEMG signal from proximal arm muscles, namely the biceps and triceps brachii. The algorithm identifies sustained EMG contraction patterns—during the tonic phase and early transition to the clonic phase—that are pathognomonic of GTCS (Fig. 1).\(^1\)–\(^13\) In this phase II study, the operating characteristics of the seizure detection algorithm were tested in an epilepsy monitoring unit, the gold standard for characterizing seizure types. The goal of this study was to evaluate the sensitivity, specificity, and latency for the algorithm to detect GTCS as well as other types of seizures or spells.

**Methods**

**Patients**

Thirty-six consecutive subjects with medically refractory epilepsy and a history of GTCS were enrolled after admission to the epilepsy monitoring unit (EMU) at University Hospital in San Antonio, Texas, between November 2011 and December 2012 (Table 1). Two subjects had faulty recordings, whereas a third subject’s EMG recordings were not retrievable. None of these three subjects experienced a GTCS during the study. During concurrent EMG recording and scalp video–electroencephalography (EEG) monitoring, subjects remained in their room exhibiting motor activities of daily living such as eating, brushing their teeth, washing up, using an exercise bike, playing computer games, or gesticulating during conversation. This study was approved by the institutional review boards of the University of Texas Health Science Center at San Antonio and University Health System.
EMG recording

Each subject had sEMG electrodes placed (34 mm Ag/AgCl electrodes; Ambu Blue Sensor M, Denmark) over the center of the bellies of the biceps and triceps brachii on the arm suspected to be primarily or mostly involved in the clinical semiology, that is, the right arm was tested in a patient with a suspected left hemispheric focus (Fig. 2). The ground electrode was placed lateral to the biceps muscle. Impedance was not specifically monitored; however, visual inspection of the EMG electrode recording was performed twice daily to evaluate electrode artifacts. The raw EMG signal was recorded using conventional amplifiers, sampling at 1,024 Hz and filtered with a 60 Hz noise detection algorithm before it was processed with three band-pass filters at pass frequencies of 3–40, 130–240, and 300–400 Hz (see Seizure-Detection Algorithm). Although both the biceps and triceps were monitored simultaneously, only the biceps sEMG recordings were utilized for analysis because of their lack of artifact and consistent signal-to-noise ratio. The electrodes were connected either to a NeXus-32 or NeXus-4 monitor (Mind Media BV, The Netherlands). The NeXus monitors transmitted the EMG signal via Bluetooth to a portable laptop or were exported using Biotrace+.

At the onset of EMG recording, each patient underwent two measurements of maximum voluntary biceps contraction (MVC) to set the baseline physiologic muscle contraction threshold. Voluntary contractions lasted 5 s and were performed one minute into the recording and again after 5 min of relaxation (see Fig. 1). sEMG recorded during the MVCs and during relaxed quiet periods were used to set the threshold.

### Table 1. Demographics and video-EEG results

| Patient | Age | Gender | Hours of EMG | GTCS | Detection lag (s)a | Other seizure types | Diagnosis or syndrome |
|---------|-----|--------|--------------|------|-------------------|---------------------|----------------------|
| 1       | 54  | F      | 31.4         | 0    | N/A               | 0                   | JME                  |
| 2       | 43  | M      | 49.3         | 2    | 54, 56            | 1 FDS               | LRE                  |
| 3       | 28  | M      | 31.2         | 1    | 16                | 12 AS               | CAE                  |
| 4       | 20  | M      | 26.5         | 0    | N/A               | 4 FDS               | TLE                  |
| 5       | 44  | F      | 18.6         | 1    | 17                | 69 GMS, 27 GTS      | SGE                  |
| 6       | 19  | F      | 22.9         | 0    | N/A               | 0                   | PNES                 |
| 7       | 47  | M      | 36.5         | 0    | N/A               | 3 FDS               | LRE                  |
| 8       | 32  | F      | 0.7          | 1    | 20                | 0                   | TLE                  |
| 9       | 32  | F      | 32           | 1    | 25                | 2 FDS               | TLE                  |
| 10      | 49  | F      | 2.3          | 1    | 8                 | 0                   | JME                  |
| 11      | 48  | M      | 47           | 0    | N/A               | 0                   | SGE                  |
| 12      | 49  | M      | 74.4         | 0    | N/A               | 4 FDS               | TLE                  |
| 13      | 54  | F      | 39.8         | 0    | N/A               | 0                   | UKN                  |
| 14      | 57  | F      | 63.9         | 0    | N/A               | 2 FDS               | TLE                  |
| 15      | 19  | M      | 62           | 0    | N/A               | 1 NCSE, 15 GMS      | JME                  |
| 16      | 21  | M      | 92.7         | 1    | 23                | 3 FDS               | LRE                  |
| 17      | 37  | M      | 73.4         | 0    | N/A               | 7 FDS               | LRE                  |
| 18      | 25  | M      | 74.6         | 1    | 7                 | 0                   | TLE                  |
| 19      | 46  | F      | 65.7         | 0    | N/A               | 0                   | TLE                  |
| 20      | 64  | M      | 20.6         | 0    | N/A               | 0                   | RBD                  |
| 21      | 50  | M      | 52.2         | 0    | N/A               | 1 FS, 5 FDS         | TLE                  |
| 22      | 19  | M      | 65.4         | 2    | 23, −4           | 1 GMS, 1 GTS        | FLE                  |
| 23      | 47  | F      | 21.6         | 0    | N/A               | 0                   | PNES                 |
| 24      | 24  | F      | 51.6         | 9    | 7.6 ± 5 (0–18)   | 0                   | JME                  |
| 25      | 14  | M      | 56.8         | 1    | 5                 | 11 GMS              | JAE                  |
| 26      | 36  | F      | 64.5         | 0    | N/A               | 0                   | LRE                  |
| 27      | 53  | F      | 16.8         | 0    | N/A               | 4 FDS               | PLE                  |
| 28      | 43  | F      | 18           | 0    | N/A               | 2 FDS               | LRE/PNES             |
| 29      | 49  | M      | 15           | 0    | N/A               | 0                   | PNES                 |
| 30      | 53  | F      | 37.6         | 0    | N/A               | 1 FDS               | TLE                  |
| 31      | 26  | M      | 34.9         | 0    | N/A               | 3 PNES              | PLE                  |
| 32      | 47  | F      | 63.6         | 0    | N/A               | 0                   | UKN                  |
| 33      | 63  | F      | 35.5         | 0    | N/A               | 1 PNES              | TLE/PNES             |

**Mean ± SD**  Percent female  Sum  Detected by algorithm, 95% CI  Mean latency ± SD  Detected by algorithm

| 39.8 ± 14.2 | 51 | 1,399 | 95% (76, 100) | 15.2 ± 15.4 | 0 |

AS, absence seizure; FS, focal seizures without loss of awareness; FDS, focal dyscognitive seizures; NCSE, nonconvulsive status epilepticus; GMS, generalized myoclonic seizures; GTS, generalized tonic seizures; LRE, localization-related epilepsy; SGE, symptomatic generalized epilepsy; JME, juvenile myoclonic epilepsy; CAE, childhood absence epilepsy; JAE, juvenile absence epilepsy; TLE, temporal lobe epilepsy; FLE, frontal lobe epilepsy; PLE, parietal lobe epilepsy; PNES, psychogenic nonepileptic spells; UKN, unknown; RBD, rapid eye movement behavioral disorder; F, female; M, male; N/A, not applicable; SD, standard deviation; CI, confidence interval.

*aTime lag of seizure detection indicates when the EMG-based seizure warning is issued relative to electroclinical generalization by video-EEG analysis.*
The recording times between the sEMG and video-EEG recording were synchronized every 12 h.

Data analysis

The primary outcome was the algorithm’s sensitivity to detect GTCS that were confirmed by video-EEG monitoring. All subjects were monitored continuously with video-EEG (Nihon-Kohden, Japan). Video-EEG recordings were reviewed by epileptologists (CAS, KMK, LCM, OVL, or LDL) who enumerated and electroclinically classified every seizure type that was recorded during the admission according to the International League Against Epilepsy (ILAE) Guidelines. GTCS were determined by evidence of generalized tonic–clonic activity associated with primarily or secondarily generalized ictal discharge, followed by postictal EEG suppression. GTCS were independently reviewed by two epileptologists to determine the time of electroclinical onset of the seizures, and more importantly, the electroclinical onset of generalization, as defined by generalized paroxysmal fast activity and appearance of the generalized tonic motor manifestation of the GTCS.

The sEMG signal was analyzed offline using a frequency-based algorithm developed by Brain Sentinel. The analysis was fully automated, with the exception of setting the power threshold for the initial matrix calculation, which required the operator to select raw EMG data collected during an MVC and a quiet period. The sample of quiet EMG data was used to calculate how to weight the gain in different frequency bins. Input to the algorithm consisted of 5 s of raw data collected during an MVC and 30–60 s of raw data during the quiet period for the variance/covariance training period (see Seizure Detection Algorithm). The output of the algorithm is reported as the time when the algorithm transitions to the seizure state. If a GTCS was identified, by the algorithm, within 60 s of the video-EEG onset, it was considered a true positive. If a GTCS was not identified, and EMG was actively being recording during the GTCS, the event was considered a false negative. Any seizure alert in the device log not associated with a seizure documented by video-EEG was a false positive. Finally, the time of onset of motor symptoms associated with GTCS observed by video-EEG analysis, was correlated with the time of seizure detection by sEMG.

Results

In 33 patients, 1,399 h of surface EMG data were recorded, averaging 42 (SD±17) h per patient. A summary of seizure diagnoses by video-EEG analyses is listed in Table 1. During EMG recording, 196 epileptic seizures and 4 psychogenic nonepileptic seizures were recorded in 23 patients. Eleven patients (33%) had 21 GTCS recorded by video-EEG. The Brain Sentinel seizure-detection algorithm detected 20 of 21 GTCS (95% sensitivity, 95% confidence interval [CI] 76–100) all within 60 s (mean 15.2 s range −4 to 56s) of clinical onset of bilateral tonic activity as identified by video-EEG monitoring. The false-negative event occurred in a patient whose arm was squeezed against the bed rail, restricting the motion of the arm. Because the algorithm activates at the tonic–clonic interface, restriction of the clonic component is one possible explanation for this false negative. The only false-positive detection was related to a patient attempting to lift his body off the bed, postictally. The seizure-detection algorithm was not triggered by any other seizures or nonepileptic events. Technical issues included occasional loss of contact between surface EMG electrodes and skin and the added difficulty of carrying around an additional box, but electrode adhesives were well tolerated overall and patients remained compliant with the testing.

Discussion

This efficacy study demonstrated excellent sensitivity and specificity of the Brain Sentinel seizure-detection algorithm to recognize GTCS with sEMG recordings. The algorithm detected the GTCS on average within 30 s of electroclinical generalization as determined by video-EEG monitoring. Hence, the Brain Sentinel seizure-detection algorithm threshold for later off-line analysis (see Data S1). The recording times between the sEMG and video-EEG recording were synchronized every 12 h.
algorithm appears equally as sensitive as other seizure-detection systems for GTCS that are under development in the United States and Europe (Table 2).16–19 Its main advantage over other seizure detection devices is its apparent specificity. Studies evaluating the mattress implants or utilizing accelerometry have high false-positive rates, in some cases occurring daily, even in a setting of normal, nonstrenuous physical activities (Table 2). Although one study evaluating a commercially available wrist accelerometer demonstrated relatively few false alarms (only one every 5 days), even these were triggered by routine activities, such as brushing teeth, or playing cards or board games.20 Similar activities of daily living did not trigger false alarms in the current study. Decreased specificity can negatively affect the response of caregivers or other providers over the long term and would be difficult to adapt for an emergency response system.

This study has shown the Brain Sentinel seizure-detection algorithm to be a useful tool for the identification of GTCS. Currently, a prospective phase III multicenter study is underway to evaluate the ability of the algorithm to identify GTCS in real time in a stand-alone system. Although the inpatient setting is suitable for recording the tonic phase at the beginning of the GTCS, the tonic phase is associated with the highest morbidity and mortality. This situation may explain the single false-positive event in this study involving the patient lifting his body off the bed, causing sustained activation of biceps.

In summary, the sEMG-based seizure detection algorithm by Brain Sentinel offers both high sensitivity and specificity for the early detection of GTCS. Relative to other seizure types, GTCS are associated with the highest morbidity and mortality. This algorithm might be an effective tool to prevent seizure-related injuries, even SUDEP, and allow family and caregivers to administer medical treatment to prevent further seizures or even status epilepticus.

### Acknowledgments

This study was presented as a poster presentation at the 2013 American Epilepsy Society Meeting in Washington, DC.

### Conflict of Interest

Brain Sentinel Inc. funded the study. MG is the President, CEO, and shareholder, and JEC is a consultant and shareholder of Brain Sentinel, Inc. 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.

### References

1. Sander JW, Bell GS. Reducing mortality: an important aim of epilepsy management. *J Neurol Neurosurg Psychiatry* 2004;75:349–351.
2. Friedman DE, Tobias RS, Akman CI, et al. Recurrent seizure-related injuries in people with epilepsy at a tertiary epilepsy center: a two-year longitudinal study. *Epilepsy Behav* 2010;19:400–404.
3. Leestma JE, Annegers JF, Brodie MJ, et al. Sudden unexplained death in epilepsy: observations from a large clinical development program. *Epilepsia* 1997;38:47–55.
4. Nilsson L, Farahmand BY, Persson P-G, et al. Risk factors for sudden unexpected death in epilepsy: a case-control study. *Lancet* 1999;353:888–893.
5. Bigland-Ritchie BR, Lippold OCJ. Changes in muscle activation during prolonged maximal voluntary contractions. *J Physiol* 1979;292:14–15.
6. Bigland-Ritchie BR, Donovan EF, Roussos CA. Conduction velocity and EMG power spectrum changes in fatigue of sustained maximal efforts. *J Appl Physiol* 1981;51:1300–1305.
Conradsen I, Wolf P, Sams T, et al. Patterns of muscle activation during generalized tonic and tonic-clonic epileptic seizures. *Epilepsia* 2011;52:2125–2132.

Conradsen I, Beniczky S, Hoppe K, et al. Automated algorithm for generalized tonic-clonic epileptic seizure onset detection based on sEMG zero-crossing rate. *IEEE Trans Biomed Eng* 2012;59:579–585.

Conradsen I, Beniczky S, Wolf P, et al. Evaluation of novel algorithm embedded in a wearable sEMG device for seizure detection. *Conf Proc IEEE Eng Med Biol Soc* 2012;2012:2048–2051.

Conradsen I, Moldovan M, Jennum P, et al. Dynamics of muscle activation during tonic-clonic seizures. *Epilepsy Res* 2013;104:84–93.

Beniczky S, Conradsen I, Moldovan M, et al. Automated differentiation between epileptic and nonepileptic convulsive seizures. *Ann Neurol* 2015;77:348–351.

Larsen SN, Conradsen I, Beniczky S, et al. Detection of tonic epileptic seizures on surface electromyography. *Conf Proc IEEE Eng Med Biol Soc* 2014;2014:942–945.

Cavazos JE, Herring RM, Jones ER, et al. EMG-based seizure detector: characteristics of spectral analysis and analog EMG data during generalized motor seizures. PAME Conference 2012: Available at: http://eweb.aesnet.org/iweb/upload/PAME_2012_LGCH_Inc_Feasibility_Abstract_FINAL.pdf.

U.S. Patent Application No. 13/275,309, Publication No. 20120108999 (published May 3, 2012 by Leininger et al., applicants).

Berg AT, Brodick SF, Brodie MJ, et al. Revised terminology and concepts for organization of seizures and epilepsies: report of the ILAE Commission on Classification and Terminology, 2005–2009. *Epilepsia* 2014;51:676–685.

Carlson C, Arnedo V, Cahill M, et al. Detecting nocturnal convulsions: efficacy of the MP5 monitor. *Seizure* 2009;18:225–227.

Kramer U, Kipervasser S, Shlitner A, et al. A novel portable seizure detection alarm system: preliminary results. *J Clin Neurophysiol* 2011;28:36–38.

Lockman J, Fisher RS, Olson DM. Detection of seizure-like movements using a wrist accelerometer. *Epilepsy Behav* 2011;20:638–641.

Poh M-Z, Loddenkemper T, Reinsberger C, et al. Convulsive seizure detection using a wrist-worn electrodermal activity and accelerometry biosensor. *Epilepsia* 2012;53:e93–e97.

Beniczky S, Polster T, Kjaer TW, et al. Detection of generalized tonic-clonic seizures by a wireless wrist accelerometer: a prospective, multicenter study. *Epilepsia* 2013;54:e58–e61.

**Supporting Information**

Additional Supporting Information may be found in the online version of this article:  
**Data S1.** Brain Sentinel’s seizure-detection algorithm.