34th Annual International Conference of the IEEE EMBS
San Diego, California USA, 28 August - 1 September, 2012

Automatic seizure detection based on the activity of a set of current dipoles: First steps

G. Gritsch, M. Hartmann, H. Perko, F. Fürbaß, and T. Kluge

Abstract— **In this paper we show advantages of using an advanced montage scheme with respect to the performance of automatic seizure detection systems. The main goal is to find the best performing montage scheme for our automatic seizure detection system. The new virtual montage is a fix set of dipoles within the brain. The current density signals for these dipoles are derived from the scalp EEG signals based on a smart linear transformation. The reason for testing an alternative approach is that traditional montages (reference, bipolar) have some limitations, e.g. the detection performance depends on the choice of the reference electrode and an extraction of spatial information is often demanding. In this paper we explain the detailed setup of how to adapt a modern seizure detection system to use current density signals. Furthermore, we show results concerning the detection performance of different montage schemes and their combination.**

I. Introduction

One percent of world's population suffers from epilepsy. One third of these patients cannot be successfully treated with anti-epileptic drugs. For these patients surgery is one of the last chances to become seizure free.

Before such a resection can take place, thorough pre-surgical evaluations have to be performed. In addition to high resolution imaging, PET and physiological testing, long term video - EEG monitoring over several days is used to gather information about the characteristics of the epileptic disease. One of the main reasons for long term EEG monitoring is to record seizures. Medical experts can gain valuable insight by analyzing the EEG during seizures.

For this reason, it is very important to find all seizures within the recorded EEG. In order to assist medical staff in doing so, we have designed and implemented an automatic seizure detection system called EpiScan [1]. The advantages of EpiScan are:

- online detection
- medical stuff can perform tests during the seizure
- prohibiting patients from injuries during seizures
- reduced effort for offline EEG review

Currently, EpiScan is tested in three medical studies at different European epilepsy centers.

There are several montages used for automatic seizure detection showing different advantages and disadvantages. Very frequently reference montage, bipolar montages or a combination of the two montages are used. Beside the main advantage of being simple and robust against artifacts, the reference montage features at least the following two limitations:

- detector performance depends on the choice of the reference electrode [2][3].
- automatic extraction of spatial information (SpI) regarding rhythmic pattern, which can be utilized for reducing false alarms, cannot be done easily.

The bipolar montage has the distinct advantage that there is no common reference. Often interesting patterns can be seen more easily. The disadvantages are:

- automatic setup of the electrode montage depends on the used electrodes and is a difficult task.
- automatic extraction of SpI is even more difficult than for reference montage.

In order to get rid of these limitations, we started to investigate an alternative montage called source montage [4]. The main idea behind this montage is that the EEG signals measured on the surface of the head are transformed into current density signals of a fix set of dipoles within the brain. With this montage we are expecting the following advantages:

- detector performance independent from reference
- simple extraction of SpI
- the channels to be analyzed are always the same
- no difficult setup of montage necessary

For this paper we want to investigate different montage schemes with respect to the performance of our seizure detector. For choosing the best montage scheme, not only the detector performance is important, but also the ability of robust automatic extraction of SpI is a key measure.

The rest of the paper is organized as follows: In chapter 2 our proposed system is explained. The used EEG data is described in chapter 3. First results of the new montage are presented in chapter 4.

II. Methods

In order to compare the source montage with the reference montage and the bipolar montage we built an experiential system consisting of three subsystems (one for each montage). The outputs of the subsystems can be combined in arbitrary fashion in order to accomplish different advantages of different montage schemes (subsystems). The overall setup of the experiential system is depicted in Figure 1.

Subsystem A consists of the new montage which acts as pre-processor for a modified version of the AIT seizure detector EpiScan. In the source montage module the EEG signals are transformed into current density signals of a certain set of dipoles. Instead of the EEG signals, the dipole current densities are analyzed in the seizure detector. Note

This work was supported in part by HIGH PROFILE. The HIGH PROFILE project has received funding from the ARTEMIS Joint Undertaking under grant agreement n° 269356.

Gerhard Gritsch, Manfred M. Hartmann, Hannes Perko, Franz Fürbaß (corresp. Author) and Tilmann Kluge are with the Austrian Institute of Technology, Donau-City-Strasse 1, 1220 Vienna, Austria (phone: +43 50550 4227; e-mail: gerhard.gritsch@ait.ac.at,).

978-1-4577-1787-1/12/$26.00 ©2012 IEEE

that EpiScan has to be modified in order to work with current density signals and to additionally provide SpI for future exploitation for false alarm rate reduction. More details of the necessary modifications of EpiScan are explained in Section II.B.

Subsystem B consists of the reference montage where the EEG signals are processed as recorded.

Subsystem C is the bipolar montage subsystem. The bipolar montage module generates the most important bipolar channels out of the transversal and longitudinal montages based on the existing reference electrodes.

Note that for subsystem B and C the standard EpiScan system is used.

In the combination module the subsystems can be combined in arbitrary fashion:

- source & reference
- bipolar & reference
- source & bipolar
- source & bipolar & reference

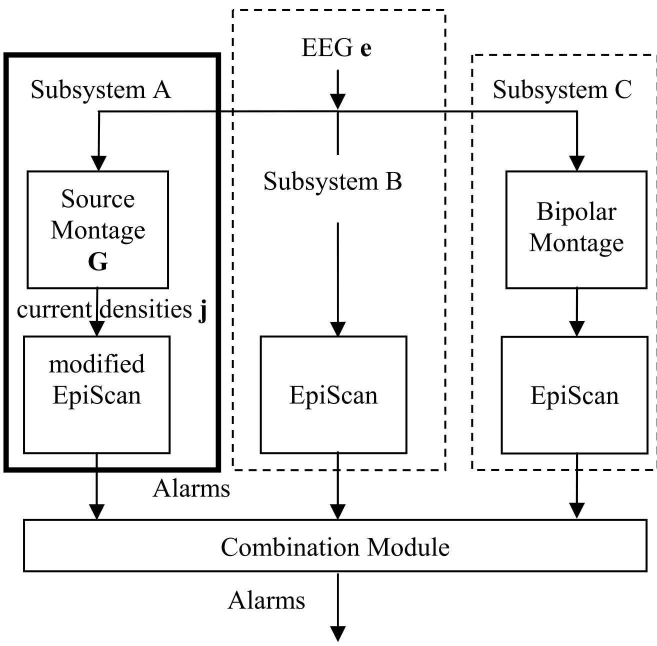

Figure 1. System Overview

In the following only the modules of subsystem A are explained. For details regarding subsystem B and C we refer to [1].

A. Source Montage

As shown in Figure 2. , instead of using the electrode signals, the signals are transformed into current density signals within the brain. In order to do so, source localization techniques [5], which are intended to solve such task, can be utilized. The most important steps to adapt source localization techniques to our needs are summarized in the following.

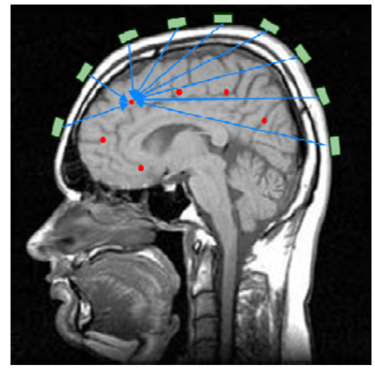

Figure 2. Principle of source montage

1) Forward Model

The so-called forward model defines the relationship between the current densities of dipoles within the brain and the EEG signal on the head surface. There are several possibilities to define this relationship. In general the electrical voltages on the scalp depend on the orientation and the position of the dipoles. The influence of the position is non-linear. Apart from some exceptions, most approaches use a linearized model, by fixing the dipole positions and thus we get the following expression:

$$\mathbf{e} = \mathbf{L} \cdot \mathbf{j}$$

The matrix **L** is called Lead Field Matrix (LFM) and is the essence of the forward model. Vector **e** and **j** contain the EEG and the current densities respectively. The LFM can be calculated using so-called head models. There is a large variety of head models, reaching form simple analytical models to complex realistic models. For example in [6] a simple analytical model was used. We invest a bit more time to calculate the LFM based on a more realistic model. We know that the best way is to use a LFM based on a realistic head model derived from the patient's own high resolution MRI. Unfortunately, high resolution MRIs are not always available and furthermore if they are available the calculation time and the necessary user interacts for calculating the LFM will hinder the clinical application. For these reasons we decided to use a realistic Boundary Element Method (BEM) head model [7] based on the colin27 standard MRI [8][9] and use the resulting LFM for all patients. The input parameters for the head model are:

- the tissue impedances
- the high resolution MRI
- positions of the electrodes
- position and direction of the dipoles

Concerning tissue impedances we use standard values: Brain and scalp 0.33 S/m and skull 0.0132 S/m. For the high resolution MRI the colin27 from the MNI is used. The positions of the electrodes were calculated according to the international 10-10 position procedure, automatically calculated by a MATLAB script based on the surface of the scalp.

The choice of the position and the direction of the dipoles is an important topic [4]. In order to capture all rhythmic activity the influence of the dipole direction is tremendously higher than the positions of the dipoles. Some groups, e.g. [4], try to choose reasonable directions based on the physiological setup of the brain. The more general way is to consider all 3 orthogonal directions, in order to do not miss any important brain activity. Based on the above, the positions have been chosen in such a way that the dipoles are reasonable distributed throughout the brain and at each position we incorporate 3 orthogonal directions. In EpiScan these three directions are combined in such a way that we obtain the maximum overall rhythmic activity. More details on this topic can be found in Section II.B.

An alternative approach to gather all brain activity with a number of dipoles can be found in [10]. The differences to our method are the large number of used dipoles and the orientation of these.

The dipole positions have been chosen as follows: The center of the brain (gray matter) of the colin27 brain is calculated. Then lines between the center and all 10-20 electrodes plus FT9, FT10, FP9 and FP10 (subset of 10-10) are determined. Starting at the positions of the electrodes, we go on these lines 3cm towards the brain center. Thus, we get one point within the brain for each electrode. These points are the positions of the dipoles and are named according to the nearest electrode, i.e. the dipole under the electrode FP1 is called dipole FP1. The procedure provides, according to the number of electrodes of our electrode setup, 23 dipoles with 3 directions per dipole.

In clinical practice the number of used electrodes varies, i.e. not all electrodes of the 10-10 system are used, therefore only the used electrodes are considered in the forward model. The LFM is adapted to each patient in such a way that for different electrode setups, the corresponding subset of rows of the LFM is used.

2) Inverse Model

Under an inverse model one understands the relationship between the current densities **j** and the EEG signal **e**. There is a huge number of inverse methods which can be categorized in three groups: non-linear dipole fitting, linear spatial filters and stochastic approaches. All of these methods have their advantages and disadvantages. We decided to use the Weighted Minimum Norm (WMN) solution [5], which is a non-adaptive linear spatial filter. Due to the linearity the model reads as follows:

$$\mathbf{j} = \mathbf{G} \cdot \mathbf{e},$$

and the matrix **G** according to WMN can be calculated with:

$$\mathbf{G} = \mathbf{L}^{\mathrm{T}} \left(\mathbf{L}\mathbf{L}^{T} + \lambda \cdot \mathbf{I} \right)^{-1},$$

where **I** is the identity matrix and λ is the regularization parameter. The convincing advantage of this inverse model is the independence of the inverse matrix **G** from the EEG data and the linearity of the model. The inverse matrix **G** has to be calculated only once for one electrode setup, i.e. if the electrode setup is kept constant during the complete recording, then the matrix has to be calculated only once. Note, that the used LFM is normalized in such a way that the column norm is one. This normalization yields the same overall contribution to the EEG regardless how deep the dipoles are located within the brain.

For numerical reasons, the matrix $\mathbf{LL}^{\mathrm{T}}$ has to regularized with a weighted unity matrix, otherwise an inversion is not possible. The regularization parameter λ is chosen in such a way that focal activity do not result in blurry spatial results, i.e. all dipoles appear to be almost equally involved. In order to avoid numerical problems, a minimum regularization (λ) is necessary.

B. Modified EpiScan

EpiScan is an automatic seizure detection system designed and implemented at the Austrian Institute of Technology. EpiScan is particularly designed to detect rhythmic activity in the EEG signal. One of the results is a rhythmicity measure for each EEG electrode or in general for each signal channel. Simply speaking, the system alerts if the rhythmicity measure reaches a certain threshold. More details about EpiScan can be found in [1][11].

For the use of EpiScan with current density values and to determine SpI, some modifications of the original EpiScan system are necessary:

1) Current Density Values

The output of the Source Montage module is three signals for each dipole corresponding to the three orthogonal directions. EpiScan is based on a rhythmicity measure which is the rhythmic energy divided by the overall signal energy. In the modified system, one direction vector for each dipole is chosen in such a way that the collected rhythmic energy from the three components is a maximum. The overall signal energy of the three components is calculated by projecting them onto the above determined direction. Thus, the combined normalized rhythmicity measure for one dipole is the combined rhythmic energy divided by the combined overall signal energy.

At this point it becomes clearer, why the directions of the dipoles are more important than the position. If only one direction is used and the rhythmic activity is orthogonal to it, we miss it. Using all directions by summing up the rhythmic energies of all three components, nothing will be missed. In contrast a not carefully chosen position leads only to a slightly weaker rhythmic activity, and never to a total loss of the signal.

2) Spatial Information

Using the alternative montage SpI can easily be extracted by determining the position (out of the fix set) of the dipole with the strongest rhythmic activity. Note that the SpI is on a very rough scale, but fine enough for our intended future use, which will be the reduction of false alarms based on the SpI, e.g. suppressing occipital alpha.

III. DATA

For our first tests we investigated 48 temporal lobe epilepsy patients featuring 186 electro-graphically visible seizures. 10 of 48 patients have no seizures. The complete dataset contains 4300 hours of EEG. Our evaluation is based on EEG markers set by experienced EEG technicians [1]. All EEGs are recorded with 256Hz sampling rate and the standard 10-20 electrode setup with additional temporal electrodes FT9, FT10 and FP9, FP10. These recordings are from an epilepsy monitoring unit and the data were not selected according to their signal quality.

IV. Results & Discussion

The performance of our seizure detection system for the three subsystems and different combinations for the above described patients group can be found in TABLE I. In the first column the names of the different montages schemes can be found. The second column shows the sensitivity of the seizure detector and the last column shows the corresponding false alarm rate. We define the sensitivity as the ratio of correctly detected seizures to all annotated seizures. A false alarm is defined as an alarm of the system without presence of a seizure. The false alarm rate is defined as the number of false alarms per hour.

TABLE I. Sensitivity and False Alarm rate for our Seizure Detector System for different Montage Schemes

Montage	Sensitivity %	False alarm rate per hour
Source	70.6	0.226
Reference	85.8	0.251
Bipolar	77.8	0.257
Source & Reference	89.2	0.384
Bipolar & Reference	89.4	0.372
Bipolar & Source	82.3	0.447
Source & Reference & Bipolar	90.6	0.539

As shown in TABLE I. , the reference montage outperforms the source montage and the bipolar montage with respect to the sensitivity. It seems that the sensitivity decreases with increasing number of involved electrodes per channel. The number of involved electrodes per channel is a measure of the interference liability. For reference montage the number is 1, for bipolar montage the number is 2 and for source montage the number is between 3 and 5. In general the false alarm rate of the system is small irrespective of the montages scheme. The false alarm rate of the uncombined montage schemes are almost in the same range. If combinations are used, the false alarm rate increases significantly.

We can further conclude that in general it makes sense to combine montages because sensitivity can be increased. Note that even with a smart variation of the seizure detector parameter the reference montage alone cannot outperform the two source & reference and bipolar & reference combination montages. Both combinations including reference montage show excellent performance, because reference montage is very robust against interference. If all but one electrode are interfered and the remaining electrode carries the rhythmic pattern, then the detector is still able to find it. In such a case the bipolar and the source montage fail.

It is surprising that the combination of the source and reference montage leads to almost the same performance as the bipolar and reference combination. Despite the pure stand-alone sensitivity of the source montage, the combined sensitivity is very good. The reason for this is that a lot of true seizure alerts provided by the source montage have not been detected by the reference montage. This is in contrast to the bipolar montage, where already the stand-alone sensitivity is high.

As results show, a combination of all three schemes is not reasonable because only a tiny rise in sensitivity at the cost of a dramatic increase of the false alarm rate can be observed.

Due to the comparable detection performance of the two combinations of reference and either source and bipolar montages and the advantage of easy automatic extraction of SpI, the source & reference combination is our favorite for the future especially with regard to false alarm rate reduction based on SpI.

Acknowledgment

We would like to thank Prof. Baumgartner form the Neurological Department Rosenhügel at General Hospital Hietzing, Vienna, Austria for providing EEG data and detailed clinical findings.

References

[1] M. M. Hartmann, F. Furbas, H. Perko, A. Skupch, K. Lackmayer, C. Baumgartner, und T. Kluge, „EpiScan: Online seizure detection for epilepsy monitoring units“, *Conf Proc IEEE Eng Med Biol Soc*, Bd. 2011, S. 6096–6099, Aug. 2011.

[2] A. S. Zandi, M. Javidan, G. A. Dumont, und R. Tafreshi, „Automated Real-Time Epileptic Seizure Detection in Scalp EEG Recordings Using an Algorithm Based on Wavelet Packet Transform“, *IEEE Transactions on Biomedical Engineering*, Bd. 57, Nr. 7, S. 1639–1651, Juli 2010.

[3] C. P. Panayiotopoulos, „CURRENT PRACTICE OF CLINICAL ELECTROENCEPHALOGRAPHY, 3rd edition“, *Brain*, Bd. 127, Nr. 1, S. 236–237, Jan. 2004.

[4] M. Scherg, N. Ille, H. Bornfleth, und P. Berg, „Advanced tools for digital EEG review: virtual source montages, whole-head mapping, correlation, and phase analysis“, *J Clin Neurophysiol*, Bd. 19, Nr. 2, S. 91–112, Apr. 2002.

[5] C. M. Michel, M. M. Murray, G. Lantz, S. Gonzalez, L. Spinelli, und R. Grave de Peralta, „EEG source imaging“, *Clin Neurophysiol*, Bd. 115, Nr. 10, S. 2195–2222, Okt. 2004.

[6] C. J. James, K. Kobayashi, und J. Gotman, „Using weighted linear spatial decomposition to investigate brain activity through a set of fixed current dipoles“, *Clin Neurophysiol,* Bd. 111, Nr. 5, S. 773–780, Mai 2000.

[7] Z. Akalin Acar und S. Makeig, „Neuroelectromagnetic forward modeling toolbox“, *Conf Proc IEEE Eng Med Biol Soc*, Bd. 2008, S. 3991–3994, 2008.

[8] D. L. Collins, „3D Model-based segmentation of individual brain structures from magnetic resonance imaging data“, *McGill University*, 1994.

[9] A. C. Evans, D. L. Collins, S. Mills, E. Brown, R. Kelly, und T. Peters, „3D statistical neuroanatomical models from 305 MRI volumes“, *in Nuclear Science Symposium and Medical Imaging Conference*, 1993., 1993 IEEE Conference Record., 1993, S. 1813–1817.

[10] B. He, D. Yao, und J. Lian, „High-resolution EEG: on the cortical equivalent dipole layer imaging“, *Clin Neurophysiol*, Bd. 113, Nr. 2, S. 227–235, Feb. 2002.

[11] T. Kluge, M. M. Hartmann, C. Baumgartner, und H. Perko, „Automatic Detection of Epileptic Seizures in scalp EEG-Recordings Based on Subspace Projections“, *Epilepsia*, Bd. 50, S. 26–27, 2009.