BSI versus the Eye: EEG Monitoring in Carotid Endarterectomy

W.A. Hofstra[1] and M.J.A.M. van Putten[2]

[1] Department of Neurology and Clinical Neurophysiology, Medisch Spectrum Twente, Enschede, The Netherlands
[2]Institute of Technical Medicine of the Faculty of Science Technology, Biomedical Signals and Systems Group, University of Twente, Enschede, The Netherlands (E-mail: m.j.a.m.vanputten@utwente.nl)

Abstract- **Carotid endarterectomy is a common procedure as an important secondary prevention of stroke. For selective shunting, continuous EEG monitoring is a standard technique, with visual assessment to track possible ischemia. Recently, the extended BSI was proposed as a pair of quantitative features to support the visual interpretation. Here, we further evaluate its potential clinical use using a large data set. The extended BSI (consisting of a spatial and temporal symmetry measure, sBSI and tBSI, respectively) was calculated retrospectively from a group of 111 patients who underwent a carotid endarterectomy in our hospital. EEG recordings were visually assessed to determine shunt placement and compared to the calculated BSI-values. All unilateral changes in the EEG found by visual assessment are reflected by Δ-sBSI ≥ 0.060 and all diffuse changes by Δ-tBSI ≥ 0.065. In EEGs with both unilateral and diffuse changes, Δ-sBSI ≥ 0.060 and Δ-tBSI ≥ 0.065. This study extends and confirms our previous pilot results, that the sBSI and tBSI correlate strongly with the visual assessment of the EEG, as performed by *experienced* neurophysiologists. The extended BSI supports the visual intraoperative EEG monitoring during carotid endarterectomies and assists in a more reliable decision for selective shunting.**

Keywords- **EEG, Carotid endarterectomy, Brain symmetry index, BSI**

I. I. INTRODUCTION

Carotid endarterectomy (CEA) is a commonly used procedure in patients suffering from a symptomatic stenosis of the internal carotid artery as an important secondary prevention of stroke [1-3]. Because performing CEA requires temporary clamping of the internal carotid artery, there is a potential risk of brain ischemia. In case of an inadequate blood flow, temporary shunting is necessary. However, as shunting has a 5-7% complication-risk [4,5], many surgeons advocate selective shunting above routine shunting [6-8]. Large differences exist between European countries in percentages of patients shunted. In the Netherlands, about 15 % of the patients is shunted [9]. A test occlusion of the carotid artery is performed to evaluate potential changes in the cerebral perfusion that may warrant (temporary) shunting [10,11]. If local anesthesia is applied, brain function and potential ischemia can safely be assessed by clinical examination [12]. However, as the majority of patients is being operated under general anesthesia, different approaches of monitoring are needed. Continuous EEG monitoring is one of the procedures most implemented at present [10,13,14]. During test-clamping the EEG is visually analyzed. If the EEG shows hemispheric asymmetries, diffuse slowing or both, ischemia is present [11,15-18], and shunt placement is indicated. However, visual EEG interpretation is not always reliable. Visual analysis has a limited sensitivity to observe asymmetries or temporal variations in patients with a low-voltage EEG or showing slow EEG changes. Also, it is not uncommon to be in doubt whether or not shunting should be performed in patients showing relatively mild EEG changes.

Quantification of the EEG and providing trend curves can assist in the decision for selective shunting, and provides objective criteria [18-21]. To quantify hemispheric changes in spectral symmetry, the spatial brain symmetry index (sBSI) was proposed to assist in the visual EEG interpretation [18]. The BSI is a normalized measure for hemispheric or *spatial* asymmetries. Its values range from 0 to 1. Perfect symmetry is indicated by 0 and maximal asymmetry by 1. The BSI$\sim$0.05 in physiological conditions and increases monotonically if (progressive) unilateral ischemia is present. The BSI has been shown to be a very useful parameter in our hospital to quantify hemispheric asymmetry in the EEG, both during CEA [18] as for monitoring stroke patients [22]. Furthermore, the BSI has been shown to be a sensitive feature to detect focal seizure activity, for example in temporal lobe epilepsy [23].

In addition to the spatial BSI, the *temporal* BSI (tBSI) was introduced [24]. This measure quantifies diffuse changes in the EEG. The tBSI is primarily sensitive for temporal changes in spectral characteristics that are not caused by changes in spatial symmetry. This provides us with two different indices, the sBSI for changes in *spatial* symmetry and the tBSI for changes in *temporal* symmetry.

The recent report about the sBSI and tBSI was a pilot study, performed on a data set of 25 patients. Here, we evaluate these features using a large EEG set from patients who underwent a CEA in our hospital in 2000-2007.

II. METHODS

A. Description of the BSI

The sBSI is defined as a normalized measure for interhemispheric spectral symmetry. Although the sBSI is originally defined in the frequency range 1- 25 Hz, we will study two additional frequency ranges as well, i.e. 1- 10 Hz and 1- 15 Hz.

$$sBSI = \frac{1}{N}\sum_{i=1}^{N}\left\| \frac{1}{M}\sum_{j=1}^{M}\frac{R_{i,j}-L_{i,j}}{R_{i,j}+L_{i,j}} \right\| \quad (1)$$

with $R_{i,j}$ ($L_{i,j}$) the Fourier coefficient belonging to frequency $i = 1, \ldots, N$ of right (left) hemispheric bipolar derivations $j = 1, 2, \ldots, M$. For a standard 10–20 system, $M = 8$.

Temporal changes in the EEG are quantified by the tBSI′, defined as the normalized difference between the actual spectral characteristics and a baseline EEG epoch, e.g. a segment prior to test-clamping.

$$tBSI' = \frac{1}{N}\sum_{i=1}^{N}\left\| \frac{1}{K}\sum_{j=1}^{K}\frac{S_{i,j}-S_{ref,i,j}}{S_{i,j}+S_{ref,i,j}} \right\| \quad (2)$$

with $S_{i,j}$ the Fourier coefficient belonging to frequency $i = 1, \ldots, N$ of bipolar derivations $j = 1, 2, \ldots, K$. Clearly, $K = 2 \cdot M$, since the total number of bipolar derivations is twice the number of the bipolar derivations of each hemisphere.

The tBSI is now defined as

$$tBSI = \frac{2tBSI' - sBSI}{2} \quad (3)$$

effectively eliminating the contribution of changes in spatial symmetry. The factor two in the nominator is introduced to account for the fact that the number of channel pairs $K = 2 \cdot M$ involved in the calculation of the tBSI′ is twice the number of pairs (M) used in the sBSI calculation. Since K is present in the denominator of Eq. (2), the tBSI′ is half as sensitive for unilateral changes compared to the sBSI. The tBSI as defined in Eq. (3) now only captures EEG changes that are not due to changes in symmetry. The division by 2 normalizes the tBSI to the range [0–1], similar to the range of the sBSI [18]. For more details we refer to [18,24]

B. Patients

Data were analyzed retrospectively from all patients (n=111) who underwent a CEA in this hospital between 2000 and 2007. Patients were obtained from our digital EEG database (Neurocenter (TM), Clinical Science Systems, Netherlands). The decision to shunt was based on intraoperative EEG monitoring by visual analysis by an experienced electroencephalographer. Typically, shunting was advised if the EEG showed significant changes, either unilateral, diffuse, or both.

C. EEG recording and analysis

EEGs were recorded according to the international 10–20 system using Ag/AgCl electrodes. Electrode impedance was kept below 5 kΩ to reduce polarization effects. Recording was performed using BrainLab (OSG, Belgium). The sampling frequency was set to 250 Hz. Sixteen bipolar derivations were subsequently used for the analysis, i.e. Fp2-F4, F4-C4, C4-P4, P4-O2, Fp1-F3, F3-C3, C3-P3, P3-O1, Fp2-F8, F8-T4, T4-T6, T6-O2, Fp1-F7, F7-T3, T3-T5, and T5-O1. Analysis of the EEGs was performed using software developed in our own department that allowed analysis of subsequent 10 s epochs of the EEG. Routines were implemented in MatLab (The Mathworks, Inc). The power was estimated using Welch's averaged periodogram method. The signal from each bipolar derivation, containing 10 s of data (5000 datapoints) was divided into overlapping sections containing N=1024 points, each of which was detrended and windowed. The magnitude of the length N discrete FFTs of the sections was averaged to form the spectral density. Subsequently, the BSI was calculated.

The baseline BSI was calculated from an epoch with duration of 60 s preceding the test-clamping procedure, using the mean value in this period. This period will hereafter be called the reference period. The post BSI was defined as the maximum value in the 180 s following clamp on (evaluation period). The reference and/ or evaluation period were reset manually when artifacts were present in the EEG that could contribute to unreliable values of the BSI, as identified with visual re-analysis. Based on visual interpretation the EEGs were classified into two groups: 1) there was an indication to shunt or 2) no indication to shunt.

III. RESULTS

In the original database of n= 111, four EEGs could not be used because clamp-time was not listed. All EEGs were checked afterwards on disturbing artifacts. Eight EEGs (7%) had to be excluded from the database because of too many artifacts to calculate reliable BSI-values. Of the remaining 99 EEGs the sBSI and tBSI have been calculated. In 24 EEGs (22%) the reference and/ or evaluation period had to be revised manually after visual re-interpretation,

Table 1 Overview of patient characteristics Characteristics of patients, whose EEGs were used for BSI calculations (n= 99). The patients were divided into two groups, based on visual analysis of the EEGs: shunt-indication or no shunt-indication.

	Shunt-indication	No shunt-indication	Total
Total	11	88	99
Male	5	61	66
Female	6	27	33
Age (years)	69.5 [51-86]	65.2 [42-83]	65.6 [42-86]
Clamp-time (min)	5.2 [0.33-25.33]	32.17 [3-84.33]	29.17 [0.33-84.33]

because of artifacts in the standard reference and/ or evaluation period, which could otherwise lead to erroneous calculations of the BSI. The remaining 79 EEGs (71%) could be used without interference. In total, EEGs from 99 patients were used to calculate the BSI.

In nine out of these patients there was an indication to shunt, based on *intraoperative* visual analysis of the EEG. In five out of these nine patients shunting was technically not possible and CEA was not performed. The other four operations were finished successfully. During re-analysis of the EEGs, there were two cases where we would have suggested shunt-placement, which was, however, not advised by the clinical neurophysiologist observing the EEG during the CEA. In one of these cases, there was moderate diffuse slowing after test-clamping; in the other patient moderate asymmetry was observed. Fortunately, no complications occurred during the procedure or afterwards. In 88 patients there was no indication to shunt, as no visual changes were observed

The calculations were done in three different frequency ranges, 1-10, 1-15, and 1-25 Hz. We found that in the 1-10 Hz range the BSI-values correlated most significantly with visually based shunt-indication.

In 88 out of the 88 patients in the non-shunting group the ΔsBSI and/ or the ΔtBSI did not reach values larger than respectively 0.05 and 0.065. In all 11 patients whose EEGs showed such changes, that shunting was indicated, we found that the ΔsBSI ≥0.05 and/ or the ΔtBSI ≥.065. This results in a sensitivity of 100% and a specificity of 100%, as shown in Table 2.

Table 2 . 2-way contingency tableThe patients were divided into two groups, based on *visual* analysis of the EEGs: shunt-indication or no shunt-indication. The results are compared to the ΔsBSI and ΔtBSI- values. Positive ΔsBSI are values> 0.06 and positive ΔtBSI-values are values > 0.065.

	Shunt-indication	No shunt-indication	Total
Positive ΔsBSI and/ or ΔtBSI	11	0	11
Negative ΔsBSI and ΔtBSI	0	88	88
Total	11	88	99

In all EEGs where unilateral changes were present, the ΔsBSI > 0.05. In all EEGs with diffuse changes, ΔtBSI > 0.065. Also, in EEGs with both unilateral and diffuse changes, the ΔsBSI > 0.05 and ΔtBSI > 0.065.

IV. Discussion and conclusions

At present visual assessment of the intraoperative EEG during carotid endarterectomy is the standard procedure to determine whether shunting is needed during test-clamping. Unfortunately, however, visual assessment of EEG is prone to human doubt and misinterpretation. Moreover, very experienced neurophysiologists are needed to perform these visual assessments. It is unknown, however, to what extent changes in an EEG can be accepted without consequences for the patient. To be safe, most physicians advice to shunt as soon as EEG changes appear. Therefore, it would be very useful to have an objective quantitative measure to assist in a more reliable decision whether to shunt or not. Furthermore, a continuous quantitative trend is helpful during the operation, to capture, more accurately, possible changes in cerebral perfusion.

Here, we show that the Δ-sBSI and Δ-tBSI can assist in the decision whether shunting is needed during CEA, as these measures capture *any* change in the EEG. These features quantify interhemispheric and diffuse changes in the EEG, respectively, providing an objective measure to help and evaluate whether significant EEG-changes are present and shunting should be performed. In this study we confirm the previous results with the sBSI [18,24], showing that the Δ-sBSI is very sensitive measure to detect hemispheric changes in spectral symmetry, with a very good correlation with the visual interpretation. If shunting was not advised, based on visual analysis, Δ-sBSI ≤ 0.050; if Δ-sBSI ≥ 0.060, visual EEG interpretation showed significant asymmetry, and shunting should strongly be considered, in agreement with the original paper [18].

The tBSI is sensitive for capturing diffuse changes. If Δ-tBSI ≤ 0.055, no significant diffuse EEG changes were present. In those circumstances where Δ-tBSI ≥ 0.065, diffuse changes were observed. The limits of the Δ-tBSI are slightly different from those presented in the original paper [24] The present BSI-values are evaluated in the frequency range 1-10 Hz, however, and show most significant correlation with the visual interpretation. Here, we show that the Δ-sBSI and Δ-tBSI can be helpful *objective* measures in the operating theatre, as they correlate strongly with the visual assessment of the EEG. However, it is important to realize that although these values may be very supportive, they are not designed (yet) to *replace* the human intraoperative monitoring, as we show that in 21% of the EEGs the reference period and/or evaluation period had to be revised in order to obtain reliable BSI-values, given their sensitivity for various artifacts. Another 7% had to be excluded because of too many artifacts. In 71% of the EEGs, BSI-values could be determined without interference. Therefore, in general, selective shunting cannot be based on the sBSI and tBSI only, and human interpretation is needed to disregard artifacts that the computer does process.

In conclusion, this study extends and confirms our previous pilot results. The sBSI is designed to indicate interhemispheric changes while the tBSI captures diffuse changes, not caused by asymmetry. These measures correlate strongly with the visual assessment of the EEG, as performed by an *experienced* neurophysiologist. Therefore, these quantitative EEG features can highly contribute to the intraoperative EEG monitoring during carotid endarterectomies, and together with visual interpretation, lead to a more reliable decision whether shunting is necessary or not.

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Author: WA Hofstra
Institute: Department of Neurology and Clinical Neurophysiology, Medisch Spectrum Twente
Street: P.O. Box 7500 KA
City: Enschede
Country: The Netherlands
Email: W.A.Hofstra@student.rug.nl