A brain symmetry index (BSI) for online EEG monitoring in carotid endarterectomy

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Abstract

Introduction: Carotid endarterectomy is a common procedure as a secondary prevention of stroke, and one of the early controversies in carotid surgery is centered around whether a shunt should be used during this procedure. Although various EEG parameters have been proposed to determine if the brain is at risk during carotid artery clamping, the common procedure is still the visual assessment of the EEG. We propose a brain symmetry index (BSI), that has been implemented as an on-line quantitative EEG parameter, as an additional criterion for shunt need in carotid endarterectomy.

Methods: The BSI captures a particular asymmetry in spectral power between the two cerebral hemispheres, and is normalized between 0 (perfect symmetry) and 1 (maximal asymmetry). The index was evaluated retrospectively in a group of 57 operations in which the EEG and the transcranial Doppler were used as criteria for shunt insertion. In addition, after online implementation of the algorithm, several patients have been evaluated prospectively.

Results: If no visual EEG changes were detected, it was found that the change in BSI from baseline, \( \Delta \text{BSI} \), was less than 0.03 in all patients. In none of these patients shunting was performed, except for 11 in whom shunting was advised based on changes in the transcranial Doppler signal. None of these patients suffered from neurological complications. In those operations with visual EEG changes during test-clamping and selective shunting, we found that \( \Delta \text{BSI} \geq 0.06 \). In this group, one patient suffered from intraoperative stroke and one patient died, most likely from a hyperperfusion syndrome.

Conclusions: The BSI may assist in the visual EEG analysis during carotid endarterectomy and provides a quantitative measure for electroencephalographic asymmetry due to cerebral hypo-perfusion. In patients with a change in the BSI (\( \Delta \text{BSI} \)) smaller than 0.03 during test clamping, visual EEG analysis showed no changes, whereas if visual EEG analysis did warrant shunting, it was found that \( \Delta \text{BSI} \geq 0.06 \).

Keywords: EEG; Carotid surgery; Endarterectomy; Brain symmetry index (BSI)

1. Introduction

Carotid endarterectomy is a common procedure as a secondary prevention of stroke. One of the early controversies in carotid surgery is centered around whether a shunt should be used during this procedure. This has resulted in either routine shunt use by some vascular surgeons and selective shunt use by most. It is generally agreed upon, however, that shunting increases the risk of perioperative stroke from arterial injury and associated thromboembolism, and, if possible, should be avoided (e.g. Salvian et al., 1997; Konstadinos et al., 1997). Selective shunt use, however, is dependent on a reliable and accurate criterion that will identify those patients at risk for cerebral ischaemia and stroke during carotid clamping if no shunt were used.

Various criteria have been used in reports of carotid endarterectomy to decide if shunting is indicated. Methods include the measurement of the carotid back pressure (Moore et al., 1973), evaluation of the awake patient under regional anesthesia (Shah et al., 1994), transcranial Doppler measurement (Ghali et al., 1997), monitoring of somatosensory evoked potentials (Schweiger et al., 1991), and continuous EEG monitoring (Konstadinos et al., 1997;
Salvian et al., 1997; McFarland et al., 1988; Visser, 1998; Pinkerton, 2002).

Although various EEG parameters have been proposed to determine if the brain is at risk during carotid artery clamping (Visser et al., 1999; Minicucci et al., 2000), the common procedure is still the visual assessment of the EEG. Quantitative EEG (qEEG) with realtime calculation of a particular index could provide additional information during this procedure, that may assist in the decision whether or not shunting is needed. To this end, we introduce a brain symmetry index (BSI) that provides a single parameter as a measure for the mean electroencephalographic brain symmetry. We will show by a retrospective analysis of 57 patients who underwent a carotid endarterectomy in our hospital that this BSI correlates well with the visually based interpretation and the decision ‘to shunt’ or ‘not to shunt’. The interpretation of the BSI, however, is much more straightforward than visual assessment, which may improve the reliability of the procedure.

2. The brain symmetry index (BSI)

As a measure for the symmetry, we consider the absolute value of the relative difference of the average spectral density of the right and left hemisphere in the frequency range from 1 to 25 Hz. Since the spectral density is estimated by fast fourier transform, we write for the absolute power of signal \( S_i(t) \) obtained from a particular channel pair \( i = 1, \ldots, N \), at frequency (or Fourier coefficient) \( j = 1, \ldots, M \) \( R_{ij}(t) \) and \( L_{ij}(t) \) for the right and left hemisphere, respectively. We now define the brain symmetry index as:

\[
BSI(t) = \frac{1}{N} \sum_{i=1}^{N} \left( \frac{1}{M} \sum_{j=1}^{M} R_{ij}(t) - L_{ij}(t) \right) = \frac{1}{N} \sum_{i=1}^{N} \frac{1}{M} \sum_{j=1}^{M} \left( R_{ij}(t) + L_{ij}(t) \right)
\]

with \( N \) the number of channel pairs and \( M \) the number of Fourier coefficients. Note that the lower bound for the BSI is zero (perfect symmetry for all channels), whereas for the upper bound we find BSI = 1, which implies maximal asymmetry.

3. Patients and methods

3.1. Clinical material

Data were analyzed retrospectively from all consecutive patients (\( n = 57 \)) who underwent a carotid endarterectomy between 2000 and the end of 2003. Selective shunt use was based on intraoperative EEG monitoring and, except in those without an acoustic window, transcranial Doppler (TCD), insonating the middle cerebral artery.

Typically, shunting was advised if the EEG as interpreted by an experienced electroencephalographer (MvP or DT) showed significant changes, as determined by visual analysis, and/or if the mean flow velocity (cm/s) of the middle cerebral artery decreased by more than 70%, according to our protocol.

3.2. EEG recording and analysis

EEGs were recorded according to the international 10–20 system using Ag/AgCl electrodes. Electrode impedance was kept below 5 k\( \Omega \) to avoid polarization effects. Recording was performed using BrainLab (OSG, Belgium). The sampling frequency was set to 500 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 10 pages (100 s) preceding the ‘test-clamping’ procedure, using the mean value in this period. The BSI during clamping was defined as the maximum value in the period during test-clamping. The final BSI was defined as the mean value of 10 pages at the end of the procedure, while the patient was still under anesthesia. All EEGs were also visually re-analyzed, in particular to determine whether artifacts were present that might contribute to erroneous values of the BSI.

Besides off-line retrospective analysis, the algorithm has also been implemented in a real-time environment. Since our EEG recorder (OSG bvba, Belgium) writes the data to disk every 10 s, this allows file opening in the time frames in between writing; to this end, a particular synchronization function was implemented. After the data was read, calculation time was approximately 1–2 s on a 1.2 GHz PC that was connected to the recorder. Besides the actual value of the BSI, results are displayed on the computer screen as a trend curve.

3.3. Anesthesia and surgical procedure

Preoperative carotid stenosis was identified with Duplex ultrasound. General anesthesia was used in all patients. Intraoperative systemic heparinization was routinely used. A longitudinal arteriotomy allowing full exposure of the proximal and distal points of plaque removal was used. Shunt use was determined by either significant TCD changes (typically > 70%) or changes in the continuously running EEG, by visual inspection. These included a decrease in fast activity and/or an increase in slow activity.
or attenuation of all EEG activity. Anesthesia was induced by either propofol/remifentanyl by continuous infusion or a bolus of etomidate/thiopental/sufentanyl. Maintenance of anesthesia was by continuous infusion of propofol and remifentanyl or by sevoflurane with additional bolus dosages of sufentanil. Muscle relaxants were solely given to facilitate endotracheal intubation. Rocuronium was used in all patients.

4. Results

We retrospectively analyzed data from 57 patients, who underwent a carotid endarterectomy in our hospital in the period 2000–2003.

An illustration of the mean spectral density curves that can be obtained for each hemisphere is shown in Fig. 1. In all 3 cases, visual assessment showed an asymmetry, with global reduction of activity (A) on the symptomatic right side; reduction of fast activity, only, on the left side, in the second patient (B); reduction of fast activity with an increase in slow activity on the symptomatic left side in patient (C). Clearly, the BSI, as a normalized measure for the area between the curves, will be larger than zero in all these 3 cases.

An example of the trend curves is presented in Fig. 2. In the first example, Fig. 2a, visual EEG analysis showed no changes, and the baseline value of the BSI ∼ 0.05 remained unchanged after clamping. The second example, shown in Fig. 2b is from a patient in whom test clamping shows an increase to BSI ∼ 0.12 from the baseline BSI ∼ 0.05, indicated by the first horizontal bar. Subsequent shunt placement shows another increase to a value of BSI ∼ 0.17. Note the slow trend in BSI, with a short increase and a decrease afterwards. Shunt removal is accompanied by a short, but large increase in BSI. The final BSI is equal to baseline value. No complications occurred in this patient. Finally, in Fig. 2c the BSI trend curve of a patient is shown, where hypotension with insufficient cerebral perfusion occurs in the period labelled with ‘low BP’, with an increase in the BSI to a value of BSI ∼ 0.28. The subsequent increase in blood pressure restores the BSI to near baseline value (BSI ∼ 0.06). Shunt placement in the right carotid artery was complicated by a long clamping time (4:30 min) with a persistent high BSI. This patient suffered postoperatively from a left-sided hemiparesis.

An overview of the patient characteristics and the values of the parameters obtained is presented in Table 1. In the non-shunted group (n = 37), we found that the baseline BSI = 0.067 ± 0.009, which was not significantly different from the group in whom a shunt was advised, independent of the presence or absence of EEG changes. In the non-shunted group, the difference between the baseline value of the BSI and the value obtained during test-clamping was nil in most patients (n = 33), 0.01 in 3, and 0.03 in one patient.

Fig. 1. Examples of characteristic differences in the mean spectral density of the left hemisphere (blue circles) and the right hemisphere (red line), as may occur during hypoperfusion of one hemisphere. Data are from 3 different patients. (A) Spectra with 1/f characteristic, where the two spectra are ‘in parallel’. This is not a general phenomenon; in several patients, curves were partially displaced, as illustrated in (B); or ‘tilted’, as shown in (C). In case (B), there is mainly a decrease in power at higher frequencies on the symptomatic left side. Case (C), the third type of asymmetry, that is most commonly encountered, shows a reduction of fast activity and an increase in slow activity (left side). Note that in the case illustrated in (A), showing a global reduction in power, the spectral edge (SE) frequency will not change. Therefore, the SE is not a general measure to differentiate between the spectral characteristics of each hemisphere, since it does not contain information about the absolute value of the frequency spectrum. A similar observation was made by Hanowell et al., who found that EEG power changes are more sensitive than spectral edge frequency variation for detection of cerebral ischemia during carotid endarterectomy (CEA) (Hanowell et al., 1992).

The shunt group was divided in two subgroups, depending on the presence of EEG changes. In the group without EEG changes (n = 11), the change in BSI was nil. In the group where visual EEG analysis did show changes...
Fig. 2. Shown are 3 trend curves of the BSI from 3 different patients. Horizontal bars indicate clamping period. The stars (*) denote the presence of artifacts. (A) Example of a patient in whom shunting was not indicated. Baseline value BSI ~ 0.05, that remains unchanged after clamping. Final value of BSI is equal to baseline value. No complications. (B) Example of a patient in whom test clamping shows increase in BSI (first horizontal bar). Shunt placement yields a temporary increase in BSI (2nd bar). Note the slow trend in BSI, with a short increase and a decrease afterwards. This most likely reflects changes in local perfusion. Finally, shunt removal is accompanied by a short, but large increase in BSI. The final BSI is equal to baseline value. No complications. (C) In this patient, hypotension with concomitant increase in the index to BSI. The change in BSI is equal to baseline value. No complications. (C) In this patient, hypotension with insufficient cerebral perfusion occurs in the period labelled with ‘low BP’. With concomitant increase in the index to BSI ~ 0.28. Increase in blood pressure restores the BSI to near baseline value (BSI ~ 0.06). Subsequent shunt placement in the right carotid artery is complicated by a long clamping time (4.30 min) with a persistent high BSI. This patient suffered postoperatively from a left-sided hemiparesis.

Table 1
Overview of patient characteristics

<table>
<thead>
<tr>
<th></th>
<th>No shunt</th>
<th>Shunt, no EEG changes</th>
<th>Shunt, with EEG changes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Male</td>
<td>23</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>Female</td>
<td>14</td>
<td>9</td>
<td>6</td>
</tr>
<tr>
<td>Age (years)</td>
<td>71 (46–81)</td>
<td>66 (41–80)</td>
<td>71 (57–78)</td>
</tr>
<tr>
<td>Stenosis (%)</td>
<td>89 (70–90)</td>
<td>90 (90–99)</td>
<td>83 (70–90)</td>
</tr>
<tr>
<td>BLS</td>
<td>6</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>Clamp time (min)</td>
<td>39.5 (26–74)</td>
<td>2.6 (1.6–3.7)</td>
<td>2.2 (1.3–4.5)</td>
</tr>
<tr>
<td>TCD (cm/s)</td>
<td>27 (21–53)</td>
<td>36 (16–60)</td>
<td>51 (34–70)</td>
</tr>
<tr>
<td>ΔTCD (%)</td>
<td>18.4 (0–50)</td>
<td>47 (10–100)</td>
<td>81 (73–100)</td>
</tr>
<tr>
<td>BSI</td>
<td>0.067 (0.03–0.12)</td>
<td>0.061 (0.03–0.14)</td>
<td>0.061 (0.03–0.10)</td>
</tr>
<tr>
<td>ΔBSI</td>
<td>0.002 (0–0.03)</td>
<td>0.002 (0–0.01)</td>
<td>0.138 (0.06–0.22)</td>
</tr>
</tbody>
</table>

Bilateral stenosis (BLS) is present if the non-symptomatic carotid artery has a stenosis larger than 70%. The change in TCD velocities (ΔTCD) is given in percent of baseline value. The change in baseline value of the BSI during test clamping (ΔBSI) is indicated in absolute values. In 9 non-shunted patients, TCD was not available; in 5 shunted patients, TCD was not available.

5. Discussion and conclusions

The current study was motivated by the notion that visual analysis of the EEG is prone to human error, and makes quantification of possible changes difficult. In addition, a particular warning system can be realized, based upon a quantitative measure. Although various parameters have been proposed to support the visual EEG analysis during carotid endarterectomy, the number of parameters that are implemented in a real-time environment is limited. In the Netherlands, for instance, only a few hospitals use real-time EEG parameter extraction during carotid endarterectomy.

The proposed measure, the BSI, captures the normalized difference in the spectral density of the two cerebral hemispheres. Although it is suggested that changes in particular frequency bands may be more sensitive to ischemia than others (Sainio et al., 1983; Jonkman et al., 1985; Faught, 1992; Visser et al., 1999), for this study it was decided to weigh all frequencies of the spectrum equally. We further note that some EEG derivations may be more sensitive to detect ischemia during carotid surgery than others (Laman et al., 2001). We decided, however, to use equally weighted 16 bipolar EEG derivations (8 channels for each hemisphere). In our measure, therefore, the contribution of all Fourier coefficients, i.e. all calculated frequencies, and all channels, are weighted uniformly.

At baseline, the BSI ranges from 0.05 to 0.14, which may partially indicate physiological asymmetry. No significant difference was found in baseline BSI between the 3 groups (non-shunt, shunt without EEG and shunt with EEG changes). It should be recognized that a few patients suffered from minor ischemic stroke prior to operation. Therefore, in normal controls the upper value of normal limits is most likely lower than 0.14.

If visual analysis by the electroencephalopgrapher did not detect any change, we found that the change in the BSI from baseline value, ΔBSI ≤ 0.03. If, however, visual analysis did reveal EEG changes during test-clamping, the BSI increased with values of 0.06–0.22. Both patients with a final BSI ≥ 0.16 suffered from neurological sequelae: one a left-sided hemiparesis, the other died a few days after the endarterectomy, most likely from a ‘delayed’ postoperative hyperperfusion syndrome, that developed a few days after surgery (Breen et al., 1996).

Although anesthesia clearly influences the EEG patterns during the procedure (Bovill et al., 1982), these variations are typically symmetrical. Since, by construction, the BSI will not detect exact symmetrical changes, such as diffuse attenuation of fast activity or diffuse increase in delta activity, the BSI is relatively insensitive to differences in...
an undesirable cross-sensitivity of the proposed BSI. Our results support these considerations, showing baseline BSI values not related to the anesthetic regime.

Another possible cause of bilateral changes is systemic hypotension. If this would induce exact symmetrical changes, this would not be reflected by changes in the value of the BSI. This phenomenon was not observed, however, in our group of 57 patients, including the patient illustrated in Fig. 2c, who suffered from systemic hypotension prior to test clamping. Whether this is generally true in this patient category is currently uncertain. As long as the BSI is not used to replace visual assessment of the EEG this is not a major concern.

Artifacts, that are quite often present during the procedure, may contribute to erroneous values of the BSI. In our current study, no attempts were made to remove artifacts. Currently, the BSI has been implemented in our real-time quantitative EEG monitor, where its value will further be evaluated by a prospective analysis.

Although TCD was applied as well as an indicator for selective shunting, in some patients in whom the TCD signal changed significantly, shunting was not performed due to technical limitations. In all these patients, EEG changes were absent or only minor. This is in agreement with previous observations, that the EEG is more sensitive for diffuse cerebral ischaemia than changes in the TCD. However, the detection of particulate emboli by TCD can lead to beneficial modifications in surgical technique, as was also pointed out in (Ackerstaff et al., 2000; Pinkerton, 2002). The study by Pinkerton (2002), using visual analysis of the EEG as the single criterion for selective shunting, showed that intraoperative EEG monitoring accurately (99.92%) identified patients who may safely have carotid endarterectomy without the need of a shunt. In this large group of 1661 operations, there was only one patient who suffered from a minor intraoperative stroke (0.08%), ‘which resolved in 1 week’, in the absence of an EEG change. Changes in the EEG tracings that prompted the use of a shunt included development of ipsilateral or bilateral slowing with the appearance of delta waves and/ or a decline in voltage amplitude of 50% or greater, which appeared in ~22% of the patients. In this latter group, 4 patients suffered from intraoperative stroke (11.1%). In our group of patients, two patients suffered from intraoperative stroke, i.e. 3.5%. This number is slightly larger than reported in the literature, with numbers ranging from 0.03% (Pinkerton, 2002) to 2.1% (Kresowik et al., 1991).

We finally remark, that the BSI is primarily intended to support, not to replace, the visual assessment of the EEG. Especially artifacts are well recognized by the human observer, and not trivially eliminated or compensated for by computer programs, although recent progress using independent component analysis may change this picture (Lee, 1998; Makeig et al., 2000; Iriarte et al., 2003). In our setup, therefore, both the raw EEG signal is displayed, as well as the BSI-trend curve and its actual value.

In conclusion, we introduce a BSI that provides a single measure for the interhemispheric difference in the spectral density. As shown by our retrospective analysis, shunting was not advised if $\Delta$BSI $\leq$ 0.03. In those patients with $\Delta$BSI $\geq$ 0.06 during test-clamping, visual EEG analysis showed significant changes, and shunting was advised.

**References**


