Prediction of Hyperperfusion After Carotid Endarterectomy by Brain SPECT Analysis With Semiquantitative Statistical Mapping Method

Kohkichi Hosoda, MD; Tetsuro Kawaguchi, MD; Kazunari Ishii, MD; Satoshi Minoshima, MD; Yuji Shibata, MD; Masaki Iwakura, MD; Shigeo Ishiguro, MD; Eiji Kohmura, MD

Background and Purpose—Hyperperfusion syndrome is a rare but disastrous complication after carotid endarterectomy (CEA). The aim of this study was to investigate the relationship between preoperative cerebral blood flow (CBF) abnormalities and postoperative hyperperfusion through the use of statistical brain mapping analysis.

Methods—For 41 patients with unilateral carotid stenosis ≥70%, CBF and cerebral vasoreactivity (CVR) were investigated with resting and acetazolamide-challenge single photon emission CT before CEA. CBF 1 day after CEA was also measured. Three-dimensional stereotactic surface projection (3D-SSP) analysis of CBF changes was performed by use of a control database of 20 subjects.

Results—Patients with reduced CVR (CVR <10%, n=15) were categorized into 2 groups based on the severity of CBF reduction relative to the control database by 3D-SSP analysis without normalization: type I (ipsilateral CBF decrease <20%, n=8) and type II (ipsilateral CBF decrease ≥20%, n=7). With thalamic normalization, the patients were also categorized into 2 groups: type A (ipsilateral Z score ≤2, n=10) and type B (ipsilateral Z score >2, n=5). Severe CBF reduction (≥20% or Z score >2) was significantly associated with postoperative hyperperfusion (CBF increase ≥100%). However, 3D-SSP with thalamic normalization (Z score) demonstrated a higher predictive value (80%) and specificity (91%) for hyperperfusion than 3D-SSP without normalization (percent reduction) (57% and 73%, respectively). No patients with normal CVR (CVR ≥10%, n=26) demonstrated postoperative hyperperfusion.

Conclusions—Objective evaluation of abnormalities of CBF and CVR with 3D-SSP could identify patients at risk for postoperative hyperperfusion. (Stroke. 2003;34:1187-1193.)

Key Words: brain ■ carotid endarterectomy ■ carotid stenosis ■ tomography, emission-computed, single-photon

Hyperperfusion syndrome is a rare but disastrous complication after carotid endarterectomy (CEA). Among the classic triad of unilateral headache, seizures, and intracerebral hemorrhage, 1–3 intracerebral hemorrhage is reported to occur in 0.4% to 2.1% of patients after CEA. 1,3–6 The prognosis is miserable, with mortality rates of 36% to 63%, and survivors have significant morbidity. Risk factors of this syndrome include hypertension, high-grade stenosis, poor collateral flow, and contralateral carotid occlusion. 7 Recently, we reported that severely impaired cerebral vasoreactivity (CVR) detected by single photon emission CT (SPECT) is significantly associated with postoperative hyperperfusion. 8 In addition, severe and diffuse asymmetric pattern of preoperative cerebral blood flow (CBF) reduction seemed to be characteristic of patients who experienced postoperative hyperperfusion. 8 However, the relationship between preoperative CBF reduction and postoperative hyperperfusion has not been fully clarified.

Most CBF studies used region of interest (ROI) approaches. These techniques have several disadvantages. The analysis does not include the entire brain; the density of the data sampling can be biased regionally; and reproducibility and consistency among different investigators are limited because of difference in experience of observers. 9 To overcome these issues, advances in image processing have been developed for positron emission tomography (PET) and SPECT in a 3-dimensional data extraction format. 9–11 Three-dimensional stereotactic surface projection (3D-SSP) is a fully automated, user-independent data extraction method that has been applied extensively to PET image analysis in Alzheimer’s disease 10 and other neurological disorders.

The present study used statistical brain mapping techniques for SPECT imaging to investigate CBF and CVR in carotid stenosis. We investigated whether this new technique could demonstrate a significant relationship between preoperative CBF abnormalities and hyperperfusion after CEA.

Received November 4, 2002; accepted November 28, 2002.
From the Department of Neurosurgery (K.H., T.K., Y.S., M.I., S.I.) and Department of Radiology (K.I.), Hyogo Brain and Heart Center, Himeji, Japan; Department of Radiology, University of Washington, Seattle (S.M.); and Department of Neurosurgery, Kobe University School of Medicine (E.K.), Kobe, Japan.
Correspondence to Kohkichi Hosoda, MD, Department of Neurosurgery, Hyogo Brain and Heart Center, 520 Saisho-ko, Himeji, 670-0981 Japan. E-mail khosoda@venus.dti.ne.jp
© 2003 American Heart Association, Inc.
Stroke is available at http://www.strokeaha.org DOI: 10.1161/01.STR.0000068781.31429.BE
Subjects and Methods
Between March 1999 and April 2002, 77 consecutive patients underwent CEA with in-dwelling shunt in Hyogo Brain and Heart Center, 41 of whom fulfilled the following criteria and entered the present study. Inclusion criterion was unilateral internal carotid artery (ICA) stenosis $\geq 70\%$. Exclusion criteria were contralateral carotid stenosis $\geq 30\%$, intracranial artery stenosis or occlusion, and/or major disabling stroke.

Of the 41 patients, 35 were male and 6 were female. Mean age was $69.8 \pm 7.5$ years (mean $\pm$ SD; range, 49 to 84 years). Thirty-three patients were hypertensive, and 13 had diabetes mellitus. Transient ischemic attacks referring to the relevant ICA were the only symptoms for 8 patients. Four patients had suffered transient ischemic attacks with subsequent strokes, and 13 patients had suffered strokes only. All stroke patients had made good functional recoveries. Sixteen patients exhibited asymptomatic ICA stenosis.

Preoperative CT and MRI demonstrated ipsilateral symptomatic infarctions in 19 patients, ipsilateral asymptomatic infarctions in 3, and contralateral asymptomatic infarction in 2. Two patients had old infarction in the pons and/or cerebellum. No infarction was seen in 19 patients.

The overall average of the degree of ICA stenosis was $83.5 \pm 11.3\%$ (range, 70% to 99%) on angiography. Twenty patients underwent surgery on the left side and 21 on the right side under general anesthesia. We obtained informed consent from all patients or their next of kin.

CBF Studies
Resting CBF was assessed by SPECT with a rotating dual-headed gamma camera (GAMA View SPECT 2000 H-20, Hitachi) before and 1 day after CEA. Details of the procedure with $N$-isopropyl-p-$^{111}$I-iodoamphetamine (IMP) using arterial blood sampling and a microsphere model were described previously. In brief, 111 MBq (3 mCi) of $^{111}$I-IMP was injected intravenously. Fifteen minutes later, SPECT acquisition was started. Five to 7 days after resting SPECT, 1 g acetazolamide was given intravenously; 20 minutes later, SPECT was repeated. The median time between the latest ipsilateral neurological event and preoperative SPECT study was 48 days (range, 18 to 168 days) for strokes and 47 days (range, 10 to 151 days) for transient ischemic attacks. The median time between the preoperative SPECT studies and CEA was 16 days (range, 6 to 73 days).

Image Analysis by ROI
We measured regional CBF (rCBF) by placing 6 to 10 ROIs (each $5.9 \text{~mm}^2$) on a hemisphere surface map, it was defined as decreased hyperperfusion for 3D-SSP analysis without pixel normalization. Reduction in absolute CBF values in each patient was compared with the normal control database of the absolute values, and the percent reduction of each pixel was displayed on 3D-SSP. Previous ROI study had demonstrated normal control values of rCBF ($45.5 \pm 5.9 \text{~mL} \cdot \text{g}^{-1} \cdot \text{min}^{-1}$), which means that 2 SD corresponds to 26% change. Therefore, we preliminarily compared 2 cutoff values (20% and 30%) of CBF reduction. The 20% CBF reduction was chosen because the 30% reduction was too insensitive to detect CBF reduction adequately. Accordingly, when pixels with a decrease of $\geq 20\%$ covered $>50\%$ of areas of a hemisphere surface map, it was defined as decreased CBF on 3D-SSP. With this definition, we could nullify the influence of infarction on the evaluation of CBF because only small infarctions were seen in the present study. For 3D-SSP of CVR, CBF increase after acetazolamide challenge was expressed as percentages of corresponding values from resting CBF in each patient. For 3D-SSP of CBF increase after CEA, postoperative CBF increase was expressed as percentages of corresponding values from preoperative resting CBF. Hyperperfusion after CEA was defined CBF increase of $>100\%$ on the first postoperative day, according to Piepgras et al.1

Statistical Analysis
Descriptive statistics are presented as mean $\pm$ SD. For the comparison study, we used analysis of variance and Student’s $t$ test. Fisher’s exact test was used for proportion analysis. Values of $P<0.05$ are reported to be significant. A commercially available software package was used (Statview 5.0, Abacus Concepts).

Results
ROI Analysis
The patients were categorized into 2 groups based on the preoperative status of CVR measured by the ROI ap-
approach: normal CVR (rCVR ≥10%, n=26) or reduced CVR (rCVR <10%, n=15). Ipsilateral CBF in the reduced CVR group (36.5±7.5 mL·100 g⁻¹·min⁻¹) was significantly lower than that in the control group (45.5±5.9 mL·100 g⁻¹·min⁻¹, n=10) (P=0.022), but ipsilateral CBF in the normal CVR group (41.7±8.3 mL·100 g⁻¹·min⁻¹) was not. In addition, all 4 patients who demonstrated postoperative hyperperfusion belonged to the reduced CVR group (Figure 1). Therefore, the analysis was applied mainly to these 15 patients with reduced CVR.

**Visualization of CBF and CVR by 3D-SSP**

In the absolute value study, the extracted 3D-SSP data of resting CBF and acetazolamide-challenge CBF could be viewed from the right, left, superior, inferior, anterior, posterior, and 2 medial aspects of the brain (Figure 2, first and second rows). 3D-SSP also demonstrated surface maps of CVR on a pixel-by-pixel basis (Figure 2, third row). Visual-

---

Figure 1. Original SPECT transaxial slices of a patient with right ICA stenosis. Top, Preoperative resting SPECT. Severe hypoperfusion is seen in the right ICA territory. Middle, Preoperative acetazolamide (ACZ)-challenge SPECT. Very little CBF response to acetazolamide is seen in the same territory. Bottom, SPECT on the first postoperative day demonstrates hyperperfusion in the right ICA territory.

Figure 2. 3D-SSP images of CBF SPECT data of the patient in Figure 1. Right lateral (R. LAT), left lateral (L. LAT), superior (SUP), inferior (INF), anterior (ANT), posterior (POST), right medial (R. MED), and left medial (L. MED) views. Rest indicates preoperative 3D-SSP of resting CBF. Severe hypoperfusion is seen in the right ICA territory. ACZ indicates preoperative 3D-SSP of acetazolamide-challenge SPECT. Very little CBF response to acetazolamide is seen in the same territory. CVR indicates 3D-SSP of CVR. Intracerebral steal is easily recognized as black pixels. CBF reduction indicates 3D-SSP of percent reduction in preoperative CBF. Post-CEA indicates 3D-SSP of CBF percent increase 1 day after CEA. Hyperperfusion is easily recognized as white pixels. Three rainbows display ranges of CBF for the first and second rows, CVR for the third row, CBF decrease for the fourth row, and CBF increase for the fifth row.
ization of the CVR could be modified by changing a range of the color scale to make visual interpretation easier. For example, if a cutoff value is 0% as in Figure 2 (third row) and Figure 3 (middle 3 columns), a region of intracerebral steal is easily recognized as black pixels.

**Relationship Between Preoperative CBF Decrease and Hyperperfusion After CEA**

By 3D-SSP analysis of absolute value, patients in the reduced CVR group detected by the ROI method were further categorized into 2 groups based on the severity of the preoperative CBF decrease compared with the control database: type I (ipsilateral CBF decrease <20%, n=8) and type II (ipsilateral CBF decrease ≥20%, n=7) (Figure 3). In type II, some patients demonstrated symmetric CBF reduction (Figure 3, second row), and others demonstrated asymmetric CBF reduction (Figure 2, fourth row, and Figure 3, third and fourth rows). Type N (bilateral CBF decrease <20%) is a typical CBF pattern of patients in the normal CVR group (Figure 3, fifth row).

No patient exhibited postoperative intracerebral hemorrhage. In 4 patients, however, postoperative ipsilateral hyperperfusion (CBF increase ≥100%) was clearly observed on 3D-SSP of percent increase 1 day after CEA, although postoperative CT scans were normal. There was no significant difference in mean systolic blood pressure during SPECT measurement between patients with hyperperfusion (137±18 mm Hg, n=4) and those without hyperperfusion (131±16 mm Hg, n=11). Hyperperfusion was easily recognized as white pixels by setting the range of the color scale from 50% to 100% (Figure 2, fifth row, and Figure 3, right 3 columns). Incidence of hyperperfusion was significantly higher in type II (4 of 7, 57%) than in type I (0 of 8, 0%) (P=0.026) (the Table, middle). Sensitivity was 100%; specificity was 73%. All patients with hyperperfusion demonstrated an asymmetric pattern of CBF reduction. It is noteworthy that even patients with intracerebral steal did not experience postoperative hyperperfusion if the preoperative CBF reduction was <20% (Figure 3, first and second rows).

On 3D-SSP images with thalamic normalization, by setting a Z score of 2 as the cutoff value, an asymmetric pattern of hyperperfusion was recognized. Hyperperfusion occurred only in asymmetric type II. Three rainbows display ranges of CBF decrease and CVR and CBF increase.

![Figure 3](http://stroke.ahajournals.org/)

**Figure 3.** Relationship between pattern of preoperative CBF reduction and postoperative hyperperfusion. To make visual interpretation easier, the side of carotid stenosis is converted to the right in all patients. Left 3 columns, 3D-SSP of CBF percent decrease. Middle 3 columns, 3D-SSP of CVR. Right 3 columns, 3D-SSP of CBF percent increase 1 day after CEA. First row shows type I; second row, type II (symmetric type); third and fourth rows, type II (asymmetric type); and fifth row, type N. See text for details. Note that hyperperfusion occurred only in asymmetric type II. Three rainbows display ranges of CBF decrease and CVR and CBF increase.

### Relationship Between CBF Reduction and Hyperperfusion After CEA

<table>
<thead>
<tr>
<th>Study Type</th>
<th>Hyperperfusion</th>
<th>Fisher’s test</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Incidence, %</td>
<td>P</td>
</tr>
<tr>
<td>ROI</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CBF decrease (percent reduction)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>&lt;20%</td>
<td>0  5  0</td>
<td>NS</td>
</tr>
<tr>
<td>≥20%</td>
<td>4  6  40</td>
<td>0.15</td>
</tr>
<tr>
<td>3D-SSP</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CBF decrease (percent reduction)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Type I (&lt;20%)</td>
<td>0  8  0</td>
<td>0.026</td>
</tr>
<tr>
<td>Type II (≥20%)</td>
<td>4  3  57</td>
<td></td>
</tr>
<tr>
<td>CBF decrease (Z score)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Type A (Z score ≤2)</td>
<td>0  10  0</td>
<td>0.0037</td>
</tr>
<tr>
<td>Type B (Z score &gt;2)</td>
<td>4  1  80</td>
<td></td>
</tr>
</tbody>
</table>
CBF decrease was recognized more clearly than on 3D-SSP images of percent reduction without normalization (Figure 4). With the use of normalization, the appearance of significant contralateral CBF decrease disappeared. In all patients, the contralateral Z score was $\leq 2$. Therefore, the patients were categorized into 2 groups: type A (ipsilateral Z score $\leq 2$, $n=10$) and type B (ipsilateral Z score $> 2$, $n=5$). Type A consisted of patients who belonged to types I and II with symmetric CBF reduction on 3D-SSP without normalization. Type B consisted of patients who belonged to type II with asymmetric CBF reduction on 3D-SSP without normalization. With normalization, the predictive value of CBF reduction for postoperative hyperperfusion was improved. Incidence of hyperperfusion was significantly higher in type B (4 of 5, 80%) than in type A (0 of 10, 0%) ($P=0.0037$) (the Table, bottom). Sensitivity was 100%; specificity was 91%. Even the final patient in type B demonstrated a CBF increase of $\geq 50\%$.

Discussion
In the present study, patterns of CBF abnormalities in carotid stenosis were investigated by 3D-SSP. This technique originally used normalization for data analysis. In addition to analysis with normalization, however, we used absolute values of CBF without normalization because it is essential to obtain the absolute values for calculation of CVR and postoperative CBF increase. The CVR to CO$_2$ or acetazolamide has been proposed as a test for cerebral hemodynamic reserve. In these studies, vasoreactivity was evaluated by quantitative CBF measurement. Conventional qualitative techniques are not appropriate for these kinds of analysis because they may incorrectly identify the ipsilateral cerebral hemodynamics as significantly compromised when the CBF increase after acetazolamide challenge is relatively higher in the contralateral than ipsilateral side.

The template used in 3D-SSP analysis was developed specifically for the reference to the Talairach 1988 atlas. The template precisely represents the original shape because it was matched initially to the Talairach atlas through 400 identifiable landmarks. This will guarantee that the stereotactic coordinates in 3D-SSP analysis can be cross-referenced to the Talairach atlas for accurate signal localization. The current template was created by averaging a large number of normal [18F]fluorodeoxyglucose (FDG) PET data. The similarity between FDG and blood flow images permits the use of the FDG template for blood flow image analysis.

In the present study, strict statistical inference was not made on statistical maps because the purpose of this mapping analysis was to demonstrate the extent and pattern of regional CBF abnormalities. 3D-SSP clearly demonstrated percent decrease in CBF, impaired CVR, and postoperative percent increase in CBF on a pixel-by-pixel basis. By setting an appropriate cutoff value for display, 3D-SSP images allow simple recognition of these abnormalities, which is likely to increase the diagnostic accuracy. In addition, 3D-SSP was less affected by the atrophy that is often seen in the brain of patients with ischemic cerebrovascular disease. Furthermore, 3D-SSP is fully automated and does not require interference by the user. It seemed evident from these findings that abnormal cerebral circulation was more easily
recognizable by this method compared with the conventional slice-based study. This is especially helpful when the reader is not experienced.

Hyperperfusion, which is defined as a CBF increase of $\geq 100\%$, was reported to be a significant risk factor for intracerebral hemorrhage. Therefore, detection of hyperperfusion after CEA is important for prevention by starting strict control of blood pressure. Previous studies had suggested that patients with preoperative hemodynamic failure run a definite risk for hyperperfusion syndrome. In the present study, we again found that postoperative hyperperfusion was seen only in the reduced CVR group detected by ROI approach. However, it is noteworthy that even intracerebral steal did not necessarily result in hyperperfusion after CEA if the preoperative CBF reduction was not severe. It would be very convenient if a certain degree of baseline CBF reduction itself could identify patients at risk for hyperperfusion because it might enable omission of acetazolamide-challenge SPECT.

According to the pattern of preoperative percent reduction in CBF, we categorized the reduced CVR group into 2 subgroups: type I and type II. A significant CBF increase on the first postoperative day was seen only in type II but not in type I, and this difference was statistically significant on 3D-SSP analysis but not on ROI analysis. The 3D-SSP analysis demonstrated higher a predictive value and higher specificity for hyperperfusion than ROI analysis.

However, only 20% reduction in absolute CBF values is not enough to predict hyperperfusion because all patients with hyperperfusion demonstrated asymmetric pattern of CBF reduction. It is well known that there is a wide variation in global CBF across subjects. This variation could cause not only an appearance of ipsilateral CBF reduction but also an increase in global CBF across subjects. This variation could cause not only an appearance of ipsilateral CBF reduction but also an increase in global CBF across subjects. This variation could cause not only an appearance of ipsilateral CBF reduction but also an increase in global CBF across subjects. This variation could cause not only an appearance of ipsilateral CBF reduction but also an increase in global CBF across subjects.


Conclusions

The present study suggests that 3D-SSP and normal control database provide a reliable and objective assessment of cortical CBF abnormalities. Severe reduction in CBF enables us to further distinguish patients at risk among those suspected to be at risk for hyperperfusion because of CVR impairment. Furthermore, 3D-SSP with normalization demonstrates a higher predictive value and higher specificity for postoperative hyperperfusion compared with 3D-SSP without normalization. This approach seems to be applicable to other cerebrovascular diseases, such as ICA occlusion.

Acknowledgments

We want to express our gratitude to all members of SPECT technical staff: Yukihito Otani, Toshiyuki Yamaguchi, Masaru Ishihara, Kenzo Sawada, Kazuyoshi Kobayashi, Shigeo Hattori, and Yasuhiro Irie.

References


Prediction of Hyperperfusion After Carotid Endarterectomy by Brain SPECT Analysis With Semiquantitative Statistical Mapping Method
Kohkichi Hosoda, Tetsuro Kawaguchi, Kazunari Ishii, Satoshi Minoshima, Yuji Shibata, Masaki Iwakura, Shigeo Ishiguro and Eiji Kohmura

*Stroke*. 2003;34:1187-1193; originally published online April 17, 2003;
doi: 10.1161/01.STR.0000068781.31429.BE

*Stroke* is published by the American Heart Association, 7272 Greenville Avenue, Dallas, TX 75231
Copyright © 2003 American Heart Association, Inc. All rights reserved.
Print ISSN: 0039-2499. Online ISSN: 1524-4628

The online version of this article, along with updated information and services, is located on the World Wide Web at:
http://stroke.ahajournals.org/content/34/5/1187

**Permissions:** Requests for permissions to reproduce figures, tables, or portions of articles originally published in *Stroke* can be obtained via RightsLink, a service of the Copyright Clearance Center, not the Editorial Office. Once the online version of the published article for which permission is being requested is located, click Request Permissions in the middle column of the Web page under Services. Further information about this process is available in the Permissions and Rights Question and Answer document.

**Reprints:** Information about reprints can be found online at:
http://www.lww.com/reprints

**Subscriptions:** Information about subscribing to *Stroke* is online at:
http://stroke.ahajournals.org//subscriptions/