Reproducibility of Quantitative CT Brain Perfusion Measurements in Patients with Symptomatic Unilateral Carotid Artery Stenosis

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BACKGROUND AND PURPOSE: To establish intraobserver and interobserver variability for regional measurement of CT brain perfusion (CTP) and to determine whether reproducibility can be improved by calculating perfusion ratios.

MATERIALS AND METHODS: CTP images were acquired in 20 patients with unilateral symptomatic carotid artery stenosis (CAS). We manually drew regions of interest (ROIs) in the cortical flow territories of the anterior (ACA), middle (MCA), and posterior (PCA) cerebral arteries and the basal ganglia in each hemisphere; recorded cerebral blood volume (CBV), cerebral blood flow (CBF), and mean transit time (MTT); and calculated ratios of perfusion values between symptomatic and asymptomatic hemisphere. We assessed intraobserver and interobserver variability by performing a Bland-Altman analysis of the relative differences between 2 observations and calculated SDs of relative differences (SDDrel) as a measure of reproducibility. We used an F test to assess significance of differences between SDDrel of absolute CTP values and CTP ratios, and the Levine test to compare the 4 perfusion territories.

RESULTS: MTT was the most reproducible parameter (SDDrel ≤ 10%). Intraobserver and interobserver variability were higher for absolute CTP values compared with CTP ratios for CBV (16%–17% versus 11%–16%) and CBF (18% versus 10%–13%) but not for MTT (5%–9%). Reproducibility was best in the MCA territory: SDDrel was ≤11% for perfusion ratios of all 3 parameters.

CONCLUSION: MTT is the most reproducible CTP parameter in patients with unilateral symptomatic CAS. Measurement variability in CBV and CBF can be improved if CTP ratios instead of CTP values are used. The MCA territory shows the least measurement variability.

CT perfusion (CTP) is a widely available diagnostic tool that provides quick and minimally invasive assessment of brain perfusion.1-2 Its main current use is to identify patients with acute stroke who may benefit from thrombolysis by discriminating penumbra (tissue with reduced perfusion but potentially salvageable) from irreversible ischemia. CTP has also been used for other kinds of cerebrovascular disease: to predict delayed ischemia in patients with subarachnoid hemorrhage,3 to measure the reserve capacity in patients with carotid occlusive disease using acetazolamide,4 and to evaluate the effect of endovascular treatment.5 Analysis of CTP can be based on visual interpretation of perfusion maps or on quantitative perfusion measurements. Visual interpretation relies on the analysis of color-coded perfusion maps, where regions with reduced perfusion can be detected by visual comparison with the surrounding tissue or the contralateral hemisphere.6,7 Quantitative analysis can be performed using a pixel-by-pixel analysis or by measuring average values in regions of interest (ROIs) in various anatomic perfusion territories of the brain. The pixel-based analysis is applied in acute stroke, where a threshold value has been suggested to distinguish between infarcted and potentially salvageable tissue.8 Regional analysis using ROIs can rely on manual tracing of anatomic regions9,10 or on placing circular ROIs.11,12 ROIs can be mirrored to compare the affected to the nonaffected hemisphere.

Quantitative measurements are complicated by the large variability of absolute perfusion values found in normal subjects and clinical patients.13 This variability makes the discrimination between normal and reduced perfusion difficult. Several authors have therefore suggested using relative perfusion data based on the ratio between measurements in the symptomatic and asymptomatic hemisphere.14-16 This method takes advantage of the basic symmetry of the brain and may correct for interpatient variability of absolute perfusion values.

CTP is becoming a widely used tool for analyzing brain perfusion,17,18 even though measurement variability (precision) is in the range of 15%–30% when ROI-based techniques are used.19 This is due to observer-dependent postprocessing steps, which can strongly influence absolute perfusion values.20 Several of these observer-dependent steps are likely to affect both hemispheres equally. The goal of our study was to examine whether variability of ROI-based measurements could be reduced when perfusion ratios between the symptomatic and asymptomatic hemispheres are used instead of absolute perfusion values. A secondary goal was to study whether the measurement variability differed between the various cerebral flow territories in patients with symptomatic unilateral carotid artery stenosis.

Materials and Methods

Patient Group

Between September 2003 and May 2005, CTP imaging was performed in 27 patients with symptomatic carotid artery stenosis (CAS). Patients were known to have more than 50% CAS based on sonography...
results were referred to our department for endovascular treat-
ment (carotid artery stent placement) or carotid endarterectomy
(CEA) as part of the International Carotid Stent Placement Study
(ICSS) trial (http://www.cavatas.com). At our institution, CTP mea-
surements were added to the ICSS protocol to study the effect of the
intervention on brain perfusion. Our institutional review board ap-
proved the study, and all patients had signed informed consent.

Exclusion criteria were the presence of 1) >50% contralateral ste-
nosis (n = 2), 2) motion artifacts (n = 2), or 3) manifest large terri-
torial infarct (n = 3). Consequently, we could evaluate 20 scans from
20 patients. Patient characteristics are shown in Table 1.

CTP Scanning

The CTP scans were acquired on a 16-channel scanner (MX 8000 IDT
or Brilliance-16; Philips Medical Systems, Cleveland, Ohio). The level
of the scan was set at the basilar ganglia, just above the level of the circle
of Willis, with the scan angle parallel to the orbitomeatal line to pre-
vent incorporation of the eye lenses. We used a collimation of 8 × 3
mm with a cycle time of 1 second and acquired 40 datasets during 40
seconds of scanning. For a compromise between patient dose and
signal-to-noise ratio, a tube voltage of 90 kVp in combination with
150 mAs22 was used. The CT dose index-volume for a single scan was
928 mAsf22 was used. The CT dose index-volume for a single scan was
seconds of scanning. For a compromise between patient dose and
mm with a cycle time of 1 second and acquired 40 datasets during 40

Table 1: Patient characteristics (n = 20)

<table>
<thead>
<tr>
<th>Patient age (SD)</th>
<th>68 ± 11.1 years (range, 48-84 years)</th>
</tr>
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<tbody>
<tr>
<td>Male/female</td>
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<td>Presenting event</td>
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<td>Amaurosis fugax</td>
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<td>Transient ischemic attack</td>
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<td>Carotid arteries</td>
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<tr>
<td>Symptomatic side, left: right</td>
<td>10: 10</td>
</tr>
<tr>
<td>Mean stenosis ± SD, symptomatic side</td>
<td>88 ± 13</td>
</tr>
<tr>
<td>Mean stenosis ± SD, asymptomatic side</td>
<td>11 ± 17</td>
</tr>
<tr>
<td>Cerebral damage (noncontrast CT)</td>
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<tr>
<td>No infarct</td>
<td>11</td>
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<td>Small infarct (small branch area)*</td>
<td>5</td>
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<tr>
<td>Medium size infarct (major branch area)*</td>
<td>4</td>
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</table>

*Infarct size was classified according to Lodder et al.36

Measurement of Absolute CTP Values and Relative CTP
Ratios

CTP maps were calculated using CTP prototype software (Philips
Medical Systems, Best, the Netherlands). The software first performs
a motion correction and then uses an anisotropic, edge-preserving
spatial filter to reduce image noise. The resulting spatially aligned and
noise-reduced dataset is further processed to obtain CTP values for
each voxel in the dataset.

CTP analysis is based on temporal changes in signal intensity dur-
ing the first pass of a bolus of an iodinated contrast agent. Changes in
CT numbers in a voxel over baseline (precontrast CT numbers) are
linearly related to the concentration of the contrast agent in that
voxel. Thus, a time concentration curve can be calculated for each
voxel. The software used relies on the central volume principle to
calculate perfusion values from the time concentration curve for each
voxel.23

The first step in the evaluation process is the manual selection of
the arterial input function (AIF) and venous output function (VOF).
For that purpose, the user selects oval ROIs that incorporate the an-
terior cerebral artery (for AIF) and superior sagittal sinus (for VOF),
after which the software then automatically identifies appropriate refer-
vexels for deriving AIF and VOF.

For each voxel, the cerebral blood volume (CBV) is calculated
as the ratio of the area under the time-concentration curve (AUC)
of this voxel to the AUC of the first passage through an artery. A
correction factor, H, is applied to account for the difference in the
hematocrit in small versus large vessels; CBV = H × AUCtissue/AUCAIF. Therefore, an absolute measurement of the AIF is re-
quired; AIF should be measured in an arterial pixel devoid of par-
tial volume effect. Because arterial pixels without partial volume
effect are not available at this level, and because the AUC of the
first passage of contrast agent through a vein is equal to the AUC of
an artery when the blood-brain barrier is intact, usually the supe-
rior sagittal sinus is preferred as reference; CBV = H × AUCtissue/AUCVOF. The mean transit time (MTT), the average time taken by
the blood to cross the capillary network, is calculated by a decon-
volution operation from the time concentration curve of a partic-
ular voxel and the AIF,24 whereby the MTT is related to the differ-
ence between the width of the tissue curve and the width of the AIF.
Cerebral blood flow (CBF) for each voxel is finally calculated
according to the formula: CBF = CBV/MTT.25 A threshold value of
85 HU was used for exclusion of vascular pixels.

Thereafter, free-form ROIs were drawn to outline various cerebral
flow territories on each of the 2 slabs, separately for each hemisphere.
The territories were selected according to the maps of Damasio,26
assuring that the ROIs were securely within the margin of the territory
that belonged to a certain artery and excluded possible watershed
areas (Fig 1). We included the cortical flow territory of the anterior
cerebral artery (ACA), middle cerebral artery (MCA), posterior cere-
bral artery (PCA), and the basal ganglia (BG), which contained both
deep ACA and deep MCA territories. ROIs were chosen to include
mainly gray matter and as little subcortical white matter as possible.

Given 4 territories per hemisphere and 2 slabs per patient, 16 ROIs
per patient were available. The average values for CBV, CBF, and
MTT within each ROI were recorded. We then calculated CTP ratios
by dividing the CTP values in flow territories in the symptomatic
hemisphere by the CTP values in the corresponding asymptomatic
hemisphere.
Data Analysis
Measurements were acquired by 2 observers (A and B) and repeated after 1 week by observer A. For this purpose, all steps from loading of the 2 × 40 slabs to drawing and evaluating the ROIs in the various perfusion territories were repeated.

For assessment of intraobserver and interobserver variability, we determined the relative differences between 2 observations and calculated the mean relative differences (mean bias) and the SD of these differences (SDD_{rel}) according to the principle of Bland and Altman. We also evaluated whether there was a difference in variability between the symptomatic and asymptomatic hemispheres using a Student t test. A test result with a P value less than .05 was considered statistically significant.

Results

Patient Characteristics
The mean and SD for the absolute CT perfusion values (CBF, CBV, and MTT) and relative CT perfusion ratios are shown in Table 2.

Intraobserver and Interobserver Variability
When evaluating the perfusion data from all territories together, analysis of intraobserver variability revealed a mean bias that varied between −1.1% and 2.2%. This range was slightly larger, between −4.4% and 2.7%, for interobserver variability. The relative SDs of the differences (SDD_{rel}) found for intraobserver and interobserver variability are given in Table 3.

Intraobserver and interobserver variability for absolute values separated for both hemispheres is shown in Table 4. Because no systematic difference was found, for further analysis, data from each hemisphere were pooled together. Intraobserver and interobserver variability was significantly lower for MTT than for CBF or CBV, independent of whether absolute CTP values or CTP ratios were considered. Intraobserver and interobserver variability for MTT values and MTT ratios were not substantially different. However, interobserver variability for CBF and CBV ratios was significantly lower than for absolute CBF and CBV values. Interobserver variability for CBF ratios was also significantly lower than for absolute CBF values, but no significant improvement of interobserver variability could be shown if CBV ratios were used instead of absolute CBV values.

Bland-Altman plots that relate relative differences between observations to the various absolute perfusion parameters are given in Fig 2 (interobserver variability). The figures demonstrate that the relative differences were independent of the magnitude of the absolute perfusion values.

Dependence of Observer Variability on Flow Territories
Intraobserver and interobserver variability for absolute MTT values was less than 10% for all territories, and no significant differences between the different territories was seen (Table 5). Absolute perfusion values ranged from 11% to 18% for CBV and from 15% to 19% for CBF.

The introduction of ratios between CTP values in the symptomatic and asymptomatic hemisphere did not substantially change variability for MTT but mostly reduced variability for CBV and CBF. For intraobserver variability, the use of ratios improved reproducibility in all territories, but the difference between the 4 flow territories was significant for CBF only (P < .05). The variability was ≤8% for CBV, CBF, and MTT in the MCA and BG territory. For interobserver variabil-

Table 2: Perfusion characteristics

<table>
<thead>
<tr>
<th>Territory</th>
<th>CBV (ml/100 g)</th>
<th>CBF (ml/100 g/min)</th>
<th>MTT (seconds)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CT perfusion values—symptomatic hemisphere</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ACA</td>
<td>4.1 ± 1.4</td>
<td>50.4 ± 18.8</td>
<td>5.0 ± 0.7</td>
</tr>
<tr>
<td>MCA</td>
<td>5.3 ± 1.4</td>
<td>56.1 ± 17.8</td>
<td>5.9 ± 1.3</td>
</tr>
<tr>
<td>Basal ganglia</td>
<td>4.3 ± 1.3</td>
<td>49.3 ± 17.6</td>
<td>5.5 ± 1.2</td>
</tr>
<tr>
<td>PCA</td>
<td>4.9 ± 1.4</td>
<td>50.9 ± 15.4</td>
<td>5.8 ± 0.7</td>
</tr>
<tr>
<td>CT perfusion values—asymptomatic hemisphere</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ACA</td>
<td>3.9 ± 1.3</td>
<td>50.9 ± 18.1</td>
<td>4.7 ± 0.7</td>
</tr>
<tr>
<td>MCA</td>
<td>5.3 ± 1.6</td>
<td>70.7 ± 22.3</td>
<td>4.5 ± 0.6</td>
</tr>
<tr>
<td>Basal ganglia</td>
<td>4.3 ± 1.3</td>
<td>57.2 ± 20.5</td>
<td>4.6 ± 0.9</td>
</tr>
<tr>
<td>PCA</td>
<td>5.0 ± 1.6</td>
<td>53.7 ± 16.9</td>
<td>5.6 ± 0.9</td>
</tr>
<tr>
<td>CT perfusion ratios (symptomatic/asymptomatic side)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ACA</td>
<td>1.05 ± 0.14</td>
<td>1.01 ± 0.13</td>
<td>1.06 ± 0.10</td>
</tr>
<tr>
<td>MCA</td>
<td>1.01 ± 0.12</td>
<td>0.81 ± 0.14</td>
<td>1.28 ± 0.17</td>
</tr>
<tr>
<td>Basal ganglia</td>
<td>1.03 ± 0.09</td>
<td>0.88 ± 0.08</td>
<td>1.18 ± 0.12</td>
</tr>
<tr>
<td>PCA</td>
<td>1.05 ± 0.22</td>
<td>1.00 ± 0.17</td>
<td>1.06 ± 0.13</td>
</tr>
</tbody>
</table>

Note—CBV indicates cerebral blood volume; CBF, cerebral blood flow; MTT, mean transit time; ACA, anterior cerebral artery; MCA, middle cerebral artery; PCA, posterior cerebral artery. Perfusion characteristics in our study group of 20 patients with symptomatic carotid artery stenosis. CT perfusion values and ratios (mean ± SD) are given for the various vascular flow territories. Note that numbers were calculated from mean values of 3 analyses, for absolute perfusion values, 80 data points (20 patients × 2 slabs × 2 hemispheres) were used for each territory. For CT perfusion ratios, 40 data points (20 patients × 2 slabs) were used for each territory.

Fig 1. Analysis of manual outlined ROIs according to territorial division of Damasio.3,26 1, ACA territory; 2, MCA territory; 3, basal ganglia; 4, PCA territory.
between gray and white matter, whereas there are major dif-
ferences in CBV and CBF between these 2 tissue types.

It is known that there is almost no difference in MTT
calculated for CT perfusion values separately for the sym-


tomy, improvement was seen in all territories except the PCA
territory. The difference between the 4 territories was signifi-
cant for all parameters and was best in the MCA territory
(≤11%).

Discussion

This study in patients with unilateral symptomatic carotid
disease reveals 3 major findings: 1) the MTT is the most repro-
ducible parameter for regional measurements of CTP, 2) the
use of CBV and CBF ratios results in better reproducibility
compared with absolute CBV and CBF values for this patient
group, and 3) when separate flow territories are analyzed in
such a patient group, the best reproducibility is observed in
the MCA territory.

Our finding that MTT is the most reproducible parameter
is in concordance with literature reports. This may be ex-
plained by the fact that manual outlining of an ROI will inev-
itably introduce variability in the amount of included white
matter. It is known that there is almost no difference in MTT
between gray and white matter, whereas there are major dif-
ferences in CBV and CBF between these 2 tissue types.

The fact that MTT showed less than 10% variability for both
absolute and relative values indicates that absolute and relative
values are robust measures for use in clinical practice. This is
confirmed by a recent publication by Wintermark et al, who
showed that both relative and absolute MTT can be used as
threshold for discrimination between final infarct size and
penumbra.

Perfusion techniques such as positron-emission tomogra-
phy and single-photon emission CT use CBF as the main per-
fusion parameter. MTT, which is defined as CBV/CBF, can be
measured by using CT or MR imaging but has thus far been
used as a nonspecific indicator of a perfusion disturbance.
However, the inverse of this ratio (CBF/CBV) was shown to be
strongly related to cerebral perfusion pressure (CPP) and has
even been suggested as a surrogate for CPP, a parameter that
thus far can only be measured invasively. The CPP is respon-
sible for maintenance of sufficient perfusion pressure in case
of ischemia by means of the autoregulation mechanism. Al-
though CBF is used mostly in clinical practice, the regional
CBF is an insensitive indicator of the severity of occlusive ce-
brovascular disease because it does not change with small
changes of CPP. In addition, clinical studies have shown that
the ratio of CBF/CBV provides better information than either
of these parameters alone. MTT is easily obtained from
CTP studies and has the lowest measurement variability.
Given its close relation to CPP, it may become an important
parameter for evaluating perfusion disturbances in clinical
practice.

Our second result indicates that intraobserver and interob-
server variability for absolute CTP values can be signifi-
cantly improved when CTP ratios between measurements in the
symptomatic and asymptomatic hemisphere are used in pa-

cents with unilateral stenoses. This can be explained by tech-
nical reasons. Calculation of ratios eliminates variations
caused by the choice of the AIF and VOF. In addition, it may
also reduce the variability in the proportion of gray and white
matter that is included in the regional analysis; if the ROIs
drawn in both hemispheres are symmetrically placed, the rel-
ative amounts of gray and white matter should be similar.
Calculating ratios will therefore eliminate part of the resulting
measurement variability.

The third result indicated least variability in the MCA ter-

| Table 3: Comparison of intraobserver and interobserver variability for CT perfusion values and CT perfusion ratios |
|-----------------|-----------------|-----------------|
| Variability     | CBV             | CBF             | MTT             |
| SDD_{rel} (%)   |                 |                 |                 |
| Intraobserver   |                 |                 |                 |
| CT perfusion values | 16% (−62%, 54%) | 18% (−59%, 63%) | 5% (−35%, 21%) |
| CT perfusion ratios | 11% (−51%, 37%) | 10% (−42%, 33%) | 6% (−30%, 23%) |
| P*              | .000            | .000            | .048            |
| Interobserver   |                 |                 |                 |
| CT perfusion values | 17% (−78%, 63%) | 18% (−67%, 55%) | 9% (−30%, 34%) |
| CT perfusion ratios | 16% (−44%, 71%) | 13% (−49%, 51%) | 9% (−36%, 30%) |
| P*              | .135            | .000            | .295            |

Note:—SDD_{rel} indicates SDs of relative differences; CBV, cerebral blood volume; CBF, cerebral blood flow; MTT, mean transit time. Pooled data from all flow territories. Variability is expressed as the SD of the relative differences for each pair of observations (SDD_{rel}) and is thus expressed as a percentage. The range of relative differences is given in parentheses.

* F test.

| Table 4: Comparison of intraobserver and interobserver variability for CT perfusion values separately for the symptomatic and asymptomatic hemisphere |
|-----------------|-----------------|-----------------|
| Variability     | Symptomatic Side | Asymptomatic Side |
| SDD_{rel} (%)   | CBV             | CBF             | MTT             |
|                 |                 |                 |                 |
| Intraobserver   |                 |                 |                 |
| ACA             | 22              | 22              | 5               |
| MCA             | 18              | 20              | 4               |
| Basal ganglia   | 18              | 20              | 4               |
| PCA             | 20              | 22              | 8               |
| Interobserver   |                 |                 |                 |
| ACA             | 15              | 19              | 9               |
| MCA             | 12              | 17              | 6               |
| Basal ganglia   | 15              | 15              | 8               |
| PCA             | 22              | 16              | 11              |

Note:—SDD_{rel} indicates SDs of relative differences; CBV, cerebral blood volume; CBF, cerebral blood flow; MTT, mean transit time; ACA, anterior cerebral artery; MCA, middle cerebral artery; PCA, posterior cerebral artery.

* Difference between asymptomatic and symptomatic hemisphere significantly different (P < .05).
medial extent of these territories is well defined by the interlobar fissure, the lateral extent is more difficult to define. This may result in variability in the amount of white matter that is included with resultant higher interobserver and intraobserver variability (Fig 1). Finally, intraparenchymal vessels such as distal ACA, MCA, and PCA branches or venous structures can lead to very high measured cerebral blood volumes when these are mistaken for parenchyma. Although we set a threshold value for removing these structures, the absolute value of CBV and CBF is influenced by AIF and VOF selection, which can lead to observer dependency in the extent of the removal of vascular structures.

In summary, we found that in the most optimized situation a measurement variability of 5%–10% can be achieved. In this case, we used the relative perfusion values in the MCA territory. Normal left-right differences are known to vary ± 10%, whereas intrapatient differences for repeated measurements are in the range of 10%–20%. Therefore, measurement variability between 2 observers should not be more than 10%. This implies that measurement of true perfusion abnormalities requires intrapatient comparison using relative values. In our hospital, no clinical decisions are yet based on quantitative perfusion data, but further research will have to reveal whether the use of CTP ratios could improve clinical care.

Our study has some limitations. First, the presence of a carotid artery stenosis influences the AIF and thereby the measured absolute MTT and CBF. However, because we used relative differences for further analysis, the absolute height of perfusion values is no longer influencing the intraobserver and interobserver variability. A second difficulty in choice of AIF selection in the ACA is the assumption that this input function is equal over all brain voxels, which is probably not true in these patients. However, the search for a method to define the localized AIF is still problematic and is currently under study. In addition, the determination of CBV carries uncertainty, because the VOF is also generalized for all voxels. However, it is expected that the AUC of the VOF is unaffected by local pathology. In addition, these effects are expected to be equally distributed over voxels in both hemispheres and all territories; the use of relative data will largely eliminate these effects. Third, we have excluded patients with large territorial infarcts from further analysis. We have done so because perfusion measures are clinically more interesting for tissues with reduced perfusion and less so for manifest (chronic) infarcts. In the latter case, the abnormality is already immediately evident from noncontrast CT, and CTP has little added value.
In conclusion, this study shows that when performing CTP studies, MTT is the most reproducible parameter independent of flow territory or the use of absolute values or perfusion ratios. Substantial intraobserver and interobserver variability ranging between 16% and 21% can be expected if regional measurements of absolute CBV and CBF values are performed. In clinical practice, such quantitative regional analysis of CBV and CBF values should therefore be interpreted with caution. Variability can be reduced by using the ratio between symptomatic and asymptomatic hemispheres. A variation on the order of ±10% can be expected for CBV and CBF ratios in the MCA territory, which makes such ratios more suitable for clinical application. MTT measurements show a similar low variability, independent of flow territory or whether absolute or relative values are used.

References


Table 5. Comparison of intraobserver and interobserver variability (SDDrel) in the four flow territories

<table>
<thead>
<tr>
<th>Variability</th>
<th>CBV</th>
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<th>MTT</th>
<th>CBV ratio</th>
<th>CBF ratio</th>
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<td></td>
<td></td>
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<td>12 18 14 16</td>
<td>4 5 7 6</td>
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<tr>
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<td>5</td>
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<td>12 4</td>
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<td>7</td>
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<td>5 6 5</td>
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</tbody>
</table>

Note—SDDrel indicates SDs of relative differences, CBV, cerebral blood volume; CBF, cerebral blood flow, MTT, mean transit time; ACA, anterior cerebral artery; MCA, middle cerebral artery; PCA, posterior cerebral artery. The test of Levine for homogeneity of variance was used to check whether variability differed between flow territories. The least variability was commonly seen for the MCA territory. For CTP ratios, the largest variability was usually found for the PCA territory. *Test of Levine for homogeneity of variance.