Clinical and Radiological Correlates of Reduced Cerebral Blood Flow Measured Using Magnetic Resonance Imaging

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Background: Methods for determining cerebral blood flow (CBF) using bolus-tracking magnetic resonance imaging (MRI) have recently become available. Reduced apparent diffusion coefficient (ADC) values of brain tissue are associated with reductions in regional CBF in animal stroke models.

Objectives: To determine the clinical and radiological features of patients with severe reductions in CBF on MRI and to analyze the relationship between reduced CBF and ADCs in acute ischemic stroke.

Design: Case series.

Setting: Referral center.

Methods: We studied 17 patients with nonlacunar acute ischemic stroke in whom perfusion-weighted imaging (PWI) and diffusion-weighted imaging (DWI) were performed within 7 hours of symptom onset. A PWI-DWI mismatch of more than 20% was required. We compared patients with ischemic lesions that had CBF of less than 50% relative to the contralateral hemisphere with patients with lesions that had relative CBF greater than 50%. Characteristics analyzed included age, time to MRI, baseline National Institutes of Health Stroke Scale score, mean ADC, DWI and PWI lesion volumes, and 1-month Barthel Index score.

Results: Patients with low CBF (n = 5) had lower ADC values (median, 430 × 10−6 mm²/s vs 506 × 10−6 mm²/s; \( P = .04 \)), larger DWI volumes (median, 41.8 cm³ vs 14.5 cm³; \( P = .001 \)) and larger PWI lesions as defined by the mean transit time volume (median, 194.6 cm³ vs 69.3 cm³; \( P = .01 \)), and more severe baseline National Institutes of Health Stroke Scale scores (median, 15 vs 9; \( P = .02 \)).

Conclusion: Ischemic lesions with severe CBF reductions, measured using bolus-tracking MRI, are associated with lower mean ADCs, larger DWI and PWI volumes, and higher National Institutes of Health Stroke Scale scores.

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Although cerebral blood flow (CBF) has traditionally been measured using positron emission tomography, single-photon emission computed tomography, or xenon computed tomography, there is great interest in developing magnetic resonance imaging (MRI) methods to determine CBF in patients with acute ischemic stroke. Perfusion-weighted imaging (PWI) using MRI seems more attractive than traditional methods because of its widespread availability and its ability to be combined with other MRI techniques, such as diffusion-weighted imaging (DWI), magnetic resonance angiography, or magnetic resonance spectroscopy. Within minutes, an integrated MRI examination can provide information on the extent of cytotoxic edema on DWI, the changes in metabolites via magnetic resonance spectroscopy, and the state of the vasculature using magnetic resonance angiography. It is thought that the information provided by MRI will benefit clinical trial design and individual patient management.

Diffusion-weighted imaging assesses the mobility of water protons within brain parenchyma. Extensive animal and human experimental data show that diffusion of protons is restricted after ischemic stroke. This reduction of water movement is probably due to cytotoxic edema associated with energy failure caused by reductions in CBF. The apparent diffusion coefficient (ADC) is a quantitative parameter that reflects the degree of mobility of water within brain parenchyma. Experimental data by animal and human experimental data show that diffusion of protons is restricted after ischemic stroke. This reduction of water movement is probably due to cytotoxic edema associated with energy failure caused by reductions in CBF. The apparent diffusion coefficient (ADC) is a quantitative parameter that reflects the degree of mobility of water within brain parenchyma. Experimental data show an association between reductions in CBF and reductions in the ADC. A regional correspondence is found between areas with the most severe CBF reduction and areas with the...
PATIENTS AND METHODS

PATIENTS

We retrospectively identified patients with acute ischemic stroke entered into the Stanford Stroke Center database in whom DWI and PWI were obtained within 7 hours of symptom onset. Patients had to have an acute PWI lesion volume (defined as the MTT lesion, see the “Postprocessing of Perfusion Images” section) that was 20% larger than the volume of the acute DWI lesion. We excluded patients without a PWI-DWI mismatch because it is thought that these patients have spontaneous or treatment-induced reperfusion, and their PWI variables do not reflect values before reperfusion. Treatment with recombinant tissue plasminogen activator and enrollment in trials of neuroprotective agents vs placebo were allowed. The following clinical characteristics were recorded: age, NIHSS score, time from symptom onset to MRI, and functional outcome measured using the Barthel Index 1 month after stroke onset. Patients who died during the first month of follow-up were assigned a Barthel Index score of zero. The study was approved by the Stanford University institutional review board.

MAGNETIC RESONANCE IMAGING

Magnetic resonance imaging was performed using echo-planar imaging on a 1.5-T magnet (Signa; General Electric, Milwaukee, Wis). Multislice whole-brain DWI was performed using the following variables: 16 slices; repetition time, 8100 milliseconds; echo time, 110 milliseconds; slice thickness, 5 mm; gap, 2.5 mm; matrix, 128 × 128; and field of view, 24 cm. B values were 0 and 829 s/mm². Diffusion-weighted images were acquired in the x, y, and z directions. The x-, y-, and z-direction DWI scans were averaged to minimize hyperintensities due to anisotropic water diffusion. Echoplanar diffusion images were processed to generate average (trace) ADC maps using a computer program (MRVision; MRVision Co, Winchester, Mass).

Perfusion-weighted imaging was performed using dynamic susceptibility contrast-enhanced MRI. Gradient-echo, single-shot echoplanar imaging was used during injection of 20 mL of gadolinium (0.2 mmol/kg). Perfusion-weighted imaging acquisition values were repetition time, 2000 milliseconds; and echo time, 60 milliseconds, with 40 time points obtained over 12 slices. Other variables were the same as for DWI. The 12 PWI slices were obtained at the same level as the 12 central slices on the DWI scans. The raw images were transferred to a computer workstation (Sun Ultrasparc; Sun Microsystems, Palo Alto, Calif) for further analysis.

POSTPROCESSING OF PERFUSION IMAGES

Calculation of relative MTT, relative CBF, and relative CBV maps was performed using the model-independent NP-SVD method described by Ostergaard et al. The tissue concentration curve was deconvolved with the arterial input function using SVD. We determined the arterial input function by manually choosing 5 to 8 pixels over the MCA of the unaffected hemisphere. These pixels had to show an average ADC. Regions with less severe reductions in CBF show either normal ADC or only mild reductions. For example, Dijkhuizen et al reported that after a 1-hour middle cerebral artery (MCA) occlusion in rats, the ADC was severely reduced in areas where CBF was reduced to less than 20% of normal. A modest reduction or no reduction at all was observed in areas where CBF was reduced to 40% to 60% of normal.

Bolus-tracking MRI is the most commonly used method of obtaining PWI in clinical situations. After administration of a bolus of intravenous contrast, a series of multislice T2-weighted images covering the brain are acquired. The loss of signal intensity induced by gadolinium on the T2-weighted images is proportional to the concentration of intravenous contrast. Curves that reflect the concentration of gadolinium on a pixel-by-pixel basis are then analyzed to generate maps of CBF, cerebral blood volume (CBV), and mean transit time (MTT). Methods for quantitatively determining CBF using bolus-tracking MRI have been proposed based on the indicator dilution theory for nondiffusible tracers. These methods typically perform a deconvolution of the tissue concentration time curve with the arterial input function. Ostergaard et al proposed a nonparametric singular value decomposition (NP-SVD) approach. Although direct validation using positron emission tomography would be desirable, practical difficulties in obtaining hyperacute positron emission tomography studies and MRI make this difficult. We attempted to validate the CBF measurement indirectly by comparing CBF with other accepted and easily measured markers of stroke severity.

Clinical studies have shown a high correlation between the volumes of DWI and PWI lesions and clinical impairment scales such as the National Institutes of Health Stroke Scale (NIHSS). These volumes also seem to partially predict functional outcome. Because the primary consequence of a vessel obstruction due to clot is a reduction in CBF, we studied the impact of a severe reduction in CBF, measured using dynamic susceptibility contrast imaging, on the size of DWI and PWI lesions and on clinical stroke severity and functional outcome. We tested the hypothesis that in acute human ischemic stroke, low CBF values were associated with lower ADC values, larger DWI and PWI lesion volumes, and higher baseline NIHSS scores.

RESULTS

Twenty-nine patients were identified who underwent DWI and PWI within 7 hours of symptom onset between August 1, 1996, and August 1, 2000. Eight patients did not have a PWI-DWI mismatch. In 4 patients, poor image quality due to motion artifact or inadequate bolus delivery prevented analysis of the perfusion images. This left 17 patients for analysis. Median age was 73 years (25th-75th percentile, 65-79 years). Nine patients were women (53%). The clinical and radiological characteristics of the patients are given in the Table. The median baseline NIHSS score was 10 (25th-75th percentile, 8-15). Three
patients died within the first month of stroke onset. The median Barthel Index score at follow-up was 70 (25th-75th percentile, 15-95). The median time between symptom onset and MRI examination was 5.0 hours (25th-75th percentile, 4.5-6.0 hours). Median DWI lesion volume was 24.7 cm³ (25th-75th percentile, 6.5-35.5 cm³). Two patients did not have a baseline DWI lesion. The median PWI lesion volume was 93.0 cm³ (25th-75th percentile, 54.2-177.7 cm³). The mismatch volume, defined as the difference between the baseline PWI and DWI lesion volume, was a median of 71.0 cm³ (25th-75th percentile, 41.0-114.8 cm³). The median ADC<sub>550</sub> was 436 × 10⁻⁶ mm²/s (25th-75th percentile, 408-505 × 10⁻⁶ mm²/s), excluding patients in whom ADC values could not be calculated because of absence of DWI lesions (n = 2), or in whom there was a DWI lesion present but no pixels were found below the threshold of 550 × 10⁻⁶ mm²/s (n = 1).

The CBF measured in the region with MTT abnormalities was decreased in all patients except 1 (median, 58% of the reference value; 25th-75th percentile, 49%-70%). In this patient, CBF was 116% of the reference value. Heterogeneity was found within the MTT abnormality: areas with CBF decrease were found and areas with CBF increase compared with the reference value. Cerebral blood volume values were increased in all patients but 1 (median, 1.6, 25th-75th percentile, 1.3-2.1).

Patients were divided into 2 groups based on CBF values. Group 1 (n = 5) comprised patients with CBF values less than 50% of the contralateral side (range, 27%-
49%), and group 2 (n = 12) comprised patients with CBF values greater than 50% (range, 52%-116%). Comparison of the 2 groups is detailed in Figure 3 and Figure 4.

Patients in group 1 had lower ADC$_{550}$ (median, 430 × 10^{-6} mm$^2$/s; 25th-75th percentile, 349-430 × 10^{-6} mm$^2$/s vs median, 506 × 10^{-6} mm$^2$/s; 25th-75th percentile, 427-550 × 10^{-6} mm$^2$/s; P = .04) values than patients in group 2. Group 1 patients had larger DWI volumes (median, 41.8 cm$^3$; 25th-75th percentile, 35.1-131.1 cm$^3$ vs median, 14.5 cm$^3$; 25th-75th percentile, 1.7-26.9 cm$^3$; P = .001) and PWI volumes (median, 194.6 cm$^3$; 25th-75th percentile, 121.5-250.0 cm$^3$ vs median, 69.3 cm$^3$; 25th-75th percentile, 41.6-118.1 cm$^3$; P = .01) and had more severe clinical strokes (NIHSS score: median, 15; range, 9-23 vs median, 9; range, 4-22; P = .02). Their MTT and CBV values were not significantly different. The functional outcome between the 2 groups was not significantly different, although there was a trend of worse functional outcomes in group 1 (Barthel Index score: median, 20; 25th-75th percentile, 15-95 vs median, 85; 25th-75th percentile, 45-100; P = .16).

We did not find a correlation between the total distribution of CBF and the ADC$_{550}$ (P = .24), NIHSS score (P = .42), or Barthel Index score (P = .18). The CBF was significantly correlated only with DWI lesion volume (Spearman ρ = -0.555; P = .02). A nonsignificant correlation was found between CBF and PWI lesion volume (Spearman ρ = -0.446; P = .08).
Our findings suggest that low CBF values, measured with bolus-tracking MRI, are associated with lower ADC values, larger DWI and PWI lesion volumes, and more severe NIHSS scores. The association between CBF and the ADC or NIHSS scores was not evident when comparing CBF with ADCs and NIHSS scores across the whole range of CBF values.

We did not measure CBF directly in our study. The ROIs used to measure CBF were derived from the areas of hyperintensity measured on the MTT maps. Choosing the MTT as the ROI probably causes overestimation of CBF. The MTT lesion includes areas that vasodilate in response to decreasing cerebral perfusion pressure and, therefore, have increased MTT but have not reached the threshold for a reduction in CBF. The finding of CBF increases, rather than decreases, in our ROI suggests that vasodilatation often occurred within the studied ROI. The overestimation of CBF due to our measurement method might explain the absence of an overall relationship between CBF and the ADC. Another explanation might be that ADC reductions are only associated with CBF reductions below a certain threshold. This explanation is backed by experimental data demonstrating that DWI hyperintensities, or ADC reductions, occur only at specific levels of CBF reduction that persist over certain amounts of time. The information gained from PWI and DWI represents an evaluation of the cerebral ischemic process at a single time point, and this might also explain the lack of correlation between these variables.\(^{10,20}\)

We chose MTT maps to measure the ROI because the borders of MTT lesions are easier to delineate on PWI than CBF or CBV maps. Differences in CBF and CBV between gray and white matter, combined with the presence of only mild changes in CBF and CBV, compared with MTT, make visual delineation of the border of the lesions on CBF and CBV more difficult, especially in white matter and at the gray/white matter junction.\(^{21}\)

The results of our study confirm the relationship between reductions in CBF and low ADC values found in animal models of ischemic stroke.\(^{9,22}\) Sorensen et al\(^{23}\) assessed the relationship between hemodynamic factors and the ADC in 23 patients with acute ischemic stroke studied within 12 hours of symptom onset. This study did not find a correlation between the overall ADC and CBF. The authors did not compare the association between the lowest CBF values and the ADC. The association of low CBF with other indicators of stroke severity, such as a low ADC, large DWI lesion volumes, and higher NIHSS scores, provides partial concurrent validation of the MRI method for measuring relative CBF. Our findings suggest that in future studies, low ADC values could be used as surrogates for low CBF values. Other studies have compared this NP-SVD MRI method of measuring hemodynamics with noninvasive CBF measurements in humans. Lie et al\(^{24}\) compared the NP-SVD MRI method with a spin-labeling MRI technique in healthy volunteers and found good agreement between both techniques. Liu et al\(^{25}\) found a curvilinear relationship between relative CBF values obtained using single-photon emission computed tomography and the NP-SVD MRI method in 11 patients with acute ischemic stroke. The same group\(^{26}\) also reported a high correlation between hypoperfusion volumes obtained using single-photon emission computed tomography and the NP-SVD MRI method in 23 patients. A nonsignificant trend of worse functional outcome in patients with low CBF values was found. The absence of a significant association is probably related to the small sample size, although this hypothesis should be confirmed in further studies. Van Everdingen et al\(^{27}\) reported significant correlations between ADC values and indicators of functional outcome in 38 patients with acute ischemic stroke.

The limitations of our study are related to the small sample size and the performance of multiple-hypothesis testing.
testing. We arbitrarily chose a reduction in CBF of greater than 50% to distinguish between severe CBF reduction and less severe CBF reduction. We were not able to analyze the spatial correspondence between a low ADC and reduced CBF values in individual voxels because the baseline DWIs and PWIs were not coregistered. The bolus-tracking MRI technique has some inherent limitations. Absence of contrast delivery in nonperfused regions makes accurate measurement of CBF within these areas impossible. Delays in contrast arrival through collateral vessels or dispersion of contrast through a stenosis may mimic decreases in CBF, although beneficial perfusion is present. Accurate determination of the arterial input function required to perform deconvolution with the tissue concentration time curve is subject to errors caused by partial volume artifacts.2,23,28-30

In conclusion, we found an association between reduced CBF measured using MRI and clinical and radiological markers of stroke severity. This association was present only with severe reductions in CBF.

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