Metabolic Counterpart of Decreased Apparent Diffusion Coefficient During Hyperacute Ischemic Stroke
A Brain Proton Magnetic Resonance Spectroscopic Imaging Study

F. Nicoli, MD, PhD; Y. Lefur, PhD; B. Denis, MD; J.P. Ranjeva, PhD; S. Confort-Gouny, PhD; P.J. Cozzone, PhD

Background and Purpose—Recent studies have shown that the brain ischemic area defined by the map of decreased apparent diffusion coefficient (ADC) obtained by diffusion-weighted imaging (DWI) during the first hours of ischemic stroke includes a significant part of ischemic penumbra. We hypothesize that the misjudgment of the final infarct size by ADC mapping may be related to a restricted ability of DWI to capture variations in the intensity of cellular suffering.

In an attempt to characterize metabolically the hyperperfused brain parenchyma, we studied the relationship between ADC values and brain metabolic parameters measured by proton MR spectroscopic imaging (SI).

Methods—Six patients with hyperacute ischemic stroke were explored within the first 7 hours after onset with the use of a MR protocol including T2*-weighted MRI, DWI, SI, perfusion-weighted imaging, and MR angiography.

Results—This study demonstrates, for the first time, a wide gradient of ischemia-related metabolic anomalies within the abnormal area delineated by DWI during hyperacute ischemic stroke. In the narrow range of decreased mean ADC values (0.60 to 0.40 \times 10^{-3} \text{ m}^2 \cdot \text{s}^{-1}), a 33% decrease in mean ADC is associated with a 122% increase in lactate/N-acetyl aspartate ratio. Mean ADC values never fall below 0.40 \times 10^{-3} \text{ m}^2 \cdot \text{s}^{-1} within the severely affected ischemic tissue, while SI still detects a large metabolic heterogeneity inside areas showing similar decreased mean ADC values close to this threshold.

Conclusions—Our results indicate that the region of very low mean ADC values observed during hyperacute ischemic stroke contains areas of various tissue damage intensity characterized by SI in relation to different stages of cellular metabolic injury. This observation may explain why ADC mapping does not reliably predict final infarct size. (Stroke. 2003;34:000-000.)

Key Words: magnetic resonance imaging, diffusion-weighted spectroscopy, nuclear magnetic resonance stroke, acute

The use of an absolute threshold in maps of apparent diffusion coefficient (ADC) values alone does not accurately delineate the area of irreversible ischemic injury during hyperacute ischemic stroke in humans or in experimental studies, although this delineation is of critical importance to evaluate the indication of thrombolysis. To understand why a severe ADC decrease does not predict irreversible tissue damage in this condition, one must keep in mind that ADC is a physical parameter indirectly reflecting cellular structural alterations during hyperacute ischemic stroke. Thus, ischemia-related cytotoxic edema is associated with an early ADC decrease proportional to the severity of hypoperfusion. However, there is no direct relationship between ADC level variations and cellular metabolic dysfunction. Parsons et al demonstrated that a combination of proton MR spectroscopy (using only a single voxel localization) and diffusion-weighted imaging (DWI) may improve the prediction of stroke outcome compared with DWI alone. However, to our knowledge, the metabolic counterpart of ADC decrease is still undefined in patients with hyperacute ischemic stroke even though it may explain the failure of DWI to discriminate tissue at risk of infarction. To address this issue, we studied the relationship between ADC values and brain metabolic parameters measured by proton MR spectroscopic imaging (SI) during hyperacute ischemic stroke.

Subjects and Methods

Six patients with hyperacute ischemic stroke not eligible for thrombolytic treatment were prospectively explored within the first 7 hours after onset with the use of a MR protocol including, in this sequence, T2*-weighted MRI, DWI, SI, perfusion-weighted imaging.
(PWI), and gadolinium bolus-tracking MR angiography (MRA). The protocol was approved by the ethics committee at Timone Hospital in Marseille, France (reference number 99/25). Four of the 6 patients (2 women and 2 men; aged 41, 36, 57, and 50 years; National Institutes of Health Stroke Scale [NIHSS] score, 25, 17, 19, and 24, respectively) were explored within 6 hours of onset (3.5, 4.5, 5, and 6 hours, respectively). They had proximal middle cerebral artery (MCA) occlusion without cervical artery stenosis or occlusion and an area of decreased ADC involving at least one third of the MCA territory. For the 2 other patients (2 women; aged 79 and 43 years; NIHSS score, 8 and 10) who were explored within 4 and 7 hours of onset, respectively, MRA showed no intracranial or extracranial artery occlusion, and the area of decreased ADC involved less than one third of the MCA territory. No brain hemorrhage was detected on T2*-weighted MRI or on CT performed just before MR examination.

MR exams were performed on a 1.5 T Siemens Vision Plus system. Isotropic ADC maps were reconstituted with the use of images acquired with a single-shot echo-planar imaging sequence (b=0, 500, 1000 x/mm² applied in the x, y, and z directions; 19 slices; thickness=5 mm; matrix=128 x 128; field of view=256 x 256 mm²). Brain perfusion was assessed by bolus tracking. Sixty-five consecutive single-shot GE echo-planar imaging acquisitions were performed at a rate of 1 acquisition per second (echo time=60 ms; flip angle=60°; 7 slices; thickness=5 mm; matrix=128 x 128; field of view=256 x 256 mm²). Time to peak (TTP) and mean transit time (MTT) maps were calculated as described by Smith et al.© Three consecutive diffusion MRI slices or perfusion MRI slices were averaged to match the regions explored by SI. Metabolic images were acquired by acquisition-weighted fast 2-dimensional spin-echo SI (echo time/repetition time=135 ms/1600 ms; slice thickness=15 mm; matrix 21 x 21; field of view=240 x 240 mm²; 454 acquisitions; water suppression performed during the acquisition with the VAPOR sequence®; 12-minute acquisition time®). These parameters resulted in an apparent nominal spatial resolution of 11 x 11 mm within a 15-mm-thick slice. However, in relation to the physical principles of the SI technique, the actual spatial resolution corresponded to elementary cylinders with a diameter of 22 mm and a height of 15 mm, resulting in a voxel volume of 5.7 mL, as explained in the report of Galanaud et al.© This spatial resolution is close to that usually obtained by the single-voxel spectroscopy technique at 1.5 T: 8 mL (20 x 20 x 20 mm³) or 3.37 mL (15 x 15 x 15 mm³). None of the patients had lesions <5.7 mL in volume or 22 mm in dimension within a single 5-mm-thick ADC slice. The strict immobility of the patient’s head during SI acquisition was helped by the use of pads and pillows and was continuously monitored by a video system. Under these conditions, we did not observe any head movements in the cohort of 6 patients. The duration of the conventional MRI protocol was <10 minutes (T2*: 128 seconds; DWI: 48 seconds; PWI: 65 seconds; MRA: 40 seconds for intracranial arteries and 17 seconds for cervical arteries). The delay between the end of the DWI and the end of the SI was approximately 15 minutes.

Images from DWI and PWI parameters and metabolic images from SI were transformed in 256 x 256 matrix images with the use of a Fourier interpolation. This interpolation optimizes the informational content of spectroscopic images by increasing their apparent resolution via a 64% increase in measuring accuracy of the intensity and localization of MR signals registered during the SI acquisition.©,© This Fourier interpolation allows a quantitative analysis of individual regions of interest (ROIs) centered on each pixel of the 256 x 256 matrix spectroscopic image, but the diameter of these ROIs cannot be <22 mm.© The apparent distortion of metabolic map contours was related to the use of a mask corresponding to the skull signal and to outer volume saturation slices applied to eliminate the lipid signals from the scalp. Moreover, peripheral artifacts on metabolic maps caused by residual lipid contamination or magnetic field heterogeneity were also removed with the use of AMARES-MRUI FORTRAN code.© After spatial realignment of images obtained by the various modalities, correlations between mean ADC values and metabolic ratios were measured in cylindrical ROIs of 22 mm in diameter and 15 mm in thickness corresponding to the SI resolution before Fourier interpolation. These ROIs were defined inside the ipsilateral hypoperfused area delineated by MTT values equal or superior to the contralateral average MTT values +3 SDs and thus including the abnormal area delineated by the ADC map. The use of this rigorous statistical approach was possible owing to the low SD among the quasi-uniform MTT values measured in the unaffected contralateral hemisphere. The coordinates of each ROI selected within the hypoperfused area were used to position the corresponding ROI of the averaged ADC map and of the spectroscopic image to perform appropriate correlations. The relationship between ADC values and metabolic parameters was not analyzed in anterior frontal regions owing to the presence of magnetic field inhomogeneities in these regions, which cause distortion artifacts in the echo-planar images and degrade the quality of spectroscopic images. Finally, 73 ROIs were defined in brain of patients with MCA occlusion (18, 17, 21, and 17 ROIs, respectively) (Figure 1) while, in relation to a smaller lesion, only 9 ROIs (1 and 8 ROIs, respectively) were defined in brain of the 2 patients without MCA occlusion. Data from SI (Figure 2) were expressed as the ratio of the resonance area of each detected metabolite over the sum of metabolites (S); N-acetyl aspartate (NAA), choline-containing compounds (Cho), and creatine-phosphocreatine (Cr). The use of metabolic ratios eliminates the bias related to a dilution effect caused by edema or cerebrospinal fluid contamination. Regression analysis between mean ADC values and metabolite ratios was performed with a linear or nonlinear regression model (Statview 5.0 software, Abacus Inc). The choice of the mathematical function performing the best-fit regression was based on the highest corresponding r value with a probability value <0.05. The use of this parametric statistical analysis was justified by the gaussian distribution of mean ADC values and metabolite ratios.
as demonstrated by a Kolmogorov-Smirnov test (probability values $>0.1$ indicated a gaussian distribution) (GraphPad InStat 3.0 software, GraphPad Software).

**Results**

The decrease in ADC is not correlated with Cho/S ratio or Cr/S ratio whether or not MCA is occluded (data not shown). In patients with MCA occlusion, there is a significant linear relationship between mean ADC values and the increase in lactate (Lac)/S ratio ($r^2=0.47; P<0.0001$; data not shown), as already described in experimental studies. Correlation is significant but more complex with the decrease in NAA/S ratio (exponential regression; $r^2=0.48; P<0.0001$) (Figure 1). The Lac/NAA ratio, expressing a combined index of the intensity of anaerobic glycolysis and neuronal suffering, is also correlated with mean ADC values (Figure 1). This correlation is polynomial (second-order polynomial regression; $r^2=0.60; P<0.0001$) in relation to a wider dispersion of values of Lac/NAA ratios in the narrow range of severely decreased mean ADC values (0.60 to $0.40\times10^{-3} \text{m}^2 \cdot \text{s}^{-1}$) compared with the hypoperfused area with normal mean ADC values (Figure 1, right part of curve). Indeed, in this narrow range of very low mean ADC values, a 33% decrease in mean ADC values is associated with a 122% increase in Lac/NAA ratio. The metabolic heterogeneity inside the area of severely decreased mean ADC is clearly illustrated with the use of SI, whether or not a diffusion-perfusion mismatch is present (Figures 3 to 5). In the 2 patients without MCA...

**Figure 2.** MR spectra recorded during SI acquisition presented in Figure 3. An exponential filtering, a zero-filling (512 zero points filled to 1024), and a zero-order phase correction were applied. Spectra are displayed at the same scale without baseline correction or postacquisition water suppression. a, Spectrum recorded from ROI located inside the infarct core. b, Spectrum recorded from the contralateral ROI. On 135-ms echo time MR spectra, the lactate signal appears as a negative doublet, which facilitates its differentiation from the positive signal of lipids resonating in the same frequency range.

**Figure 3.** Multimodal MR maps of a patient brain (57-year-old man; NIHSS score, 19) with an acute proximal MCA occlusion explored within 5 hours of onset without a diffusion-perfusion mismatch. ADC units are expressed in $10^{-3} \text{m}^2 \cdot \text{s}^{-1}$. TTP and MTT units are expressed in seconds. The area delineated with a dotted line was manually defined from the corresponding averaged ADC map and represents the area of decreased ADC values. The heterogeneity of ADC values visible inside that area clearly did not match well the metabolic heterogeneity demonstrated by SI.
occlusion but explored in the same time window as patients with MCA occlusion, the relationship between mean ADC values and NAA/S ($r^2 = 0.57; P = 0.02$) or Lac/NAA ($r^2 = 0.63; P = 0.01$) ratios is linear in relation to a slighter decrease in mean ADC values that does not reach the minimal threshold observed in the group of patients with MCA occlusion (data not shown).

**Discussion**

The wide dispersion of values of Lac/NAA ratios in the narrow range of severely decreased mean ADC values may reflect the large heterogeneity in tissue damage inside the ischemic area that cannot be evaluated with DWI alone. Indeed, mean ADC values do not decrease below a threshold of approximately $0.40 \times 10^{-3} \text{ m}^2 \cdot \text{s}^{-1}$, representing for water molecules the maximal possible restricted state of the extracellular space relative to the acute ischemic cytotoxic edema. In fact, this lowest value of mean ADC during severe ischemia was also observed in experimental studies in which a similar ROI analysis was performed. A limitation of our study is that analysis of correlations between ADC values and brain metabolic parameters needs to merge the ADC pixel values into relatively large ROIs, thereby blurring potentially important ADC heterogeneities at the pixel level. This heterogeneity of ADC values in the narrow range of low ADC values characterizing the ischemic area is demonstrated on 3 individual ADC slices with a pixel-based analysis and on the corresponding averaged ADC map measured on a patient with MCA occlusion explored within 6 hours of onset (Figure 5). This observation is in excellent agreement with the mean ADC value of $0.40 \times 10^{-3} \text{ m}^2 \cdot \text{s}^{-1}$ measured in the severely affected ischemic tissue. Nevertheless, despite their higher spatial resolution, these nonaveraged ADC images failed to detect the gradient of the metabolic consequences of ischemia on brain parenchyma demonstrated by SI (Figure 5). In addition, moderate ischemic injury defined by low Lac/NAA ratios was observed in areas characterized by very low values of mean ADC (Figure 1), demonstrating the limitations of DWI to evaluate the severity of cellular suffering. Recent data confirm that these lowest ADC values observed during the hyperacute phase do not correspond to maximal tissue injury. Indeed, the early decrease in ADC is almost complete as early as 1.5 hours after the onset of ischemia. This time is shorter than the accepted threshold of irreversible tissue injury (3 to 6 hours), whereas the brain parenchymal density evaluated by CT shows a continuous linear decrease long after this period.

Whether or not the short 15-minute delay between the end of DWI acquisition and the end of SI acquisition in patients with MCA occlusion may be a confounder in our results is difficult to appreciate. Indeed, the duration of ischemia is one of the most important factors to consider when the reversibil-
ity of tissue injury is predicted. One can assume that a 15-minute delay is probably sufficient to observe significant changes in ADC values when DWI is performed during the first 2 hours of ischemia. However, this assumption probably does not hold beyond the initial 2-hour period because the decrease in ADC is then almost complete. This is the case in our patients who were explored between 3.5 and 7 hours after the onset of ischemia, when mean ADC had probably already reached its asymptotic lower values. Moreover, after the first 3 hours of ischemia, the short 15-minute delay is probably not sufficient to observe significant measurable changes in lactate and NAA signals owing to their respective kinetics of evolution, as analyzed in an experimental model of focal ischemia. The mismatch between diffusion and metabolic parameters brings novel insight to the understanding of the pathophysiology of ADC variations during hyperacute ischemic stroke, highlighting the added value of SI over DWI (Figures 3 to 5). As illustrated in Figure 1 (right part of curves), SI also discriminates between 2 metabolically distinct hypoperfused areas with subnormal to normal mean ADC and normal NAA/S level, modulated by the
presence or the absence of lactate. The first hypoperfused area characterized by a subnormal to normal mean ADC value, a normal NAA/S level, and the presence of lactate matches well the diffusion-perfusion mismatch area (Figure 4), while the other hypoperfused area characterized by a subnormal to normal ADC mean value, a normal NAA/S level, and the absence of lactate (Lac/NAA = 0) might possibly correspond to an oligemic zone. However, further studies with combined DWI and SI performed before and after early reperfusion using thrombolysis are needed to confirm this hypothesis. In addition, modern advances in SI techniques using an echo-planar sequence should soon provide fast 3-dimensional SI covering the entire brain in the same acquisition time as 2-dimensional SI. This new sequence might be of interest in the clinical assessment of acute ischemic stroke.

The present study demonstrates the potential of SI to evaluate early consequences of acute ischemia on brain cells and the existence of a gradient of cellular metabolic injury within the area of decreased mean ADC values. Interestingly, this metabolic gradient supports the idea that heterogeneity of ADC within infarcts is not only related to a difference in ADC reduction between gray and white matter but is also associated with a heterogeneity of the tissue metabolic injury, which in turn may explain why ADC is not a reliable predictor of final infarct size.

Although further studies of hyperacute ischemic stroke performed before and after thrombolysis are needed to definitely assess the prognostic value of SI, it is clear that brain evaluation by SI in ischemic patients provides a new metabolic dimension that is already presenting valuable information on the heterogeneity and gravity of lesions identified by DWI.

References
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