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

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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 hypoperfused 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 \( \times 10^{-9} \) \( m^2 \cdot s \)), 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 \( \times 10^{-9} \) \( m^2 \cdot s \) 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:e82-e88.)

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 humans1–3 or in experimental studies,4 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,2 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.5 However, there is no direct relationship between ADC level variations and cellular metabolic dysfunction. Parsons et al4 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...
Maps were calculated as described by Smith et al. Three/H1105
60 ms; flip 
vutive single-shot GE echo-planar imaging acquisitions were per-
MR exams were performed on a 1.5 T Siemens Vision Plus
system. Isotropic ADC maps were reconstructed with the use of images acquired with a single-shot echo-planar imaging sequence (b=0, 500, 1000 s/mm² applied in the x, y, and z directions; 19 slices; thickness=5 mm; matrix=128×128; field of view=256×256 mm²). Brain perfusion was assessed by bolus tracking. Sixty-five consec-
tive single-shot GE echo-planar imaging acquisitions were per-
formed at a rate of 1 acquisition per second (echo time=60 ms; flip angle=60°; 7 slices; thickness=5 mm; matrix=128×128; field of view=256×256 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 with acquisition-weighted fast 2-dimensional spin-echo SI (echo time/repetition time=135 ms/1600 ms; slice thickness=15 mm; matrix=21×21; field of view=240×240 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 11×11 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 (20×20×20 mm³) or 3.37 mL (15×15×15 mm³). None of the patients had lesions <5.7 mL in volume or 22 mm in diameter 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.
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 m2 · 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).

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 $10^{-9}$ m2 · 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 (r²=0.57; P=0.02) or Lac/NAA (r²=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 0.40×10⁻⁹ m²·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 0.40×10⁻⁹ m²·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-

Figure 4. Multimodal MR maps of a patient brain (36-year-old woman; NIHSS score, 17) with an acute proximal MCA occlusion explored within 4.5 hours of onset with a diffusion-perfusion mismatch. ADC units are expressed in 10⁻⁹ m²·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. Note the preserved NAA level in the posterior part of that area and the lactate detection in the absence of decrease in NAA level in the diffusion-perfusion mismatch area.
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. Under these conditions, the delay between DWI and SI acquisitions is unlikely to be a significant confounder in our results.

The metabolic heterogeneity that we found in the ischemic area is probably related to different stages of tissue injury and metabolic dysfunction, ranging from an anaerobic glycolysis without detectable neuronal injury (isolated increase in lactate level) to a more severe metabolic degradation defined by an anaerobic glycolysis associated with a moderate or severe neuronal injury (combination of different levels of increase in lactate and decrease in NAA). The metabolic heterogeneity within the ischemic area is a well-known feature that has been related to the severity and the duration of hypoperfusion in human and animal studies. The slighter decrease in mean ADC value observed in the 2 patients without MCA occlusion but explored in the same time window as that for patients with MCA occlusion is in accordance with experimental studies that demonstrate moderately low ADC values inside the ischemic area after early reperfusion.

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
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

Editorial Comment

ADC and Metabolites in Stroke: Even More Confusion About Diffusion?

Recently, permanent and transient early ADC renormalization has been reported in stroke patients. Several other articles with different focus report on patients with substantial decrease of lesion volume from initial DWI to outcome T2-weighted imaging. Differences in the reported rates of patients showing ADC normalization may be due to varieties in imaging time points and application of thrombolytic therapy. These reports resulted in some confusion among stroke physicians about the clinical value of the ADC.

The accompanying article by Nicoli et al provides novel insights into the pathophysiological basis of DWI in patients with acute ischemic stroke. Using spectroscopic imaging, the authors describe a heterogeneous cellular metabolic injury within the region of decreased ADC values. This finding may
help us to understand why severe ADC decreases do not necessarily predict irreversible tissue damage in stroke patients.1,2

What do we know about the ADC? Diffusion in tissues is referred to as random walk of water molecules restricted by fibers, membranes, and macromolecules. Despite some lack of understanding about the biophysical background of ADC decrease, we have learned much about its pathophysiological correlates from stroke models.3 It has been shown by different experimental modalities that cerebral ischemia results in failure of ion pumps and anoxic cell membrane depolarization. Water shifts from the extracellular to the intracellular space with consecutive cell swelling. The increase of the intracellular osmolarity as a result of lactate accumulation is considered the reason for cell swelling beyond depolarization. The time course of these changes corresponds to the evolution of ADC decreases,4 even when the precise biophysical link to ADC is not exactly known. The fundamental association between ion homeostasis and ADC has been shown by blocking the Na+ channels, which results in a delay of the rapid ADC decrease.5 The association between the degree of the perfusion deficit and the severity of ADC decrease has been confirmed in humans6 and recently has been shown to be time dependent.7

Unfortunately, the relationship between ADC and prediction of final tissue injury is less explicit. The degree of ADC decrease has been related to the location and extent of neuronal injury.8 On the other hand, similar ADC values may reflect various histological states of ischemic tissue changes.9,10 However, recent animal studies show that ADC mapping performed before thrombolysis provides reliable risk assessment of brain injury but, as a result of uncertainties of postschismic reperfusion, does not allow precise outcome prediction.11 The link between severe absolute ADC decreases and progress to infarction is also missed in individual stroke patients.2 The observations of Nicoli et al suggest that the use of ADC thresholds as parameter of tissue viability should be discussed critically at least; regions with comparable ADC values may be associated with heterogeneous metabolic injury and, possibly, heterogeneous fate.

How can we exploit ADC values for stroke imaging? The degree of ADC decreases during stroke evolution tells us much about pathological tissue properties related to age, degree, and duration of the perfusion deficit, modulated by the local susceptibility to ischemia. These changes are associated with the local tissue impairment but not necessarily with tissue outcome. One should keep in mind that hyperacute lesions in ADC maps may reverse transiently or permanently, especially after thrombotic treatment. However, most acute stroke patients will show the time course of further ADC decrease if reperfusion is not achieved in a timely manner.

ADC is just one side of the coin and should be interpreted in context with time after stroke onset, perfusion- and T2-weighted imaging, localization, occlusion type, and clinical data. Multiparametric prediction maps may facilitate the review of this complex information in the future.

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