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Stroke onset time estimation from multispectral quantitative magnetic resonance imaging in a rat model of focal permanent cerebral ischaemia

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ABSTRACT

Background: Quantitative T$_2$ (qT$_2$) relaxation Magnetic Resonance Imaging (MRI) allows estimation of stroke onset time.

Aims: We aimed to examine the accuracy of quantitative T$_1$ (qT$_1$) and qT$_2$ relaxation times alone and in combination to provide estimates of stroke onset time in a rat model of permanent focal cerebral ischaemia and map the spatial distribution of elevated qT$_1$ and qT$_2$ to assess tissue status.

Methods: Permanent middle cerebral artery occlusion (MCAo) was induced in Wistar rats. Animals were scanned at 9.4T for qT$_1$, qT$_2$ and Trace of Diffusion Tensor (D$_{av}$) up to 4 hours post MCAo. Time courses of differentials of qT$_1$ and qT$_2$ in ischaemic and non-ischaemic contralateral brain tissue (∆T$_1$, ∆T$_2$) and volumes of tissue with elevated T$_1$ and T$_2$ relaxation times (f$_1$, f$_2$) were determined. TTC staining was used to highlight permanent ischaemic damage.

Results: ∆T$_1$, ∆T$_2$, f$_1$, f$_2$ and the volume of tissue with both elevated qT$_1$ and qT$_2$ (V$^{\text{Overlap}}$) increased with time post MCAo allowing stroke onset time to be estimated. V$^{\text{Overlap}}$ provided the most accurate estimate with an uncertainty of ±25 minutes. At all times-points regions with elevated relaxation times were smaller than areas with D$_{av}$ defined ischaemia.

Conclusions: Stroke onset time can be determined by qT$_1$ and qT$_2$ relaxation times and tissue volumes. Combining qT1 and qT2 provides the most accurate estimate and potentially identifies irreversibly damaged brain tissue.
INTRODUCTION

A growing body of evidence shows quantitative $^1$H MRI is sensitive to changes in brain tissue that occur during early moments of an ischaemic stroke and can enable identification of patients with an unknown onset time who may be eligible for drug therapies (1–3). Research from preclinical stroke models and stroke patients suggest MRI can provide an estimate of stroke onset time (1–4) and a means for assessing tissue status (4–6), two methods that could aid stratification of patients to treatment.

Within minutes of ischaemia onset, the apparent diffusion coefficient (ADC by quantitative diffusion MRI) has been shown to decrease to approximately 60% of physiological values in brain parenchyma, enabling ischaemic tissue to be identified (7–10), thereafter stabilizing (14) (15). This early ADC decrease is attributed to energy failure and cytotoxic oedema (7,8) and is often assumed to represent the irreversibly infarcted core (11), however preclinical (12) and clinical (13) studies suggest greater complexity.

Within regions of decreased ADC in rat focal ischaemia, quantitative T$_2$ relaxation times (qT$_2$) also decrease due to metabolic changes (6,16) and cytotoxic oedema (17). The decrease is followed by a quasi-linear increase over time (2,4) caused by altered hydrodynamics and tissue degradation (17,18). This relationship between qT$_2$ and time from stroke onset has enabled estimates of stroke onset time in rat models of ischaemia with good accuracy (2,4). Interestingly, a quadratic dependency of qT$_2$ and time from symptom onset was also reported in acute stroke patients suggesting clinical applicability of qT$_2$ MRI (3). Over time, the qT$_2$ increase will have inevitable contributions from vasogenic oedema, which coincides with the transition to irreversible tissue damage (6,9,14).

The time-dependency of quantitative T$_1$ relaxation times (qT$_1$) in the ischaemic brain is less well characterized. qT$_1$ increases gradually over time from stroke onset within regions of decreased diffusion (16,9). Pathophysiological mechanisms thought to underlie this qT$_1$ increase are similar to qT$_2$, including altered water dynamics and content in ischaemic tissue (14,19) qT$_1$ is additionally sensitive to changes in cerebral blood flow and volume (16,20), temperature (21), pH (22) and tissue oxygen tension (16). Thus, by combining data from time courses of qT$_1$ and qT$_2$ in the ADC lesion, one would expect to obtain a fuller picture of
ischaemic pathology in brain tissue, which may aid in the estimation of stroke onset and assessment of tissue viability.

The current study was undertaken to determine time-dependent changes in $qT_1$ and $qT_2$ relaxation times in ischaemic brain tissue and to compare their abilities in estimating time since stroke onset. The second aim was to map the spatial distributions of elevated $qT_1$ and $qT_2$ relaxation times within regions of decreased ADC with a view to assessing tissue status. Given that these MRI parameters are influenced by the same and different pathophysiological changes during stroke, ischaemic areas with combinations of $qT_1$ and $qT_2$ signatures were also identified. Previous research (4,9,17,23) has shown that the volume of tissue with elevated relaxation times increase with time. Therefore we also quantified the volumes of tissue with elevated $qT_1$ and $qT_2$ in the ADC lesion as a function of time.
METHODS

Animal Model

Animal procedures were conducted according to the principles of Three Rs and European Community Council Directives 86/609/EEC guidelines and approved by the Animal Care and Use Committee of the University of Eastern Finland.

Five male Wistar rats (300 – 400 g, Animal Resource Facility, University of Eastern Finland, Kuopio, Finland) underwent permanent middle cerebral artery occlusion (MCAo) (24). All rats were anesthetized with isoflurane through a facemask (maintained at 1.5 – 2.4%) for the duration of the operation and MRI. Before MRI arterial blood gases and pH were analysed (i-Stat CO, East Windsor, NJ). During MRI breathing rate and rectal temperature were monitored. Core temperature was maintained close to 37°C using a water heating pad under the torso.

One rat died during MRI (~ 3.5 hours post MCAo) and others were sacrificed five hours after MCAo by decapitation in deep isoflurane anaesthesia. Following decapitation, the brain was extracted, placed in refrigerated 0.01M phosphate buffered saline and sectioned into 1mm axial slices. Immediately after sectioning, a Triphenyletrazolium chloride (TTC 0.5% or 1% in phosphate buffered saline) staining method (25) was used to confirm ischaemic damage to brain tissue.

Magnetic Resonance Imaging

MRI data were acquired using a 9.4T/31cm horizontal Varian magnet interfaced to a Direct Drive console (Agilent Inc., Palo Alto, CA, USA) and equipped with an actively decoupled linear volume transmitter and quadrature receiver coil pair (RAPID Biomedical GmbH, Rimpar, Germany). Immediately after MCAo rats were secured in a cradle at the centre of the magnet bore. Protocol included twelve axial slices of: the trace of diffusion tensor (\(D_{av} = \frac{1}{3} \text{trace}[D]\)) with three bipolar gradients along each axis, three b-values (0, 400 and 1400 s/mm\(^2\)), TE = 36 ms, TR = 4000 ms and acquisition time = 7.36 minutes, a Carr-Purcell-Meiboom-Gill T\(_2\) sequence with 12 echoes (echo-spacing = 10 ms, TR = 2000 ms, acquisition time = 4.20 minutes) and Fast Low Angle Shot (FLASH) for T\(_1\), where the time from inversion to the first FLASH sequence (T\(_{10}\)) was 7.58 ms, TI = 600 ms, TR = 5.5 ms, time between inversion pulses (T\(_{relax}\)) = 10 s and acquisition time = 8.20 minutes. MRI data were
congruently sampled with slice-thickness = 1 mm, slice-gap = 0.5 mm, field-of-view = 2.56 x 2.56 cm², matrix = 128 x 128. MRI data were acquired sequentially at 60, 120, 180 and 240 minutes after MCAo.

Image Post-processing and Data Analysis

Data analysis was performed using Matlab (MathWorks, Natick, Massachusetts, USA) scripts written in-house and MRI software ‘Mango’ (Research Imaging Institute, UT Health Science Center at San Antonio, Texas, USA) and ‘FSL’ (FMRIB, Oxford UK). See Supplementary Materials for specific details of methods and criteria used.

Quantitative maps were computed using a mono-exponential fit in a logarithmic space (26). Ischaemic tissue was identified and ischaemic volumes of interest (VOI) were generated by applying Knight et al.’s (17) automatic lesion detection method to reciprocal Dav images (1/Dav). Reflecting ischaemic VOIs about the vertical axis identified homologous regions in the non-ischaemic hemisphere. To quantify changes in relaxation times, the percentage difference in mean \( qT_1 \) and \( qT_2 \) between ischaemic and non-ischaemic VOIs were calculated (\( \Delta T_1 \) and \( \Delta T_2 \)). To picture the spatial distribution of elevated relaxation time changes within ischaemic VOIs, voxels with high \( qT_1 \) or \( qT_2 \) and voxels with both high \( qT_1 \) and \( qT_2 \), termed \( T_1 \) & \( T_2 \) Overlap, were colour-coded. Voxels were high if relaxation times exceeded the median relaxation time of the non-ischaemic VOI by more than one half-width at half maximum. To determine the size of the lesion according to \( T_1 \) and \( T_2 \), parameter \( f \), as introduced by Knight et al. (17) was computed. Where \( f_1 \) and \( f_2 \) represent the number of voxels with high \( T_1 \) or \( T_2 \) (respectively) as a percentage of the size of the ischaemic VOI. The extent of \( T_1 \) & \( T_2 \) Overlap was determined by calculating the volume of \( T_1 \) & \( T_2 \) Overlap (\( V_{Overlap} \)) as a percentage of whole-brain volume.

Statistical Analysis

Statistical analysis was performed using Matlab and IBM Statistical Package for the Social Sciences (SPSS) Version 21 (Armonk, NY: IBM Corp) on pooled rat data. To compare lesion sizes, one-way related ANOVAs and Fisher’s least significant difference post-hoc were conducted on the average number of voxels in ischaemic VOI and with high \( qT_1 \) and \( qT_2 \). Differences were considered significant at \( p < .05 \). Linear least square regression analyses
were performed to determine whether time since stroke onset could be predicted by quantifying a parameter of interest (\(\Delta T_1, \Delta T_2, f_1, f_2, V^{\text{Overlap}}\)) at a single time-point. The root mean square error (RMSE) was used to assess the accuracy of onset time estimates. To compare the magnitude of \(\Delta T_1\) and \(\Delta T_2\), average \(\Delta T_1\) and \(\Delta T_2\) at 3 hours post MCAo were estimated using trend-line equations.

**RESULTS**

Across rats the blood gas profiles were: \(\text{SO}_2 = 95.8\pm3.2\%\), \(P_a\text{CO}_2 = 51.6\pm2.9\ \text{mmHg}\) and \(\text{pH} = 7.30\pm0.04\). In agreement with previous reports at 9.4T (33), mean \(qT_1\) and \(qT_2\) of the non-ischaemic VOI were 2,023±116 ms and 47±1 ms respectively. Figure 1 shows a central \(1/D_{av}\), \(qT_2\) and \(qT_1\) MRI slices of a representative rat at each time-point and a TTC slice. It should be pointed out that both in \(qT_2\) and \(qT_1\) MR images ischaemic stroke causes increased brightness with time, whereas in \(T_2\) and \(T_1\)-weighted images stroke lesion becomes brighter and darker, respectively. TTC staining verified irreversible ischaemic damage located predominantly in gray matter in all rats.

Figure 2 shows the spatial distribution of elevated relaxation times within ischaemic VOIs during the first four hours of ischaemia. As seen, the extent of \(T_1\) & \(T_2\) Overlap increases with time and at all time-points regions with high \(qT_1\) and \(qT_2\) appear smaller than the ischaemic VOI. Regions of high \(qT_1\) also appear larger than and occur in different regions to high \(qT_2\) areas.

At one and two hours post MCAo, regions with high \(qT_1\) were significantly larger than high \(qT_2\) and the ischaemic VOI was larger than high \(qT_1\) and high \(qT_2\) although this latter difference just missed significance for \(qT_1\) at two hours \((p = .058)\). There was no difference between lesion sizes of all parameters at three hours post MCAo and at four hours, the ischaemic VOI was significantly larger than high \(qT_2\). Overall, in the initial hours of ischaemia, regions of decreased diffusion \((1/D_{av}\) Ischaemic VOI) were larger than regions with high \(qT_1\) and \(qT_2\) and regions with high \(qT_1\) were larger than regions with high \(qT_2\) but converged with time.

As shown in Figure 3, all parameters \((\Delta T_1, \Delta T_2, f_1, f_2, V^{\text{Overlap}})\) were significant predictors
of tMCAo (p < .001), which enabled estimates of stroke onset time using linear trend-line equations (see Figure 3). $V^{Overlap}$ was the strongest predictor ($R^2 = 0.87$) and provided the most accurate estimate of time since stroke onset, with an uncertainty of ±25 min. $f_2$ ($R^2 = 0.82$) and $\Delta T_2$ ($R^2 = 0.75$), had uncertainties of ±34 and ±28 minutes, respectively. The increase in $\Delta T_1$ ($R^2 = 0.71$) and $f_1$ ($R^2 = 0.53$) over time were more gradual than other parameters and thus uncertainties were higher, at ±37 minutes and ±47 minutes for $f_1$ respectively. At 3 hours post MCAo the average $\Delta T_1$ was +6% and $\Delta T_2$ +5%.

**DISCUSSION**

Both $\Delta T_1$ and $\Delta T_2$ relaxation times provided estimates of stroke onset time where $\Delta T_2$ was superior to $\Delta T_1$. The volume of tissue with elevated $qT_1$ and $qT_2$ ($f_1$, $f_2$) also increased with stroke duration and quantification of $V^{Overlap}$ enabled estimates of onset time with better accuracy than individual measures. The ability to estimate stroke onset time by $^1$H MRI is regarded beneficial for patients with unknown onset, as currently they are ineligible for thrombolytic therapy (27). The fact that the volume of elevated relaxation times was smaller than regions of reduced $D_{av}$ indicates MRI relaxometry may also be informative of tissue status in hyperacute stroke.

The increase in $qT_2$ with tMCAo and its utility in estimating stroke onset time agrees with preclinical studies using single-slice MRI data acquisition (2,4) and a clinical study with multi-slice acquisition (3). Previous studies have reported a $qT_1$ increase in hyperacute ischemia (16,9) but this study is the first to identify $qT_1$ as a significant predictor of time from ischaemia onset and thus, a potential proxy for stroke timing. We introduce $f_1$ and $f_2$ parameters as indices for abnormal $qT_1$ and $qT_2$ relaxation times in the ischaemic tissue to eliminate MRI technical shortcomings, including magnetic field variation within the lesion (17). A combination of these parameters, $V^{Overlap}$, provided the most accurate estimate of stroke duration thus motivating further exploration as a proxy for onset time.

While both $qT_1$ and $qT_2$ enabled stroke onset time to be estimated, $qT_1$ had higher levels of uncertainty, which is likely to be due to the shallow slope of $\Delta T_1$ vs. time plot (Figure 3D). Previous studies showed within the ADC lesion, $qT_1$ and $qT_2$ (5,6) change in opposite
directions in the early moments of ischaemia; $qT_1$ increases within the first minute (20) and $qT_2$ decreases for about an hour (5,6). Recent data point to two-phase response of $qT_1$ upon ischaemia onset; in complete forebrain ischaemia the fast response levels by two minutes (20) whereas in the core, the rapid increase lasts up to 25 minutes post MCAo (16). A further issue to be considered is that inherent $qT_1$ and $qT_2$ change with magnetic field strength. For example a previous study found after 10 minutes of ischaemia the $\Delta T_1$ was approximately two-fold greater at 9.4T than 4.7T (20). However at three hours post MCAo, $\Delta T_1$ of a similar magnitude has been determined; at 4.7T the $\Delta T_1$ was +9% (8) and here at 9.4T, it was +6%.

In contrast to $\Delta T_1$, in the early moments of ischaemia $\Delta T_2$ is negative in the core (2,6) and becomes positive after an hour at both 4.7T (2,4) and 9.4T. The initial negative $\Delta T_2$ is likely to be due to combined effects of deoxyhaemoglobin build up (6) and cytotoxic oedema (17). However, at three hours of MCAo $\Delta T_2$ are similar at 4.7T (+5%) (2) and 9.4T (+5%) (Figure 3E) in the core of ischaemia. These observations indicate that while the polarity of early changes and time-dependent kinetics of $qT_1$ and $qT_2$ differ in stroke tissue, the increases in both relaxation times at clinically relevant time-points are comparable and independent of magnetic field strength.

The spatial distribution of elevated relaxation times (Figure 2) and the $f_1$ and $f_2$ parameters revealed that the volume of tissue with elevated $qT_1$ is initially larger than the volume of tissue with elevated $qT_2$, but these volumes converge with time. This observation agrees with a recent report (23), where at 70 and 150 minutes post MCAo the $qT_1$ lesion area was significantly larger than the $qT_2$ lesion, but comparable at 24 hours. Anatomical differences in volumes with elevated $qT_1$ and $qT_2$ may reflect the fact that these relaxation times probe different factors of early stroke pathophysiology, yet some of the same mechanisms during later stages of ischaemia (18). In line with earlier studies (4,9), volumes of tissue with elevated $qT_1$ and $qT_2$ were smaller than those with low diffusion during the initial hours of ischaemia. Close to normal $qT_1$ and $qT_2$ values are observed in early moments before transition to irreversible ischaemia (14). Thus present findings support current notions that diffusion MRI overestimates the true extent of the ischaemic core (4,12,13). Combining $qT_1$ and $qT_2$ and ADC data may provide a method for identifying salvageable tissue, where ‘normal’ $qT_1$ and $qT_2$ in the presence of decreased ADC could indicate tissue viability.

Increased $qT_2$ and low ADC represents irreversible tissue damage (5,6,10,14). The viability
of tissue with elevated $qT_1$ is unknown, but it was previously reported that in transient MCAo of 90 minutes, $qT_1$ normalised in the striatum and core upon reperfusion, but the striatum proceeded to infarction two days later (20). We therefore speculate that volumes with both elevated $qT_1$ and $qT_2$ relaxation times, $V_{\text{overlap}}$, represent irreversibly damaged tissue. This conclusion is supported by the fact that prolonged $qT_1$ and $qT_2$ times in ischaemic brain were shown to signify transition to necrosis by histological methods (14). We believe that $V_{\text{overlap}}$ represents tissue with irreversible vasogenic oedema and thus, increased total water content as both $qT_1$ and $qT_2$ are influenced by total tissue water content (19).

To conclude, the present study indicates that quantification of absolute $T_1$ and $T_2$ relaxation times and $V_{\text{overlap}}$ could provide information about tissue status and onset time that would be invaluable for treatment stratification of acute stroke patients with unknown onset.

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**CONFLICT OF INTEREST**

The authors declare no conflicts of interest.

**REFERENCES**


Legends to Figures:

**Figure 1** (colour). A single representative slice from a typical rat shown as 1/Dav, qT₂ and qT₁ images over tMCAo and a TTC stained slice from the same rat verifying irreversible ischaemic damage five hours post MCAo.

**Figure 2** (colour). A central 1/Dav slice from the same representative rat in Figure 1 shown over tMCAo. The image remains the same in the x direction and is overlaid with colour-coded regions depicting the 1/Dav defined ischaemic VOI, areas with high qT₂, high qT₁ and T₁ & T₂ Overlap.

**Figure 3** (colour). MRI parameters as a function of tMCAo. ΔT₁ and ΔT₂ represent the percentage difference between the ischaemic and non-ischaemic hemispheres.  

**A:** \( f_1 \), where \( \text{tMCAo} = 13.16 (±6.40) * f_1 - 999.15 (±558.5). \)  

**B:** \( f_2 \), where \( \text{tMCAo} = 3.449 (± 0.817) * f_2 - 110.90 (± 64.00). \)  

**C:** \( V_{\text{overlap}} \), where \( \text{tMCAo} = 37.41 (± 14.92) * V_{\text{overlap}} + 50.52(± 22.47). \)  

**D:** \( \Delta T_1 \), where \( \text{tMCAo} = 42.83 (± 13.88) * \Delta T_1 - 93.03 (± 83.17). \)  

**E:** \( \Delta T_2 \) where \( \text{tMCAo} = 24.41 (± 7.2) * \Delta T_2 + 64.74 (± 30.86). \)
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