Simple, Reliable and Precise Quantitative Quality Assurance of in-vivo Brain ADC

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Aim: to develop a simple and reliable method for quantitative quality assurance measurements of ADC values measured using a clinical sequence.

Introduction

In spite of the rapid growth in the application of diffusion imaging, there has been little development of a quantitative quality assurance (QA) methodology for diffusion. QA is vital to reassure the validity of subsequent data collected on patients [1]. By performing QA regularly it is possible to identify where a technique has failed and may also provide some help in rescuing data affected by such a failure. When absolute values of ADC are accurate, multi-centre comparisons and studies also become possible. However, without concurrent quantitative QA data the tests run on patients may become valueless. Current barriers to good ADC QA include: the difficulty of obtaining a large artefact-free ROI with a clinical EPI sequence; ensuring the chemical stability of samples; dealing with temperature changes (ADC increases 2-3% per °C [1]).

We introduce a new QA methodology for MR diffusion imaging. Diffusion coefficients (DC) are determined for three liquid straight-chain alkanes [2], chosen because they are similar to the ADC values observed in the human head *in vivo*. They are also stable, safe to handle and readily available, with no on-site preparation required. We demonstrate how DC values are referenced to a standard temperature to take account of temperature fluctuations over the course of a longitudinal QA study.

Diffusion-weighted MRI (DW-MRI) is a popular and well-established technique for investigating brain tissue. The apparent diffusion coefficient (ADC) quantifies the extent of diffusion and can be used to probe brain lesions in ischemia, multiple sclerosis (MS), epilepsy and tumours. Furthermore, diffusion tensor imaging (DTI) has also opened up the possibility for determining connectivity of white matter by following fibre tracts in the brain.

Method

System: GE Signa 1.5 T with gradient strength 33 mT m^{-1}, slew rate 120 T $m^{-1}s^{-1}$. Samples were decane, dodecane and tetradecane, all delivered in 0.5 L cylindrical bottles. Cost: (Sigma-Aldrich, UK) US$90 each. Dodecane is a good model for normal white matter, which has ADC in the region of $800\times10^{-12}m^2s^{-1}$. Decane has a DC similar to that found in MS ($\sim1310\times10^{-12}m^2s^{-1}$), whilst tetradecane has a DC comparable to that observed in ischemic brain ($510\times10^{-12}m^2s^{-1}$). Samples were kept in their original unopened glass bottles (80 mm diameter × 120 mm height) to avoid evaporation, oxidation or uptake of water from the atmosphere. Each bottle was packed in a larger plastic container (160 mm diameter × 220 mm height) filled with polystyrene foam chips to isolate the liquid from vibration and temperature change. Temperature was measured to within 0.2°C using a thermocouple attached to the side of the glass bottles.

Scanning parameters: The bottles were scanned with a single-shot DW-EPI sequence containing two gradient pulses with Stejskal-Tanner diffusion parameters [3]: δ = 21 ms, Δ = 39 ms; b_{max} = 600 s mm^{-2}. Additional parameters: matrix 64 × 64, FOV 160 × 160 mm, slice thickness 4.3 mm, TR/TE = 4 s / 92 ms. For each of 12 slices, a set of 4 b ≈ 0 images and 12 b_{max} along three orthogonal directions were acquired, yielding a total of 492 images in a scan time of 3 min. Images were averaged offline to improve SNR.

DC values were calculated for each pixel to yield a mean diffusivity map using the equations in Ref. [1]. This was repeated for a series observations acquired as part of the local QA programme. Each observation was made on a different day and the temperature of the phantom was recorded before and after the scan. A ROI (6 × 6 pixels; 15 mm × 15 mm) was placed at the centre of the phantom to avoid EPI artefacts. A temperature-independent, or "standard" diffusion coefficient is calculated referenced to a standard temperature T_0 = 295 K (22°C), using the relation [2]

$$\ln D = \ln D_0 - B(1/T - 1/T_0) + C(1/T - 1/T_0),$$

where D is the observed diffusion coefficient at temperature T, $D_0 = D(T_0)$, B and C are temperature correction factors (Table 1). Individual gradient directions were also analysed, to look for any systematic error in the setup of each gradient amplitude.

Results

Minor EPI image distortions are observed within 10 mm of the alkane-glass interface, although the central region of the phantom was not affected. Temperature was shown to change by ±0.1°C at most during the scan. Measured DC values for each alkane were in agreement with published values (Table 1).

The DC values show temperature dependence, as expected (Fig. 1). However, this temperature dependence was removed by referencing DC values to a standard temperature. Analysis of individual DC directions showed no signs of gradient miscalibration.

Table 1: Averaged standard DCs with uncertainties (U_T) for test liquids at 295 K with temperature correction factors B and C.

Alkane	D_0 / $10^{-12}m^{2-1}$	U_T%[a]	Tofts[b] D_0 / $10^{-12}m^{2-1}$	Tofts[b] U_T%	B / K	C / 10^{-6}K
Decane (≈ MS)	1299	2.0	1310	1.6	1658	2.98
Dodecane (≈ NWM)	794	2.5	818	1.8	1937	2.55
Tetradecane (≈ ischemia)	510	2.0	514	1.9	2056	3.44

[a]Total uncertainty including uncertainty in temperature, gradient strength and diffusion coefficient in mean diffusivity map. [b] Diffusion coefficient and uncertainty from Ref. [2]. NWM=normal white matter.

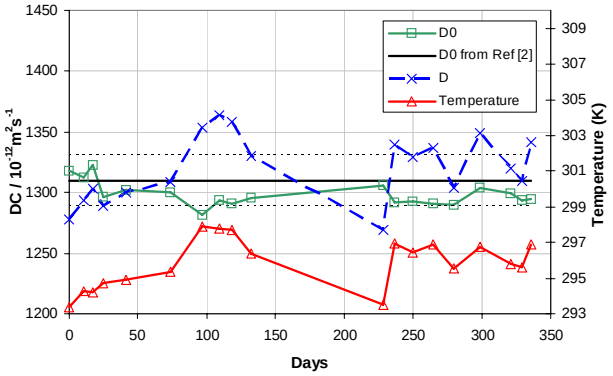

Figure 1
Serial observations showing how the observed DC (D) for decane changes with temperature. By referencing D to a standard temperature (295 K) this temperature dependence is removed (D_0). The horizontal line shows D_0 from Tofts *et al.* [2] with uncertainty limits (dotted lines). Although a calculated D_0 value appears to fall outside the uncertainty limits of Ref. [2], the point lies within the uncertainty limits of both sets of data. Data for dodecane and tetradecane show a similar behaviour, but have been omitted for clarity.

Conclusions

We present a simple, reliable quantitative QA methodology, using a clinical DW-EPI sequence, for diffusion using materials that are similar to ADC values observed in the brain. The materials are stable, readily available and safe to handle. A temperature-independent "standard" DC is calculated for serial measurements in ongoing QA programmes. The existing three methodological barriers (EPI artefacts, chemical stability and temperature fluctuations) have been overcome with the approach introduced here.

References

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