Use of a Multi-Exponential Attenuation Model for Sequential Registration of Diffusion Weighted Imaging in the Abdomen and Pelvis

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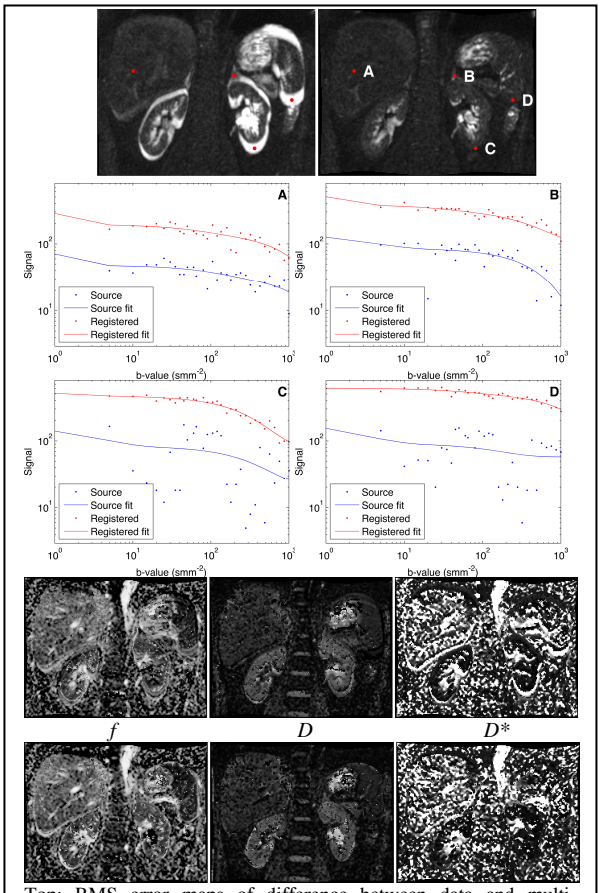
Introduction Imaging in the abdomen and thorax is more challenging than other regions due to various forms of tissue motion. Unlike cardiac and bowel motion, respiratory motion can be controlled relatively easily using breath-holds or gated acquisitions. However, these approaches have limitations when the overall scan time exceeds a single breath-hold, which is often the case with more advanced functional imaging techniques. In such cases the extra time taken for motion control typically has to be recovered by making compromises in the design of the imaging sequence. This abstract focuses on multiple b-value diffusion-weighted imaging where the use of breath-holds or gating forces an undesirable reduction in the number of b-values and/or signal averages for a given imaging time. An alterative is to acquire images continuously without motion control and use registration techniques to post-process the images, which implies more data can be acquired in a given time. With diffusion-weighted imaging, the image brightness and contrast vary dramatically over the range of b-values typically used, and these differences imply that a simple approach where images from all b-values are registered to a fixed image is not possible. In this abstract we present a novel approach using a multi-exponential model of signal attenuation in conjunction with a sequential registration procedure. Source images are registered to target images synthesised at the matching b-value, which avoids difficulties with varying brightness and contrast leading to a highly effective motion reduction strategy.

Materials and Methods ***Signal Model*** This approach makes use of a signal attenuation model to generate synthetic target images at any b-value on which to register source images. For this application we are not concerned with the diffusion process in itself, but rather with the signal attenuation curve, so it is not necessary to use a model that affords a physical interpretation. The model proposed is the multi-exponential function[1] shown in the boxed equation, where D_i are a set of fixed positive decay rates and a_i are corresponding amplitudes to be estimated. The constraint $a_i > 0$ ensures that $S(b)$ is a positive attenuating curve, which means the amplitudes can be estimated using an un-regularized non-negative least-squares (NNLS) algorithm.

$$\boxed{S(b) = \sum_i a_i \exp(-b \cdot D_i)}$$

Registration Procedure The image registration procedure is sequential in b-value, starting with the lowest b-value. At step n assume we have $n-1$ registered images for b-values b_1 to b_{n-1}. The multi-exponential model is fitted to every pixel in the registered images using an efficient NNLS algorithm and the estimated parameters used to synthesize the image for $b = b_n$ using the above equation. The corresponding source image is then registered to this synthetic image, completing iteration n. The model fitting and registration steps are then repeated until all images have been registered. The initialisation procedure is to register the second lowest b-value image onto the lowest b-value image directly. Although this does not account for contrast changes with b-value, in practice any changes do not noticeably affect the registration. ***Implementation*** This algorithm was implemented in MATLAB (The MathWorks, Inc., Natick, USA) using the function *lsqnonneg* and a publicly available Medical Image Registration Toolbox[2] (MIRT). Fifty-one multi-exponential rate constants were used: $D_0 = 0$, and D_1 to D_{50} logarithmically spaced from 10^{-4} to 1 ($mm^2\ s^{-1}$). In this study we consider single slices only so that 2D registration is required. The MIRT settings were as follows: 2 hierarchical resolution levels of registration, mesh size of 10 pixels, transformation regularisation parameter lambda = 0.05, sum of squared differences similarity measure. ***Test Images*** Data were acquired from a volunteer at 1.5T on a Siemens Aera without breath-holds or triggering and using the following parameters: Prototype 2D multi-slice EPI sequence, TR/TE = 4000/72 ms, 1.48×1.48 mm pixels, 5mm slice thickness, 20 slices, field of view 380×345 mm, 1 NSA for 3 orthogonal directions with 32 approximately logarithmically spaced b-values between 0 and 1000 s mm^{-2}. To avoid effects of anisotropy, only data with diffusion gradients in the y-direction were fitted and images were cropped.



Top: RMS error maps of difference between data and multi-exponenital model fits (left, source data; right, registered data). Middle: data curves for four example pixels (A = liver, B = adrenal gland, C = kidney, D = spleen) showing source and registered data and the multi-exponential fitted curves. Registered data and fits are shifted up, both axes logarthmic and b=0 displayed at b = 10^0. Bottom: IVIM maps for source (above) and registered data (below).

Results and Discussion Visual assessment of all 32 images before and after registration confirmed that the registration has removed the majority of the motion. The registration quality was assessed by comparing the RMS errors from fitting the multi-exponential model to the source and registered data – see the top pair of images in the figure which show a clear improvement after registration. The RMS error image after registration suggests that there is unrecoverable motion in the renal pelvis and stomach – the individual images show that there is through-plane motion affecting the kidney, while the stomach contents cannot (and need not) be registered. Four anatomical locations are indicated on the images for which the data and model fits are also shown in the figure. The improvement in the liver is modest as this is a relatively homogeneous organ, whereas the lower boundaries of the kidney and spleen are dramatically improved after registration, as is the adrenal gland. An interesting property of the attenuation model is that although it is over-parameterized (i.e. the model has 51 parameters but there are only 32 data points) and therefore liable to overfit the data, the constraint $a_i > 0$ guarantees that the attenuation curves will be monotonically decreasing with b-value, which is a requirement for a diffusion-weighted MR measurement. A variety of such curves shapes are shown in the figure – the source data fits for cases C and D have a number of turning points in the curve that suggest over-fitting, while the fits for the registered data are simpler curves without turning points. The IVIM parameter fits demonstrate the utility of registration when functional read-outs are of interest. The effects of motion are clearly seen in the liver, kidney and spleen boundaries of all three parameters for the source data, and these are reduced in the registered data. Similar boundary effects persist in the registered f map but not in D or D*, which is consistent with a partial volume effect that cannot be removed with registration. We have successfully developed a novel model based approach for registration of DWI data.

References [1] Madler and Gieseke, Proc. ISMRM 2014, no. 2257. [2] https://sites.google.com/site/myronenko/

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