Measurement of the Diffusion Coefficient Within Lumbar Intervertebral Disks using High Dose Gadodiamide Enhanced MRI

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Abstract: The lumbar intervertebral disks are the largest avascular structure in the human body and there is considerable interest in the study of nutrient transport into and within these disks. High dose Gadolinium chelates have been used with MRI to visualize transport via T_1 change. In this work the subsequent enhancement has been modeled with a 1D solution of the diffusion equation to estimate the diffusion coefficient of Gadodiamide within the disks. Diffusion coefficients of $1.67x10^{-10}m^2s^{-1}$ and $1.8x10^{-10}m^2s^{-1}$ have been calculated from single disks in two healthy volunteers.

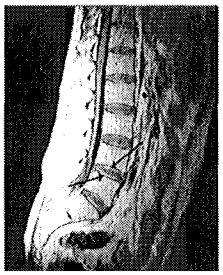
Introduction: Intervertebral disks are the largest avascular structure in the human body, and their mechanisms for nutrient transport have generated considerable interest. The first direct visualization of solute transport *in vivo* in humans has paved the way for more quantative measurement. (ref. 1). Other work in a canine model (Urban *et al.*)[2], has postulated that diffusion is the dominant mechanism and has measured diffusion coefficients of $3.0x10^{-10}m^2s^{-1}$ for glucose. The diffusion constant for self diffusion of water within human vertebral disks has been measured with diffusion weighted imaging to be $2.0x10^{-9}m^2s^{-1}$ (ref 3).

Model: Here we model gadodiamide transport through lumbar intervertebral disks utilizing the 1D spatial solution to the diffusion equation. Several basic assumptions are made: 1) that the 1D model is valid within the center of the disk; 2) that the intrinsic concentration of gadodiamide within the disk is low such that signal intensity is linearly proportional to concentration; 3) that the gadodiamide is delivered to the endplate in a pulse. Signal data was taken from the superior to inferior edges of a disk imaged at $2^1/_2$ hours post contrast. Figure 1 shows a typical image from which data was extracted. These data were fitted using a gradient expansion algorithm to a symmetric solution of the diffusion equation assuming similar input from both endplates. The functional form of the solution is $A e^{-Bz^2} + A e^{-B(z-z_0)^2}$. Where A is related to the concentration, z is distance and z_0 is the size of the disk. Figure 2 shows one such fit. The resulting decay coefficient, B is equal to 1/4Dt and for a given time, t, the diffusion coefficient, D can be calculated.

Data: A quadrature receive coil was used to acquire 35cm FOV, 384x512 image matrix, T1 weighted (Spin Echo TE/TR 20/500) images with three signal averages. Such images were acquired pre administration of a 0.3mmol/kg gadodiamide bolus and again at various time points post contrast, the first being 2.5 hours and the next 8.5hrs. These were all performed in the sagittal plane. Two asymptomatic male volunteers were examined, (aged 42 and 56 years). The images were rotated such that the vertical axis of the disk of interest was vertical in the image and a block of up to 11x17 pixels was extracted from the center of the disk. The mean of these data are used and a statistical error (standard deviation) used as weight in the fit. In one subject two discs were found suitable for analysis, in the other subject only one disc with sufficient width was centrally located with respect to the receive surface coil. Lower resolution data was also acquired at more frequent time points.

Results: In each of the volunteers the lower resolution data demonstrated signal enhancement within normal disks. There was band enhancement superiorly and inferiorly at the edge of the disk after one hour and evidence of this enhancement moving centrally after four hours was seen. The values obtained for the two healthy volunteers at $2^1/_2$ hours were $(1.7\pm0.3)\ x10^{-10}m^2s^{-1}$ and $(1.8\pm0.4)\ x10^{-10}m^2s^{-1}$. The measured values were lower than for the diffusion coefficient of water within the spinal disk[2]. This would be expected since the molecular size of Gadodiamide is greater, thus resulting in a slower diffusion process. At $8^1/_2$ hours, the data no longer exhibited a two-peak structure.

Discussion: The data has been shown to agree well with the solution to the diffusion equation. Clearly direct concentration measurement via $1/T_1$ would be preferable and the extension to fit multiple time points simultaneously will give more validation of the model. Further refinements are necessary in order to account for decay mechanisms and endplate offset, since the data fit begins at the intensity peak. The model is currently based on a pulse input function. Based on diffusion alone, this indicates that the highest concentration will always be at the edge. However, in some data the high signal bands have been seen to propagate toward the disk center. The body half-life of Gadodiamide is approximately 1.3 to 1.5 hours, and so a step input function may closer to the true input on the time scale of the present study.



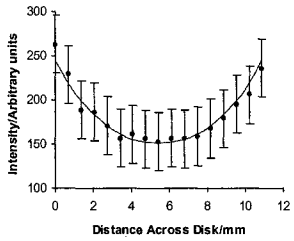


Figure 1(left): Lumbar spine image clearly showing contrast bands from each endplate within the disk (arrows).

Figure 2(right): The extracted data and fitted model. Lines of pixels spanning a disc from endplate to endplate were averaged and the standard deviation used for the curve fit weighting.

References

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Acknowledgement: Thanks to Diagnostic Investigation of Spinal Conditions and Sciatica (DISCS), The Arthritis Research Campaign (ARC) and Philips Medical Systems for supporting this work.