Clinical application of gamma distribution model for spinal lesions: Initial clinical results

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Target audience: Diagnostic radiologists

Purpose: Diffusion-weighted (DW) imaging has been used for the diagnosis and the assessment of treatment response of primary osseous and soft-tissue neoplasms[1]. The apparent diffusion coefficient is a quantitative measure of Brownian motion. Although DW imaging offers quantitative functional assessment of cellularity at the molecular level, it is still difficult to differentiate benign from malignant lesions. In recent years, non-Gaussian diffusion methods permitting the analysis of the DW signal over a larger range of b-values have gained an increasing importance in tissue characterization[2, 3]. Among them, it has shown that gamma distribution model exhibited a better performance than the conventional method and allowed for a significantly enhanced visualization of lesions[3]. Our purpose was to investigate the applicability and the performance of gamma distribution model in differentiating vertebral lesions in human subjects.

Methods:

Theoretical Background: Generally, heterogeneous systems give rise to more than one single diffusion coefficient. Assuming a continuous distribution of diffusion coefficients, P(D), the DW signal can be written as follows:

$$S(b) = \int P(D)\exp(-bD)dD \quad (1)$$

The gamma distribution function, PG(D) has been suggested recently[2]:

$$P_G(D,\kappa,\theta) = D^{\kappa-1}\frac{\exp(-D/\theta)}{\Gamma(\kappa)\theta^{\kappa}} \quad (2)$$

where Γ is the gamma function, θ is the scale parameter of the same dimensionality as the diffusivity, and κ is the shape parameter. Replacing P(D) in Eq. (1) by PG(D), Eq. (2), gives the following expression for the DW signal attenuation[2]:

$$S(b) = (1+b\theta)^{-\kappa}$$

The excess kurtosis K of the diffusion probability distribution function (PDF) can be calculated as:

$$K = \frac{\mu_4}{(\mu_2)^2} - 3 = \frac{12t^2(k^2\theta^2 + k\theta^2)}{4t^2k^2\theta^2} - 3 = \frac{3}{k} \quad (3)$$

where μn is n-th moment of the PDF.

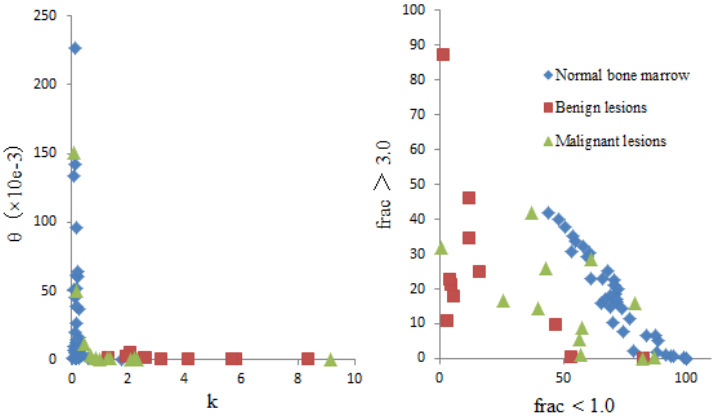
MRI examination: DW images of the lumbar spine were obtained from 23 spinal lesions in 50 subjects. Subjects were categorized as follows: patients with normal bone marrow (n=33), patients with benign spinal lesions (n=11; schwannona; 9, hemangioma; 2), and patients with malignant spinal lesions (n=12; metastatic tumor from pancreatic cancer; 1, breast cancer; 1, lung cancer; 2, prostatic cancer; 1, hepatocellular carcinoma; 1, chordoma; 1, multiple myeloma; 2, acute lymphocytic leukemia; 1, lymphoma; 1, myelodysplastic syndrome; 1).

Table 1 MR parameters for the three groups.

	Normal BM	*Benign lesion*	*Malignant lesion*
κ	0.252 ± 0.32	3.94 ± 2.18**	1.79 ± 2.44$^{**,+}$
θ	32.2 ± 48.4	0.99 ± 1.25**	18.4 ± 43.9*
frac <1	72.3 ± 15.0	22.1 ± 25.6**	52.2 ± 24.8$^{*,+}$
frac >3	17.1 ± 12.7	24.9 ± 24.8	15.9 ± 13.7
PG (D)	50.06 ± 35.60	1963 ± 2554**	473.9 ± 602.9$^{**,+}$
K	20.3 ± 14.2	1.02 ± 0.58**	8.20 ± 14.43$^{**,+}$

$^{**}P < 0.01$, normal bone marrow vs. benign or malignant lesion.
$^{**}P < 0.05$, normal bone marrow vs. benign or malignant lesion.
$^{+}P < 0.05$, benign lesion vs. malignant lesion.

Figure 1. Scatter plots of θ vs κ (Right) and frac > 3 vs frac <1 (Left).



MRI examinations were performed on a 3T system (Ingenia; Philips Healthcare) equipped with the anterior coil and the integrated posterior coil. Single shot DW EPI with 5 values (0,500,1000,1500,2000) on three orthogonal axes were performed with the following acquisition parameters: TR/TE =8000/84 ms, FOV= 35×35 cm^2, matrix size 192×192, in-plane voxel size 1.8×1.8 mm^2, slice thickness 4 mm, number of slices 11, slice gap 1 mm, factor of 3 SENSE on the phase direction, and 1 averages.

Mean signal intensity was calculated by placing operator-determined regions of interest (ROIs) within the spinal lesions or within normal bone marrow (BM) for each b-value in each subject. The ROI for normal BM was defined manually within the internal part of the L1–L3 vertebral bodies in the midsagittal images because these spinal levels were less affected by degenerative disc disease compared to lower lumbar elements. Signal intensity values for BM were then calculated as the mean value obtained from the three vertebral bodies and used as normal BM data. The ROI was placed at the same location on all DW images. The largest focal lesion in each patient was measured.

For each of normal BM and spinal lesions, θ, κ, the area fraction of D < 1.0mm^2/s (frac <1), the area fraction of D > 3.0 mm^2/s (frac >3), PG (D) and K was measured using equations (1-3). High D values were thought to reflect highly cellular microenvironments in which diffusion is limited by an abundance of cell membranes, whereas low D values were thought to be observed in acellular regions that allow free diffusion of water molecules.

Parameters of the three groups (i.e., normal-, benign-, and malignant group) were compared by the Kruskal-Wallis test. A scatter plot of θ vs κ and frac > 3 vs frac <1 were also generated.

Results and discussion: Table 1 summarizes the MR parameters for the three groups. All MR parameters except for frac > 3 were significantly different between normal BM and lesions. κ, frac <1, PG (D), and K proved to be useful for differentiation of malignant lesions from benign lesions (Table 1).

Figure 1 shows scatter plots of θ vs κ and frac > 3 vs. frac <1. Malignant lesions tended to be located between normal BM and benign lesions in the both parameter spaces. In the θ vs. κ space, normal BM data distributed along y-axis, while benign lesions located near x-axis. In the frac > 3 vs. frac <1 space, normal BM data were more linearly distributed than those of malignant or benign lesions, which suggested that MR signal decay patterns had certain specific tendency in BM of the normal subjects. In contrast, data of 11 benign lesions were widely distributed in spite that most of them were schwannoma (9 out of 11), which could reflect difference in tumor tissue characteristics.

Conclusion: In conclusion, we have shown initial clinical results that gamma distribution model was useful in the characterization of spinal lesions and provides potentially valuable information for tissue characterization. This also refers to differentiation of malignant lesions from benign lesions, in which κ, frac <1, PG (D), and K proved to be useful.

References: [1] Herneth, AM, et al. Radiology. 2002 225: 889-894. [2] Oshio K. Magn Reson Med Sci. 2014 13:191-195. [3] Grinberg F, et al. PLoS One. 2014 9:e89225.