Simultaneous Determination of Pore Sizes and Direction in Tilted Microcapillaries by Angular-Double-Pulsed-Field-Gradient (d-PFG) NMR.

Darya Morozov[1], Leah Bar[1], Nir Sochen[1], and Yoram Cohen[1]

[1]*The Raymond and Beverly Sackler Faculty of Exact Science, Tel-Aviv University, Tel-Aviv Yaffo, Tel-Aviv Yaffo, Israel*

Introduction. Axon size is an important parameter which affects conduction velocity in neuronal tissues [1] and, indeed, in recent years, efforts have been directed to measure this parameter non-invasively [2,3]. More recently angular d-PFG MR experiments [4] were used to obtain microstructural information in different neuronal tissues [5-7]. However, since in many cases the ground truth of the studied samples is not known a priori, other and we have used microcapillaries phantoms of different complexity to challenge the microstructural information that can be obtained by modeling the signal in different NMR experiments [8-10]. More recently such phantoms were used to challenge the microstructural information that can be obtained from angular d-PFG NMR experiments [11]. In the present study, we attempted to evaluate simultaneously the size and direction of such systems from angular d-PFG NMR experiments.

Objectives. To evaluate the ability of angular d-PFG diffusion MR to provide, after proper modeling, both the size and the tilted angle, i.e. the direction of the sampled compartment simultaneously with very little prior knowledge.

Methods. Diffusion measurements were performed on a 8.4 T NMR spectrometer equipped with a gradient system capable of producing pulse gradients of 1900 mT/m in each direction. Experiments were performed first on microcapillaries having an ID of 23±1 µm and then on a ~1:1 mixture of microcapillaries having IDs of 23±1 µm and 15±1 µm. The angular d-PGSE MR experiments were performed when the orientation of the first gradient pair (G_1) was in the x-direction while the second gradient pair (G_2) was varied in the xy plane. For each q-value 25 phi (φ) angles for G_2 were collected between 0° and 360°. Since we could not physically rotate the microcapillaries in our vertical probe magnet, we rotated the coordinates of G_1 and G_2 as to achieve an effective known rotation. G_1 was rotated in the xz plane from α of 0 (G_1 along the x-direction) to α of 90° (G_1 along the z-direction) while G_2 was rotated accordingly from the xy plane when α was 0 to the zx plane when α was 90. The angular d-PGSE experiments were performed with the following parameters: 20 q-values were collected with G_{max} of 80 G/cm and $\delta_1 = \delta_2 = \delta_3 = 2$ ms, resulting in a maximal q-value of 681 cm^{-1}. The diffusion times, Δ_1 and Δ_2, were set to 150 ms and the t_m was set to zero. The fittings were performed with and without prior knowledge of alpha during the fitting procedure, assuming for the 23±1 µm microcapillaries that their diameters are in the range of 16 to 40 µm. For the fittings of the experimental data of a mixture of microcapillaries having IDs of 23±1 µm and 15±1 µm, a diameter range of 10 to 40 µm was assumed. In all fittings, D_0 was set to $2 \cdot 10^{-9}$ m^2, i.e. the diffusion coefficient of the water in the microcapillaries along the z-axis where diffusion is free.

Results and Discussion. Figure 1A shows the simulated E(φ) profiles of an angular d-PGSE experiments with zero mixing time for a 23.4 µm microcapillaries sample aligned in different directions, i.e. for different alphas. Here ten different alphas from 0° to 90° were used. Clearly, when the alpha is equal to zero (G_1 is along the x-direction and G_2 is rotated in the xy-plane) the well-known bell-shaped function is obtained. As alpha becomes larger two maxima are observed for each E(φ) profiles at (φs) of 90° and 270° with a minimum observed for φ of 180°, as expected. Figure 1B shows the experimental E(φ) profiles of the angular d-PGSE experiments and their fittings performed on a mixture of 23±1 and 15±1 µm microcapillaries with and without prior knowledge of alpha values during the fitting procedure. One can observe that the results of the two fittings are very similar and are both in good agreement with the experimental data. The results from the modeling of the d-PFG NMR experiments for both samples are summarized in Table 1. The above results show that the modeling procedure is indeed able to provide both the main direction and the size of the microcapillaries simultaneously with high accuracy and with very little prior knowledge even for phantoms which are not monodisperse in size. However, Table 1 also shows that for sample comprising of different sizes, although the modeling is able to reproduce the direction of the microcapillaries, only a weighted average of the sizes is obtained.

Conclusions. We demonstrated that through modeling of the signal in angular d-PFG NMR experiments one can determine accurately both the size and direction of microcapillaries with high precision. However, when samples having different sizes are investigated at high tilted angle, only a weighted average of the sizes was extracted.

Figure 1. (A) Simulations of E(φ) profiles for angular d-PGSE experiments performed on 23.4 µm microcapillaries for ten different alphas. (B) E(φ) profiles of the angular d-PGSE experiments and their fittings performed on a mixture of 23±1and 15±1 µm microcapillaries. Symbols represent experimental data, the dash and dots represent the fitting curves with and without prior knowledge about alpha value during the fitting procedure, respectively.
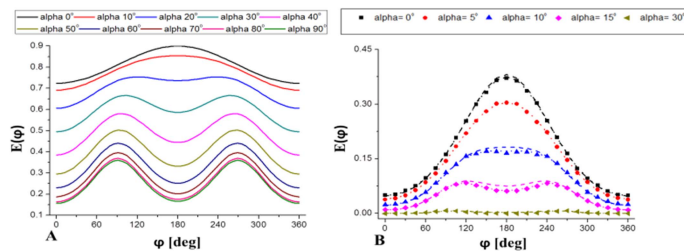
Table 1. Compartment sizes and alphas obtained from the fittings of the experimental angular d-PGSE data.

	alpha [deg]	ID [µm]	measured alpha [deg]	SD of fit		alpha [deg]	ID [µm]	fraction	measured alpha [deg]	alpha [deg]	SD of fit
23±1 µm	0	23.5	1.4	3.02·10^{-2}	**15-23 µm**	0	15.3 / 23.5	0.57 / 0.43	1.3 / 0.8	1.1	1.65·10^{-2}
	5	23.4	4.8	3.51·10^{-2}		5	15.2 / 23.4	0.54 / 0.46	4.9 / 5.6	5.2	1.78·10^{-2}
	10	23.5	9.9	3.29·10^{-2}		10	15.0 / 23.4	0.55 / 0.45	11.1 / 9.4	10.4	4.49·10^{-2}
	15	23.3	15.5	4.20·10^{-2}		15	14.9 / 23.2	0.57 / 0.43	16.9 / 14.6	15.9	8.16·10^{-2}
	30	22.5	31.4	5.64·10^{-2}		30	18.0	1	32.3	32.3	0.213

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