New sequence for a fast and accurate measurement of hyperpolarized helium-3 diffusion

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Introduction

Small flip angles sequences have been widely used for MRI and diffusion weighted MRI of hyperpolarized nuclei[1]. However other sequences with better signal to noise ratio (SNR) can be also used, such as multi-echo sequences[2-3]. Restricted diffusion in the lungs cause a complex behavior of signal attenuation as a function of both gradient intensity and diffusion time[4-5], thus rising the interest in measurement sequences with several b-values for HP gases. In this work, a new sequence based on the CMPG scheme was compared to a small flip angle sequence. Achievable SNRs per unit time were experimentally compared.

Materials and Methods

A cylindrical sealed glass cell (4.5 cm length and diameter) filled with helium-3 at 16 hPa at room temperature was used. Helium-3 was polarized by the metastable exchange method[6]. A 40% polarization in the cell was reproduced within 10%, as confirmed from the NMR signal amplitude. Experiments were performed on a 0.1 T scanner (Magnetech, France), controlled by an Apollo sequencer (Tecmag, Houston, TX, USA). A 40-cm saddle-shaped RF coil was used for transmission (Q=45), and a 10-cm diameter Helmholtz coil for reception (Q=340). Two sequences were used, a small flip angle sequence (S1) and a CPMG sequence (S2) (Fig. 1). S1 consisted of a series of 22 FIDs. After a RF hard pulse, a bipolar gradient (ramp duration 2.2 ms, plateau duration 0.6 ms, gradient amplitude G varying from 0 to 0.21 mT/m) was applied and signal was acquired. The remaining transverse magnetization was finally destroyed with a crusher gradient. The 10 first repetitions were used to accurately determine the signal loss by RF excitation and T_1 relaxation between two repetitions, and the last 12 FIDs to obtain signal attenuation by diffusion. S2 consisted of a series of 34 echoes, generated by $180°_y$ hard pulses following an initial $90°_x$ RF pulse. Similarly to S1, the 10 first echoes were used to accurately determine the T_2 relaxation. The same bipolar gradient as in S1 was applied every 2 echoes for the last 24 echoes to measure signal attenuation. Experiments were performed for G applied along each of the three gradient axes. Sequence parameters are compared in Table 1. The raw SNR was defined as the ratio of the mean magnitude to the standard deviation of the real part. Each signal magnitude was deduced by fitting the complex data to an exponential decay. For S1 (resp S2), a nonlinear fit of the 10 first FID (resp echo) magnitudes was used to assess signal loss by RF excitation and T_1 (resp T_2). Diffusion-weighted signals were then corrected to get signal attenuation induced by diffusion in the bipolar gradient. Signal attenuation was compared to numerical simulations performed with the Multiple Correlation Function approach[7].

Results

For the first echo with non-zero applied diffusion gradient, the raw SNR with S2 was 190, about 2 times higher than with S1, in good agreement with the ratio expected from the bandwidth BW and flip angle used with each sequence. When taking into account the difference in total acquisition times, the raw SNR per unit time with S2 was 7.7 times superior to that with S1 and remained superior for all G values. However, for the last 4-G values, the raw SNR became up to 2 times higher for S1 relative to S2. Signal attenuation corrected for flip angle and T_1 losses for S1, and corrected for T_2 for S2, is plotted on Fig. 2 as a function of the bipolar gradient amplitude, for G applied along X. Adjustment of complex data improved the accuracy on signal magnitude by one order of magnitude compared to the available raw SNR. The behavior of the signal attenuation with the two sequences was similar for the same 12 values of the diffusion bipolar sensitizing-gradient, in excellent agreement with the numerical simulation. Similar observations were made for the two other directions Y and Z.

Table 1: Parameters of the two sequences S1 and S2, experimental raw SNR and raw SNR per unit time for the first non-zero G value.

	flip angle	RF duration	BW	samples	repetition time	total duration	raw SNR	raw SNR per unit time
S1	23°	30 µs	4 kHz	300	TR = 130 ms	2.9 s	94	32 s^{-1}
S2	180°	237 µs	38 kHz	256	tcp = 20 ms	0.76 s	190	250 s^{-1}

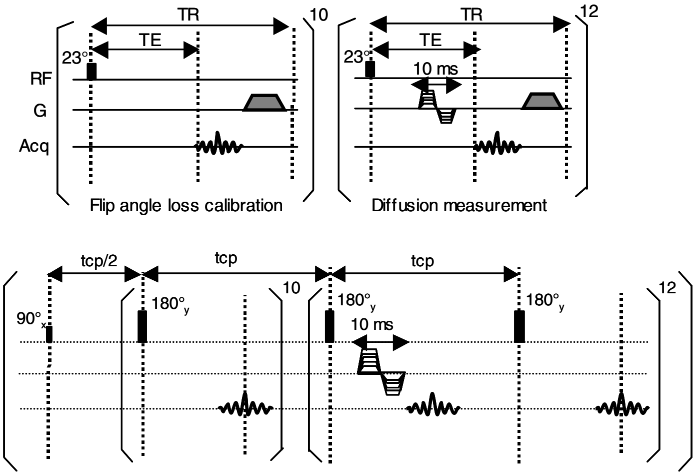

Fig. 1: sequences: 22 FIDs for S1 and 34 echoes for S2

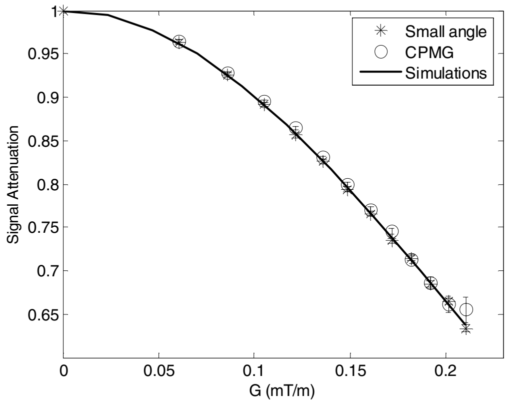

Fig. 2: HP-^{3}He NMR signal attenuation as a function of G at 16 hPa

Discussion and Conclusions

The SNR per unit time was much higher with S2 for the majority of G values. Although more echoes with S2 were collected than FIDs with S1, the total acquisition time for S2 was almost 4 times shorter. For interconnected porous media, signal attenuation follows the $\exp(-k \cdot G^2)$ dependence only for low gradients, in which limit the ADC can be defined[8]. But with low gradients the attenuation is lower and the sensitivity reduced. Thus our technique provides a fast and accurate ADC assessment. Note however that irreversible signal losses are caused by each bipolar gradient, which implies a cumulative sensitivity decay with S2. On the other hand, long T_2s and T_2*s found on animals[9] and humans[2] at low magnetic field open the possibility of using longer tcps; thus the delay between the two pulses of the bipolar gradient can be increased to study the ADC time-dependence. Preliminary *in vivo* results on an animal model (rat) confirm this possibility. Finally the CPMG sequence gives faster and more accurate results than the small flip angle one, and opens new possibilities for fast assessment of ADC time and wavelength dependences.

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