Relaxation of Hyperpolarized ^{129}Xe in a Flexible Gas Reservoir

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Introduction: MRI with the hyperpolarized (HP) noble gas isotopes ^{3}He and ^{129}Xe holds great promise for regional assessment of ventilation, perfusion, gas exchange, and lung microstructure [1]. In many experiments, especially those involving high-resolution imaging of small animals where HP gas consumption does not represent a severe experimental limitation, data is acquired over many consecutive scans and many repeated deliveries of the HP gas. In these experiments, it is typically assumed that the input signal, i.e. the magnetization inside the HP gas reservoir, is constant for all scans. However, this condition of constant magnetization is usually not fulfilled for long experiments due to unavoidable relaxation during HP gas storage. Moreover, the spin-lattice relaxation time, T_{1R}, inside flexible plastic bags, which often serve as HP gas reservoirs, is not constant because surface induced relaxation caused by interactions between the HP gas atoms and the container walls becomes comparable to, or even exceeds, the bulk gas relaxation when the bag is deflated [2]. Precise knowledge of T_{1R} as a function of the time-dependent reservoir volume is thus required for addressing (or correcting) such effects in quantitative MRI.

Methods: Natural abundance xenon was hyperpolarized to 5-10% in batches between 100 and 300 mL by using a prototype commercial polarizer (MITI, Durham, NC). Following cryogenic accumulation, xenon ice was thawed into 350-ml Tedlar bags (Jensen Inert Products, Coral Springs, FL) located within a Plexiglas cylinder (Fig. 1). The cylinder was immediately placed within the fringe field of the magnet and aligned with its bore. The bag was then pressurized to ~1.2 kPa above ambient pressure by flowing N_2 gas from a supply tank into the cylinder. The flow of xenon out of the bag was controlled using a direct-reading gas flow meter (Cole-Parmer, Vernon Hills, IL). Using polyethylene tubing, HP ^{129}Xe was passed through the RF coil (6.6-cm long, 3.3-cm diameter solenoid) for repetitive spectroscopy. HP ^{129}Xe spectra were acquired using a 2-T, 30-cm horizontal-bore magnet (Oxford Instruments, Oxford, UK) controlled by a GE EXCITE 12.0 console (GE Healthcare, Milwaukee, WI). Dynamic measurements of the signal decay were performed with a series of evenly spaced 1° RF pulses. A total of seven experiments were performed with variation of the initial inflation volume, $V(0)$, xenon gas flow, Q, and the repetition time, TR.

A model developed by Fujiwara et al. [3] to describe T_1 of ^{129}Xe inside different sized rigid cavities was adapted for studying the deflating Xe reservoir (Box 1). The overall relaxation rate is given by contributions from the relaxation rate of bulk xenon gas, $1/T_{1\infty}$, and the surface relaxation rate, $1/T_{1s}$ (Eq. 1). T_{1s} is obtained from the number of wall collisions per unit time, which can be computed from the average squared distance to an arbitrary point on the surface and the Einstein relation. Assuming spherical reservoir geometry, the decay of the HP magnetization is given by Eq. 2.

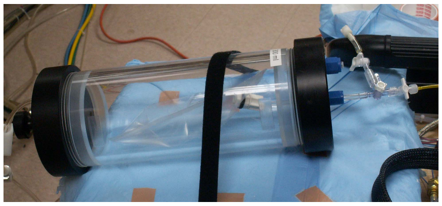

Fig. 1. HP ^{129}Xe reservoir (Tedlar bag) inside a pressurized Plexiglas cylinder.

$$\frac{1}{T_{1R}}=\frac{1}{T_{1\infty}}+\frac{1}{T_{1S}}=\frac{1}{T_{1\infty}}+\frac{6D}{\langle l^2\rangle}\kappa=\frac{1}{T_{1\infty}}+\frac{375^{1/3}\pi^{2/3}D}{4^{1/3}V^{2/3}}\kappa \qquad (1)$$

$$M_z(t)\approx M_z(0)\exp\left(-\frac{t}{T_{1\infty}}\right)\exp\left(-\frac{375^{1/3}\pi^{2/3}}{4^{1/3}V^{2/3}}\kappa Dt\right) \qquad (2)$$

Box 1. D: diffusion coefficient, $\langle l^2\rangle$: average squared distance; M_z: magnetization, T_{1s}: surface relaxation time; $T_{1\infty}$: gas-phase relaxation time; t: time. V: volume, κ: wall relaxivity.

Results and Discussion: Depolarization within the reservoir is demonstrated in Fig.2, which shows the signal intensity observed by passing the HP ^{129}Xe gas at 5 mL/min directly through the RF coil. Fitting results are summarized in Table 1. Because bulk ^{129}Xe gas is slow, estimates of $T_{1\infty}$ were only obtained in only three scans with sufficient accuracy due to the comparatively short experimental duration. However, the resulting $T_{1\infty}$ values are in good agreement with studies of relaxation due to transverse magnetic field gradients. Variations in the obtained surface relaxivities between scans are explained by different amounts of absorbed impurities, such as paramagnetic O_2. Despite the simplifications inherent in the model (e.g., spherical geometry; no consideration of a constant surface area of the bag), the fits show excellent agreement with the experimental data.

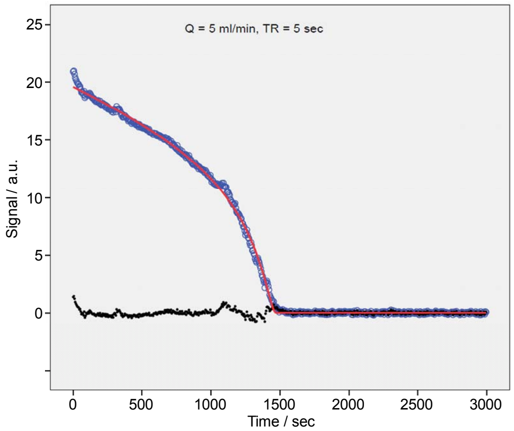

Fig. 2. Example of fitting results (blue circles: exp. data, red solid line: fitted decay, black dots: residuals).

Exp.	Q [ml/min]	TR [sec]	$M_z(0)$ [a.u.]	$V(0)$ [ml]	$T_{1,\infty}$ [sec]	κ	r^2
1	2	10	60480 ± 170	173.9 ± 3.4	—[a]	0.04032 ± 0.00086	0.998
2	5	5	195490 ± 400	123.4 ± 0.2	9520 ± 820	0.00879 ± 0.00019	0.999
3	10	2.5	171180 ± 410	142.3 ± 0.1	—[a]	0.00374 ± 0.00009	0.997
4	7.5	3	187200 ± 550	128.9 ± 0.2	32000 ± 15000	0.00853 ± 0.00023	0.996
5	15	2	235230 ± 570	138.0 ± 0.1	—[a]	0.00651 ± 0.00016	0.999
6	5	5	190700 ± 1100	262.8 ± 5.3	—[a]	0.0239 ± 0.0024	0.986
7	10	5	180680 ± 370	261.1 ± 0.4	5130 ± 210	0.01030 ± 0.00023	0.999
Average values:[b]					**5430 ± 210**	**0.00592 ± 0.00007**	

[a] No reliable result obtained from fit (*i.e.*, error estimate exceeded fitted value).
[b] Weighted means ± standard deviations.

Table 1. Fitting results.

Conclusion: The change of T_{1R} of HP ^{129}Xe in a deflating Tedlar bag is accurately described by a model based on simple spherical geometry and the kinetic theory of gases. A change of T_{1R} leading to a depletion of the input signal over the course of raw data sampling results in sub-optimal signal utilization, degrades the point-spread function, and may produce artifacts or errors in quantitative MRI. Such effects might be avoided if, e.g., the change of T_{1R} is explicitly considered by use of a variable flip angles to obtain uniform k-space weighting.

References: [1] H.E. Möller; Magn. Reson. Med 47, 1029 (2002). [2] H.E. Möller; J. Magn. Reson. 135. 133 (1998). [3] H. Fujiwara; J. Magn. Reson. 150, 156 (2001).

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