Signal Dynamics during Dissolved-Phase Hyperpolarized 129Xe Radial MR Imaging of Human Lungs


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Introduction: Direct MR imaging of HP 129Xe dissolved in the gas exchange tissues and capillary blood of rat lungs was recently demonstrated using a multiple breath, 2D radial imaging strategy. In this work we extend these efforts to the direct, 3D imaging of dissolved 129Xe in humans. Because data acquisition in humans is confined to a single breath hold, it is essential to make optimal use of the available dissolved 129Xe magnetization. Several Fick’s second law-based models have been proposed to describe dissolved 129Xe dynamics within lungs that yield information about alveolar surface-to-volume ratios, dissolved Xe diffusion coefficients, and interstitial barrier thickness. However, these approaches, which rely upon infinite series solutions to the diffusion equation, are not well-suited to optimizing dissolved 129Xe MRI. Further, dissolved Xe excitations attenuate the source gas-phase magnetization through diffusive exchange and, thus, indirectly reduce the dissolved 129Xe signal during imaging. In this work, we develop a more suitable mathematical framework for analyzing the dissolved 129Xe magnetization dynamics in the context of single-breath radial imaging in humans. Because each radial view contains the k-zero value as the first data point, every image contains dynamic information that can be used to extract additional insights into global processes within the lungs using our model.

Methods: Studies were performed during a GE Healthcare sponsored, Phase I clinical trial for 129Xe MRI and involved 24 healthy volunteers who provided informed consent. Work was conducted under a GE Healthcare IND and approved by our IRB. MR data were obtained at 1.5 T using a GE EXCITE 14M5 MR scanner. Subjects received a 200 ml calibration and 4, 1-L doses of isotopically enriched Xe (83% 129Xe) polarized to 6-9% using 2 prototype GE polarizers. Dissolved 129Xe images were acquired within a 16 s breath hold period using a constant flip angle, 3D radial sequence (3471 k-space views, matrix=32×40×48 cm, TR/TE=4.2 s, BW=15.6 kHz). Spectra were acquired with various BWs, TRs, and numbers of points. For both spectroscopy and imaging, dissolved 129Xe was selectively excited using a 1.2 ms 3-lobe sinc pulse applied 3826 Hz above the gas phase 129Xe frequency.

Results: Even when using a selective RF pulses, small levels of gaseous 129Xe are often excited (Fig.1A). While this introduces a small level of off-resonance noise in imaging, the resulting spectra can be used to determine the contribution of dissolved 129Xe excitation to the apparent gas-phase relaxation rate (1/TE, Fig. 1 B,C). Using this information, three coupled 1st order differential equations can be constructed to describe the effects of relaxation, gas exchange, and pulmonary perfusion on the dissolve HP 129Xe magnetization. The solution to these equations, coupled with the effects of RF, is given below. A summary of more complex, equation describes the magnetization present in the pulmonary venous blood. In the equation, 1/TF is the apparent relaxation rate in tissues, which depends upon diffusion, relaxation, and perfusion. K, which is on the order of 100 ms e, is the rate of diffusive magnetization replenishment in the gas exchange tissues, and MT(n-1) is the dissolved magnetization present immediately before the n-th RF pulse. This model indicates that the initial dissolved magnetization dynamics are dominated by the interplay of RF attenuation and diffusive replenishment of dissolved magnetization. The longer-time dynamics are dominated by the apparent gas-phase relaxation rate of 129Xe, which depends indirectly on the RF attenuation. Further, it is possible to define an ‘optimum’ flip angle that minimizes image distortions due to signal decay throughout the image acquisition by maximizing the signal intensity obtained from the final RF pulse. A simulation demonstrating the flip angle dependence of the final signal intensity, based on our model, is shown in Fig. 1D. These results suggest that dissolved 129Xe MRI is optimized by using rather large flip angle RF pulses (>6°), which is in agreement with our empirical observations (Fig. 1F).

Conclusions: Directly imaging HP 129Xe dissolved in human lungs within a single, 16 s breath hold is feasible using 3D radial imaging. The image quality obtained from dissolved 129Xe is optimized by using relatively high (>8°) RF pulses. This observation can be rationalized in light of a relatively simple, closed-form mathematical model, which incorporates known pulmonary physiology including perfusion, O2 partial pressure, and gas exchange tissue volume. These results also highlight a unique advantage of radial imaging, which allows information about whole-lung magnetization dynamics to be extracted from raw image data.

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