Continuous Flow 1.5T in-bore Overhauser DNP for 1H and 13C hyperpolarization: Quantification of Polarization Build-up to Optimize the MR-Imaging Efficiency

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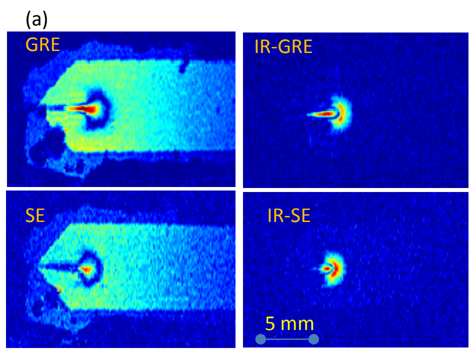
Motivation

Dynamic Nuclear Polarization (DNP) is a technique to achieve hyperpolarization of MRI agents by microwave irradiation of electron spins in radicals, which are coupled to the nuclear spins. The factor 1840 difference in the value of electron and nuclear magneton makes it possible to enhance NMR signal significantly over that at thermal equilibrium. Recently, the first in-bore **liquid-state** "Overhauser DNP" (ODNP) at 1.5 T for ^{1}H nuclei that was reported which allows placing the polarizer core inside MRI magnet very close to the imaging objects and delivery of hyperpolarized (HP-) agent **in continuous flow mode** [1][2]. The volume of continuously DNP-hyperpolarized substrate, which can be pumped during certain time through the polarizer cavity, is limited by the flow-rate and microwave power. Furthermore, the amount of polarization build-up per time depends both on flow-rate and T_1. Therefore, a net polarization efficiency of polarizer is a complicated trade-off for which, to our knowledge, no comprehensive theoretical model has been established. We performed the study in order to establish the method of magnetization build-up quantification in order to optimize the SNR and CNR of the images obtained with ODNP hyperpolarization of ^{1}H and ^{13}C nuclei.

Theory

At steady-state conditions the amount of magnetization contributed to MRI image intensity under continuous flow ODNP is governed by the balance equation which includes the DNP-build-up function $B(T_1)$, net volume inflow V and losses due to T_1 and rf-pulses irradiation $R(T_1, \cos(\alpha))$: $\Delta M = (\Delta B \cdot V - \Delta R) \cdot \Delta t$. The simulated image intensity S_N is the cumulative sum of the ΔM weighted with the k-space trajectory function E(k) over the encoding time period PE*TR, where PE is the number of k-space encodings and TR is repetition time. The S_N will be the function of both TR and flip angle α. Measuring the image intensity $S_{exp}(TR)$ and knowing the loss function $R(T_1,\cos(\alpha))$ the built-up function $B(TR,T_1)$ can be constructed. However, when performing the ^{1}H experiment the inflowing hyperpolarized substrate always mixes with the thermally polarized one that would distorts quantification of the volume. This can be avoided if to use the fact that DNP-built magnetization is inverted relative to the thermal one. Therefore, by applying preparation inversion pulse and adjusting inversion period to $TI=2\cdot\log(T_1)$ the signal of "thermal" background magnetization can be suppressed.



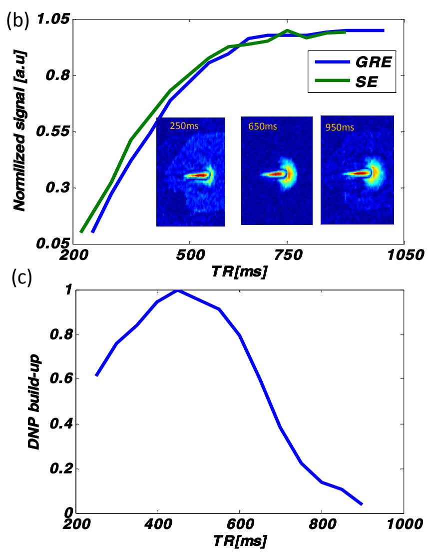


Fig 1
(a) Suppression of "thermal" signal by inversion recovery preparation for SGRE and Spin-Echo sequences. Resolution **0.1mm²** in-plane with slice thickness 0.4mm (determined by flat-cell gap). The dark hallo in non-IR images marks the border between "DNP" and "thermal" magnetization which is too fuse for the non-IR measurements for quantifying of the volume but perfectly sharp with IR-preparation.
(b) Establishing steady-state conditions between fresh magnetization inflow and signal losses due to T_1-relaxation and rf-pulses traced by TR variation
(c) Polarization build-up function in polarizer reconstructed from steady-state condition establishing profile (b)

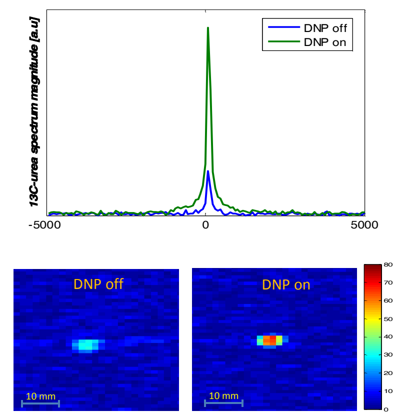


Fig 2 ^{13}C-urea MR-signal enchancement by continuous flow ODNP. Top: Single-shot FID spectrum (magnitude); Bottom: MR-imaging. Imaging parameters: GRE, TR/TE=650/2.2ms, matrix size 64x64, FOV=100mm;

Materials and method

The microwave energy for DNP at frequency 42 GHz are transferred to the hollow-bore copper resonator (ID=11 mm) inside the scanners magnet by the 3m wave-guide. The hyperpolarized agent in resonator streams through the ID=0.4mm quartz capillary. The outlet capillary (ID=0.15 mm) transfers it to 0.4 mm plexiglas flat-cell is used as a phantom. Using of flat-cell allows quantitative measurements of amount of polarized substrate without partial volume effect. Both ^{1}H and ^{13}C MR-images were acquired by 1.5T MR-Scanner Sonata, (Siemens, Erlangen, Germany). The 20 mmol/l solution of TEMPOL (with addition of 30mmol ^{13}C-urea for ^{13}C experiments) was streamed with flow rate of 10-30 ml/hours. SE and SGRE sequences with IR-preparation have been used. All numerical simulations were done using MATLAB (Mathworks, USA).

Results and Conclusion

Fig 1a shows that the background thermal magnetization signal can be effectively suppressed by the IR-preparation both for SE and GRE sequence. Thus, the pure DNP-magnetization volume without "thermal contribution" was measured by varying TR time. For both sequences the acquired signal $S_{exp}(TR)$ (measured as sum of pixel intensity) demonstrates the expected saturation plateau indicating approaching to a steady-state balance between fresh magnetization inflow and relaxation losses (Fig 2b).

The proposed method to study the establishing of steady-state flow of hyperpolarized liquid allows quantifying the efficiency of the ODNP net magnetization build-up. The reconstructed polarization built-up efficiency function (Fig 1c) allows determination of the optimal time of substrate passage the polarizer cavity, which can be used for adjustment of flow-rate for substrates with different T_1 time to get optimal SNR at given imaging time. We performed the pilot measurements using ^{13}C-urea substrate (Fig 2). The spectroscopic enhancement of 10 and imaging by factor 2 is achieved. The result is yet below expected value probably due to the significant changes the viscosity introduced by the urea in the TEMPOL solution that is limiting factor for the ODNP efficiency in our experiment. Thus, the new optimization and adjustments must be done specifically for this substrate to get optimal enhancement of ^{13}C-images.

References [1] Krummenacker at al, JMR, DNP in MRI: An In-bore Approach at 1.5 T. JMR, 215(0):94-99, 2012. [2] E.R. McCarney et al, "Hyperpolarized water as an authentic magnetic resonance imaging contrast agent, PNAS , 104 (6) pp.1754–1759, 2007

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