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The Need and Initial Practice of Parallel Imaging and Compressed Sensing in Hyperpolarized ^{13}C MRI *in vivo*

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Editorial Dissolution dynamic nuclear polarization (dDNP) development, which involves rapidly dissolving hyperpolarized compounds mixed with an electron paramagnetic agent, has enhanced the signal-to-noise ratio 10,000+-fold of MRI signals [1]. MR imaging of these hyperpolarized ^{13}C substrates allow for non-invasive detection of various disease processes via metabolic and physiological alterations [2]. However, the major limitation of dDNP is the rapid decay of the hyperpolarized state, which is governed by the T1 of the compound, such as pyruvate, resulting in a short imaging window [3]. As a compounding effect, the non-recoverable magnetization is further depleted with every applied radiofrequency pulse, which creates challenges directed at efficiently using the hyperpolarized magnetization for fast imaging [3].

Different k-space acquisitions, such as compressed sensing echo-planar spectroscopic imaging [4], multiband excitation echo planar imaging [5], and spiral trajectories, have been designed to meet the aforementioned challenges [6]. While these acquisitions have the necessary spectral resolution, the trade-off is that they are limited in spatial resolution. In that sense, the balanced steady-state free precession sequence has the advantage of offering the highest signal-to-noise ratio per unit time among all sequences [7,8], and has consequently been utilized in HP ^{13}C imaging for high resolution imaging [9]. However, depending on the probe of interest, due to differing T1 and T2 values, the need to further speed up acquisitions to elucidate more information, such as metabolism, kinetics, and dynamics, is still a high priority in HP ^{13}C imaging.

One prominent method used to speed up MRI acquisitions is parallel imaging [10–12], which will be the focus of this paper, focusing mainly on its applicability in HP ^{13}C imaging, which has only recently been investigated due to the relatively novel concept of dDNP and its consequent application to preclinical models and its potential translation to the clinic. In general, parallel imaging MRI involves utilizing multiple receiver RF coils or sometime transceive RF coils [13–25] to obtain spatial information of the object of interest,

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and consequently reconstructing the images based on the sensitivity information of each individual RF coil element [26]. Thus, k-space can be under sampled, thereby speeding up an MRI acquisition by some acceleration factor, and the desired image can still be reconstructed even with fewer k-space lines acquired. Therefore, parallel imaging is not a change in the pulse sequence, but rather a reconstruction technique, of which different approaches exist.

The acquisition strategy and reconstruction algorithm from a given under sampled MRI parallel imaging experiment can be split into two current approaches: a sensitivity encoding (SENSE) approach, which uses the explicit knowledge of the sensitivity of each coil [11] gained from a pre scan; or a generalized auto calibrating partially parallel acquisition (GRAPPA) approach, where the missing k-space lines are calculated using portions of acquired k-space [12]. Parallel imaging acquisitions for both proton and HP ^{13}C utilize one of these main reconstruction methods, or some variety or extension as continued development occurs in the field.

In the context of HP ^{13}C , a SENSE reconstruction was applied to initial in vivo studies involving hyperpolarized compounds as described by Arunachalam et al. [27] and Tropp et al. [28]. Both studies used multi-channel receive coils and separate transmitter coils in their in vivo setup, with Arunachalam et al. using a four-channel receive coil and square loop transmit coil, and Tropp et al. using a three-channel receive coil and clamshell transmit coil [29]. Both studies ultimately did chemical shift imaging with an acceleration factor of ~ 2 to ultimately obtain images of pyruvate and lactate after injection of $[1-^{13}\text{C}]$ pyruvate, demonstrating the feasibility of faster scan times without sacrificing spatial or temporal resolution for carbon imaging on clinical scanners. The main difference in the two studies is the obtainment of coil sensitivities required for proper reconstruction, whereby Arunachalam et al. used a self-calibrating SENSE reconstruction with the acquisition of a fully sampled set of k-space center for estimation of coil sensitivities at the pyruvate frequency, while Tropp et al. used an oil phantom to obtain the sensitivity profiles. While these methods worked for these particular studies, they have inherent disadvantages, mainly the increased relative scan time required to fully sample k-space center as in Arunachalam et al., or not being able to use flexible coil arrays with phantom references, which is desirable for clinical translation.

Ohliger et al. [30] took the use of SENSE reconstruction by using partial Fourier to compensate for the time needed to acquire extra calibration lines to accurately perform the reconstruction. Furthermore, the experiments were similar in setup to the ones performed in Tropp et al., but with the use of an 8-channel receive array, which allowed for acceleration factors of up to 3.75. The 3D echo planar spectroscopic imaging acquisition yielded pyruvate, lactate and alanine images from an injection of $[1-^{13}\text{C}]$ pyruvate, demonstrating the feasibility of using a combined partial Fourier and parallel imaging acquisition on a clinical scanner for HP compounds. Furthermore, the matrix sizes used ($30 \times 10 \times 16$) can be also applied for clinical abdominal imaging without much loss in spatial resolution. The authors discuss the potential challenges associated with this technique, which mostly centers on obtaining proper coil sensitivities for carbon imaging, which is a general problem for parallel imaging, and can considerably affect the reconstruction. The authors also mention

GRAPPA as an alternative reconstruction approach for improving quantitative reconstructions.

Recent HP studies have utilized new advances in parallel imaging reconstruction, specifically SAKE [31], which stands for simultaneous auto calibrating and k-space estimation and does not require additional data for calibration by structuring the reconstruction as a low-rank matrix completion problem, and ESPIRiT [32], which is an auto calibrated method that uses eigenvector maps to generate sensitivity maps and relates to both SENSE and GRAPPA. Feng et al. [33] used a SAKE reconstruction with a 2D under sampled EPI sequence and an 8-channel receiver coil setup same as in Ohliger et al. to demonstrate feasibility of applying the SAKE reconstruction in HP experiments with a fast imaging pulse sequence that can be readily translated to clinical patients. Initial studies by Jiang et al. [6] recently showed feasibility of combining a concentric ring acquisition with parallel imaging with an 8-channel ^{13}C phased-array rat coil followed by an ESPIRiT reconstruction.

Another way to speed up an acquisition has been to exploit the sparsity of the HP acquisitions, either in the spectral domain [4,34], along the time dimension [3], or using the images themselves, via compressed sensing. This method has been successfully discussed and demonstrated in proton imaging [35–38], and is currently being investigated further with HP ^{13}C imaging for potential clinical translation.

The future of parallel imaging use in HP studies will ultimately come down to the exact information one wants to obtain from a given acquisition. The benefits of parallel imaging for HP imaging have been thoroughly presented in various studies within the past decade, effectively speeding up acquisitions to more efficiently utilize HP magnetization to extract as much information as possible in one scan, similar to compressed sensing. Both methods have similar SNR tradeoffs when under sampling since the SNR compared to a fully sampled acquisition decreases as, where R is the acceleration factor. Parallel imaging also has a dependence on the g-factor, which describes the properties and geometry of the receiver coil array. Optimal solutions going further would be to combine compressed sensing and parallel imaging, as demonstrated by Otazo et al. [39], which combined k-t SPARSE and SENSE for 8-fold acceleration, an improvement over each method applied individually. This powerful combination of methods can exploit joint sparsity in multi coil images, and go beyond the limitation of either spectral, dynamic, or image sparsity, as described previously for HP ^{13}C acquisitions, when compressed sensing is used individually.

As a final note, for our own HP studies with the bSSFP sequence on a 3T clinical scanner, the use of either a SAKE reconstruction as in Feng et al. [33] or the combination of partial Fourier and SENSE as in Ohliger et al. [30] would be good first attempts to demonstrate the feasibility of using parallel imaging with this particular sequence. The results can be compared to the current compressed sensing implementation [40] in terms of SNR, spatial resolution, and dynamic acquisition capabilities. The 3D version of the sequence (two phase encoding dimensions), with an extension to the temporal dimension, would be a good

candidate for parallel imaging due to the potentially large matrix sizes, especially as this approach is possibly transferred from preclinical to clinical imaging.

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References

1. Ardenkjaer-Larsen JH, Fridlund B, Gram A, Hansson G, Hansson L, et al. Increase in signal-to-noise ratio of > 10,000 times in liquid-state NMR. *Proc Natl Acad Sci U S A*. 2003; 100:10158–10163. [PubMed: 12930897]
2. Kurhanewicz J, Vigneron DB, Brindle K, Chekmenev EY, Comment A, et al. Analysis of cancer metabolism by imaging hyperpolarized nuclei: prospects for translation to clinical research. *Neoplasia*. 2011; 13:81–97. [PubMed: 21403835]
3. Larson PE, Hu S, Lustig M, Kerr AB, Nelson SJ, et al. Fast dynamic 3D MR spectroscopic imaging with compressed sensing and multiband excitation pulses for hyperpolarized ¹³C studies. *Magn Reson Med*. 2011; 65:610–619. [PubMed: 20939089]
4. Hu S, Lustig M, Balakrishnan A, Larson PE, Bok R, et al. 3D compressed sensing for highly accelerated hyperpolarized (¹³C) MRSI with in vivo applications to transgenic mouse models of cancer. *Magn Reson Med*. 2010; 63:312–321. [PubMed: 20017160]
5. Gordon J. Ramp-Sampled, Symmetric EPI for Rapid Dynamic Metabolic Imaging of Hyperpolarized ¹³C Substrates on a Clinical MRI Scanner. *Proceedings of the International Society for Magnetic Resonance in Medicine*; 2015. p. 4605
6. Jiang W, Lustig M, Larson PE. Concentric rings K-space trajectory for hyperpolarized ¹³C MR spectroscopic imaging. *Magn Reson Med*. 2014
7. Bieri O, Scheffler K. Fundamentals of balanced steady state free precession MRI. *J Magn Reson Imaging*. 2013; 38:2–11. [PubMed: 23633246]
8. Scheffler K, Lehnhardt S. Principles and applications of balanced SSFP techniques. *Eur Radiol*. 2003; 13:2409–2418. [PubMed: 12928954]
9. Reed GD, von Morze C, Bok R, Koelsch BL, Van Criekinge M, et al. High resolution (¹³C) MRI with hyperpolarized urea: in vivo T(2) mapping and (¹⁵N) labeling effects. *IEEE Trans Med Imaging*. 2014; 33:362–371. [PubMed: 24235273]
10. Sodickson DK, Manning WJ. Simultaneous acquisition of spatial harmonics (SMASH): fast imaging with radiofrequency coil arrays. *Magn Reson Med*. 1997; 38:591–603. [PubMed: 9324327]
11. Pruessmann KP, Weiger M, Scheidegger MB, Boesiger P. SENSE: sensitivity encoding for fast MRI. *Magn Reson Med*. 1999; 42:952–962. [PubMed: 10542355]
12. Griswold MA, Jakob PM, Heidemann RM, Nittka M, Jellus V, et al. Generalized autocalibrating partially parallel acquisitions (GRAPPA). *Magn Reson Med*. 2002; 47:1202–1210. [PubMed: 12111967]
13. Zhang X, Ugurbil K, Chen W. Microstrip RF surface coil design for extremely high-field MRI and spectroscopy. *Magn Reson Med*. 2001; 46:443–450. [PubMed: 11550234]
14. Zhang X, Ugurbil K, Chen W. A microstrip transmission line volume coil for human head MR imaging at 4T. *J Magn Reson*. 2003; 161:242–251. [PubMed: 12713976]
15. Adriany G, Van de Moortele PF, Wiesinger F, Moeller S, Strupp JP, et al. Transmit and receive transmission line arrays for 7 Tesla parallel imaging. *Magn Reson Med*. 2005; 53:434–445. [PubMed: 15678527]
16. Zhang X, Zhu XH, Chen W. Higher-order harmonic transmission-line RF coil design for MR applications. *Magn Reson Med*. 2005; 53:1234–1239. [PubMed: 15844152]
17. Wu B, Wang C, Kelley DA, Xu D, Vigneron DB, et al. Shielded microstrip array for 7T human MR imaging. *IEEE Trans Med Imaging*. 2010; 29:179–184. [PubMed: 19822470]

18. Li Y, Xie Z, Pang Y, Vigneron D, Zhang X. ICE decoupling technique for RF coil array designs. *Med Phys*. 2011; 38:4086–4093. [PubMed: 21859008]
19. Wu B, Wang C, Krug R, Kelley DA, Xu D, et al. 7T human spine imaging arrays with adjustable inductive decoupling. *IEEE Trans Biomed Eng*. 2010; 57:397–403. [PubMed: 19709956]
20. Wu B, Zhang X, Wang C, Li Y, Pang Y, et al. Flexible transceiver array for ultrahigh field human MR imaging. *Magn Reson Med*. 2012; 68:1332–1338. [PubMed: 22246803]
21. Yan X, Zhang X, Feng B, Ma C, Wei L, et al. 7T transmit/receive arrays using ICE decoupling for human head MR imaging. *IEEE Trans Med Imaging*. 2014; 33:1781–1787. [PubMed: 24710826]
22. Yan X, Xue R, Zhang X. A monopole/loop dual-tuned RF coil for ultrahigh field MRI. *Quant Imaging Med Surg*. 2014; 4:225–231. [PubMed: 25202657]
23. Yan X, Wei L, Xue R, Zhang X. Hybrid monopole/loop coil array for human head MR imaging at 7T. *Appl Magn Reson*. 2015; 46:541–550. [PubMed: 26120252]
24. Yan X, Pedersen J, Wei L, Zhang X, Xue R. Multi-channel double-row transmission line array for human MR imaging at ultrahigh fields. *IEEE Trans Biomed Eng*. 2015
25. Zhang, X.; Burr, AR.; Zhu, X.; Adriany, G.; Ugurbil, K., et al. A Dual-tuned Microstrip Volume Coil Array for Human Head parallel 1H/31P MRI/MRS at 7T. *Proceedings of the International Society for Magnetic Resonance in Medicine*; Miami, Florida. 2005. p. 896
26. Deshmane A, Gulani V, Griswold MA, Seiberlich N. Parallel MR imaging. *J Magn Reson Imaging*. 2012; 36:55–72. [PubMed: 22696125]
27. Arunachalam A, Whitt D, Fish K, Giaquinto R, Piel J, et al. Accelerated spectroscopic imaging of hyperpolarized C-13 pyruvate using SENSE parallel imaging. *NMR Biomed*. 2009; 22:867–873. [PubMed: 19489035]
28. Tropp J, Lupo JM, Chen A, Calderon P, McCune D, et al. Multi-channel metabolic imaging, with SENSE reconstruction, of hyperpolarized [1-(13)C] pyruvate in a live rat at 3.0 tesla on a clinical MR scanner. *J Magn Reson*. 2011; 208:171–177. [PubMed: 21130012]
29. Nelson SJ, Kurhanewicz J, Vigneron DB, Larson PE, Harzstark AL, et al. Metabolic imaging of patients with prostate cancer using hyperpolarized [1-¹³C]pyruvate. *Sci Transl Med*. 2013; 5:198ra108.
30. Ohliger MA, Larson PE, Bok RA, Shin P, Hu S, et al. Combined parallel and partial fourier MR reconstruction for accelerated 8-channel hyperpolarized carbon-13 in vivo magnetic resonance Spectroscopic imaging (MRSI). *J Magn Reson Imaging*. 2013; 38:701–713. [PubMed: 23293097]
31. Shin PJ, Larson PE, Ohliger MA, Elad M, Pauly JM, et al. Calibrationless parallel imaging reconstruction based on structured low-rank matrix completion. *Magn Reson Med*. 2014; 72:959–970. [PubMed: 24248734]
32. Uecker M, Lai P, Murphy MJ, Virtue P, Elad M, et al. ESPIRiT—an eigenvalue approach to autocalibrating parallel MRI: where SENSE meets GRAPPA. *Magn Reson Med*. 2014; 71:990–1001. [PubMed: 23649942]
33. Feng, Y. Application of Calibrationless Parallel Imaging Reconstruction to Hyperpolarized 13C MRI for Clinical Applications. *Proc Exp Nucl Magn Reson Conf*; 2015. p. 190
34. Hu S, Lustig M, Chen AP, Crane J, Kerr A, et al. Compressed sensing for resolution enhancement of hyperpolarized 13C flyback 3D-MRSI. *J Magn Reson*. 2008; 192:258–264. [PubMed: 18367420]
35. Lustig M, Donoho D, Pauly JM. Sparse MRI: The application of compressed sensing for rapid MR imaging. *Magn Reson Med*. 2007; 58:1182–1195. [PubMed: 17969013]
36. Lustig M, Donoho DL, Santos JM, Pauly JM. Compressed sensing MRI. *Ieee Signal Processing Magazine*. 2008; 25:72–82.
37. Jung H, Ye JC, Kim EY. Improved k-t BLAST and k-t SENSE using FOCUSS. *Phys Med Biol*. 2007; 52:3201–3226. [PubMed: 17505098]
38. Pang Y, Zhang X. Interpolated compressed sensing for 2D multiple slice fast MR imaging. *PLoS One*. 2013; 8:e56098. [PubMed: 23409130]
39. Otazo R, Kim D, Axel L, Sodickson DK. Combination of compressed sensing and parallel imaging for highly accelerated first-pass cardiac perfusion MRI. *Magn Reson Med*. 2010; 64:767–776. [PubMed: 20535813]

40. Milshteyn, E.; Von Morze, C.; Reed, G.; Shang, H.; Shin, P., et al. Development of High Resolution 3D Hyperpolarized ^{13}C Imaging Techniques. Proceedings of the International Society for Magnetic Resonance in Medicine; 2015. p. 4599