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Editorial Open Access

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, 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}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}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 (30×10×16) 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 trade-offs 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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