Partial Fourier techniques in single-shot cross-term spatiotemporal encoded MRI

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Partial Fourier Techniques in Single-Shot Cross-Term Spatiotemporal Encoded MRI

Zhiyong Zhang and Lucio Frydman*

Purpose: Cross-term spatiotemporal encoding (xSPEN) is a single-shot approach with exceptional immunity to field heterogeneities, the images of which faithfully deliver 2D spatial distributions without requiring a priori information or using postacquisition corrections. xSPEN, however, suffers from signal-to-noise ratio penalties due to its non-Fourier nature and due to diffusion losses—especially when seeking high resolution. This study explores partial Fourier transform approaches that, acting along either the readout or the spatiotemporally encoded dimensions, reduce these penalties.

Methods: xSPEN uses an orthogonal (e.g., z) gradient to read, in direct space, the low-bandwidth (e.g., y) dimension. This substantially changes the nature of partial Fourier acquisitions vis-à-vis conventional imaging counterparts. A suitable theoretical analysis is derived to implement these procedures, along either the spatiotemporally or readout axes.

Results: Partial Fourier single-shot xSPEN images were recorded on preclinical and human scanners. Owing to their reduction in the experiments’ acquisition times, this approach provided substantial sensitivity gains vis-à-vis previous implementations for a given targeted in-plane resolution. The physical origins of these gains are explained.

Conclusion: Partial Fourier approaches, particularly when implemented along the low-bandwidth spatiotemporal dimension, provide several-fold sensitivity advantages at minimal costs to the execution and processing of the single-shot experiments. Magn Reson Med 00:000–000, 2017. © 2017 International Society for Magnetic Resonance in Medicine.

Key words: single-shot MRI; spatiotemporal encoding; xSPEN; resolution enhancement; sensitivity enhancement; partial Fourier transform

INTRODUCTION

Cross-term spatiotemporal encoding (xSPEN) is a novel approach delivering single-scan NMR images with unprecedented resilience to field inhomogeneities (1). Like its spatiotemporally encoded (SPEN) predecessors (2–11), xSPEN relies on imprinting a shaped phase during an initial encoding process, which then serves as the focal point for a subsequent, gradient-driven image readout. In both experiments, this nonlinear phase encoding \( \Phi_p(t) \) leads to destructive interferences among signals emitted from neighboring spins, except for those positioned close to positions fulfilling the stationary-phase condition \( \nabla \Phi_p \approx 0 \). The action of an acquisition gradient, \( G_o \), which provides to this initial encoding phase an additional evolution profile, \( \Phi_o = k_o \cdot \tau \), with \( k_o = \gamma G_o t \) displaces this stationary phase point throughout the targeted field of view (FOV). If properly steered, this will eventually reveal the full \( \rho(t) \) spin density over the targeted FOV during a time-domain acquisition. Both SPEN and xSPEN thus differ from echo planar imaging (EPI, (12,13)) in that their image readout occurs in direct, physical space.

SPEN imparts its encoding as a quadratic, \( y^2 \), phase modulation, whereas xSPEN relies on a \( y, z \)-type phase (1.14). When applying such hyperbolic encoding, the option arises of activating either the \( G_{y}^2 \) or \( G_{z}^2 \) acquisition gradients to unravel, respectively, either the \( \rho(z) \) or the \( \rho(y) \) spatial profiles. The physical basis of how these acquisition gradients allow one to read, in direct space, the spins’ profile along an orthogonal axis has been explained elsewhere (1). Such analysis also reveals that utilizing a \( z \)-axis gradient to both encode and unravel a \( \rho(y) \) image enables one to perform an acquisition that can be entirely free from chemical shift or field inhomogeneity effects. This reflects that, rather than viewing frequency dispersions as artifacts that need to be overcome by application of an overpowering external field gradient, this approach to MRI incorporates any disturbing frequency broadening as part of both the initial phase encoding and the subsequent image decoding processes. This capability is particularly valuable when considering single-shot 2D acquisitions, experiments that although central in numerous diffusion- and functional-oriented applications are known to be particularly sensitive to field inhomogeneity distortions (15–17). Figure 1a illustrates one method whereby the xSPEN strategy was adapted for the realization of such single-shot 2D acquisitions. This sequence imparts its hyperbolic phase encoding by turning on a \( G_z \) along the slice-selection axis; this is used for exciting a slice of width \( L_y \) and is kept on throughout the rest of the scan. In combination with two linearly swept adiabatic inversion pulses (5,18) applied in the presence of a bipolar gradient \( \pm G_y \), this results in xSPEN’s characteristic \( \Phi_x = -Cy \cdot z \) phase profile, in which \( C \) is a spatiotemporal encoding constant under the experimentalist’s control and \( y, z \) are positions in the \( -FOV_y/2 < y < FOV_y/2, -L_y/2 < z < L_y/2 \) ranges. Then, over the course of the acquisition, the continued action of the constant \( G_y \) displaces \( \Phi_x \)‘s saddle-shaped profile along the \( y \)-axis. In synchrony with this, an
oscillating \( + G_x \) gradient applied along an orthogonal read-out dimension explores the \( k_y \)-axis in a conventional, EPI-like manner. The mechanism by which the constant application of a \( G_z \) gradient delivers an image free from offset-derived in-plane distortions has been discussed in detail elsewhere (1,19). Basically, even in the presence of a shift or inhomogeneity \( \delta \sigma (r) \), the xSPEN signal collected as a function of the oscillating wavenumber \( k_x \) and the acquisition time \( t \) can be expressed as

\[
S(k_x, t) = \int dx \cdot e^{ik_y x} \int dy \cdot p(x, y) \cdot \frac{L_x}{1 + jf(\delta \sigma)} \cdot \text{sinc} \left[ (-C_y + \gamma G_z t) \frac{L_x}{2} \right].
\]

Thus, rearrangement of these data and 1D Fourier transformation (FT) along \( k_x \) leads, apart from potential distortions related to the slice selection and represented by the function \( f(\delta \sigma) \), to a 2D \( p(x,y) \) image as a function of \( t \) that will be devoid of all offset-derived misregistrations.

Although delivering single-shot images devoid from in-plane distortions, xSPEN's lack of FT along the low band-width dimension carries substantial signal-to-noise ratio (SNR) penalties. These penalties are compounded by the losses of this technique. In the absence of inhomogeneities, this makes single-shot xSPEN less sensitive than methods such as EPI or even its SPEN predecessors—particularly if using the long acquisition times \( T_a \) required for achieving high in-plane resolutions. A well-known route to alleviate such effects is the partial FT (pFT, (20,21)), an approach that leverages the properties of the image being sought to reduce the acquisition coverage along one of the \( k \)-domains. Indeed, given the real nature of the NMR spectral correlations, in principle it is possible to sample only half the extent of the full \( k \)-space and still achieve the same levels of spatial resolution that would arise from sampling a full \( -k_{\text{max}} \leq k \leq k_{\text{max}} \) range of values (22,23).

In practice, such maximal reduction in the sampled data rarely is achieved, and partial sampling factors \( 0.6 \leq p \leq 0.8 \) are more common. The \( T_a - p \cdot T_a \) shortening of the overall acquisition times associated to this partial sampling can lead to a considerable reduction in relaxation and in diffusion-driven losses—particularly for constant-gradient sequences such as xSPEN. The question then arises of how to exploit these \( k \)-based phase-conjugation arguments in sequences that, like SPEN or xSPEN, are based on the hybrid sampling of \( k_x \) and of \( y \)-domains. The physical basis of pFT experiments along the readout and low-bandwidth dimensions, and demonstrations of pFT's usefulness to achieve resolutions that so far have been out of xSPEN's experimental reach, are presented below.

METHODS

Theoretical background

pFT seeks to retain spatial resolution, while reducing MRI's acquisition times, by estimating part of the \( k \)-space data using complex conjugation. Thus, although 1D MRI's inherent resolution depends on the maximal sampled wavenumber \( |k_{\text{max}}| \), blurring will characterize magnitude images unless a symmetric \( -k_{\text{max}} \leq k \leq + k_{\text{max}} \) region is sampled. pFT relies on the fact that \( k \)-domain data have to fulfill \( S(-k) = S(k) \) in order to calculate the images that would arise from the full \( -k_{\text{max}} \leq k \leq k_{\text{max}} \) support, while limiting actual samples to a \( -(2p-1) k_{\text{max}} \leq k \leq +p k_{\text{max}} \), \( 0.5 \leq p \leq 1 \) fraction (20,24). When extending these considerations from a 1D axis to a 2D plane, two potential strategies emerge. One is to exploit the \( S(-k_x - k_y) = S(k_x, k_y) \) symmetry along the directly detected readout domain; the other is to apply it along the phase-
encoded dimension. In conventional multi-shot MRI, the latter is the preferred option because it may shorten by a factor p the duration of the experiment. Single-shot techniques such as EPI generally also apply pFT only along the phase-encoded domain because doing so along the readout axis tends to complicate even/odd artifact corrections. In single-shot xSPEN, the readout (x) dimension is k-based, and these even/odd complications are absent because there is no FT along the low bandwidth (y) dimension. Consequently, pFTx in xSPEN is to some extent simpler than what generally is the case in EPI: xSPEN’s pFTx simply does a 1D phase conjugate reconstruction separately on positive and negative k_y-axis acquisitions and then recombines the two datasets in image space without phase problems to deliver its image (Fig. 1b).

Less straightforward is envisioning how pFT could be exploited along the xSPEN y-dimension. As mentioned, single-shot xSPEN imparts a preacquisition hyperbolic phase-encoding \( e^{i\gamma y} \), the stationary point of which is shifted over the course of the acquisition by a constant z-gradient. Such gradient in essence performs an analog Fourier analysis of the encoded data, delivering a y-axis image while simultaneously removing all \( AB_q \) inhomogeneity effects. This in turn means that an inverse FT of the data collected while under the action of the \( G_z \) gradient will be equivalent to a conventionally \( k_y \)-encoded MRI acquisition, with \( k_y = -C_z \) being the Fourier-conjugate to the y-position. Therefore, in the same way that conventional pFT relies on breaking the echo symmetry of a \( k_y \)-domain acquisition by applying a prewinding \( G_z \) gradient, performing an asymmetric encoding of the xSPEN image would demand the introduction of a prewinding \( G_z \) pulse, even if the image is subsequently unraveled by the action of a \( G_z \). Figure 1a highlights how this route to performing pFTy along the low-bandwidth dimension can be included in the original 2D sequence by introducing a short prephasering gradient pulse \( k_y^0 \). Such prephasering effectively shifts xSPEN’s virtual \( k_y \) encoding, thereby opening a route by enhancing the y-axis resolution via pFT. To see how this arises, we revisit Equation [1] in the absence of inhomogeneities for a 1D case that for simplicity ignores the \( k_x \) readout dimension. Approximating the \( \text{ sinc} \) function in that formula as

\[
L_y \text{sinc} \left( \frac{-Cy + \gamma G_z t}{2} \right) \approx \int_{-\frac{C_y}{2}}^{\frac{C_y}{2}} dz \cdot e^{i(-C_y + \gamma G_z t)z} \tag{2}
\]

enables us to describe the effect of the prephasering pulsed gradient \( K_y^0 \) on the detected signal as

\[
S(k_z(t)) = \int \int \int \int (y) e^{i\gamma y} e^{i(-C_y + \gamma G_z t)z} dy \approx e^{i\gamma y} r(y') \tag{3}
\]

where \( y' = k_y/C \) is the coordinate decoded by the action of the acquisition wavenumber \( k_y = \gamma G_z t \), and \( r(y') \) is a function representing the xSPEN image, given by a convolution of the \( p(y) \) spin density with the \( \text{sinc} \)-based sampling point spread function. The \( e^{i\gamma y} \) prefactor clearly represents a shift in the \( k_y \)-space origin associated with \( r(y') \)’s inverse Fourier transform signal \( S(k_y) \int r(y')e^{i\gamma y} dy' \). In other words, if in conventional xSPEN the maximum y-axis spatial resolution is given by the \( \text{sinc} \)'s width \( \frac{\pi}{C_y} \), the equivalent \( k_y \) sampling associated to the prefactor in Equation [3] will be shifted from \(-CL_{yz}/2 \leq k_y \leq CL_{yz}/2 \) to an interval of \(-CL_{yz}/2 + k_y^0 \leq k_y \leq CL_{yz}/2 + k_y^0 \). Hence, an inverse FT of the acquired xSPEN image, a suitable phase-conjugation processing, and a forward FT should yield images arising from an extended \( k_y \) support and thus possessing an enhanced y-axis resolution.

Similar pFT considerations would apply to single-shot 2D experiments if the imaging processes along xSPEN and readout axes were fully decoupled; this would be the case if the \( G_z \) acquisition gradient would be pulsed in between the bipolar readout gradients. In practice, however, it often is convenient to leave on \( G_z \) continuously because this frees not only the low bandwidth but also the readout dimension from field inhomogeneity distortions. The simultaneous action associated with the oscillating \( G_x \) readout and the constant \( G_z \) gradients acting during xSPEN’s 2D single-shot acquisition bring about new features that need to be corrected before attempting a pFTy. For deriving these features and their corrections, we consider for simplicity an xSPEN evolution that is free from relaxation, diffusion, or field inhomogeneities. The full 2D signal observed in such experiments can be expressed as

\[
S(k_x, k_y) = \left\{ \begin{array}{ll}
S^{\text{odd}}(k_x, k_y) = \int \int \int \int p(x, y) e^{i\phi^{\text{odd}}} e^{-i(Cz y + k_y^0 y)} e^{i(k_y x + ik_y z)} dx dy dz & \text{if } G_x \geq 0 \\
S^{\text{even}}(k_x, k_y) = \int \int \int \int p(x, y) e^{i\phi^{\text{even}}} e^{-i(Cz y + k_y^0 y)} e^{i(k_y x + ik_y z)} dx dy dz & \text{if } G_x < 0
\end{array} \right. \tag{4}
\]

Here, the integrals extend over the targeted slice and FOVs; \( k_y \) and \( k_x \) are the acquisition wavenumbers along the low-bandwidth and readout axes; \( \beta \) is a zigzag factor (23,25) reflecting the fact that the \( k_x \) wavenumber advances/recedes in conjunction with \( k_y \) over the course of the readout oscillation; and \( \phi^{\text{odd}}, \phi^{\text{even}} \) are unknown phase terms associated with imperfections in the readout gradients. To adapt the \( s(k_y) = \int r(y')e^{ik_y y} dy' \) notation introduced above to this 2D sampling case, we introduce functions related to what would be the conventional k-space signal associated to this acquisition; that is,

\[
S^{\text{odd}}(k_x, k_y) = \int \int p(x, y) e^{i\phi^{\text{odd}}} e^{ik_x x} e^{ik_y y} dx dy \\
S^{\text{even}}(k_x, k_y) = \int \int p(x, y) e^{i\phi^{\text{even}}} e^{ik_x x} e^{ik_y y} dx dy. \tag{5}
\]
These virtual signals arising from positive and negative readout gradients can be used to rewrite Equation [4] as

$$
S(k_x, k_z) = \begin{cases} 
S^{\text{odd}}(k_x, k_z) = \int \frac{S^{\text{odd}}(k_x, k_y + k_y^0)}{Z} e^{i(k_x y + 2k_y x)} dz \\
S^{\text{even}}(k_x, k_z) = \int \frac{S^{\text{even}}(k_x, k_y + k_y^0)}{Z} e^{i(k_x y + 2k_y x)} dz 
\end{cases}
$$

Furthermore, because $k_x$ rasterizes the $y$-axis, this is equivalent to the mixed-domain interferogram

$$
S(k_x, y') = \begin{cases} 
S^{\text{odd}}(k_x, y') = \int \frac{S^{\text{odd}}(k_x, k_y + k_y^0)}{k_y} e^{i(k_y y' + 2k_x y)} dk_y \\
S^{\text{even}}(k_x, y') = \int \frac{S^{\text{even}}(k_x, k_y + k_y^0)}{k_y} e^{i(k_y y' + 2k_x y)} dk_y 
\end{cases}
$$

where $y' = k_y^0/C$.

If not for the $\beta$-related terms, one could apply the same arguments that followed Equation [3] to justify the extraction from these data of a pFT-y-enhanced resolution. To appreciate the effects associated to the $\beta$-terms, we perform on Equation [7] a final change of variables $k_y^0 = k_x + k_y^0$:

$$
S(k_x, y') = \begin{cases} 
S^{\text{odd}}(k_x, y') = e^{-ik_y^0 y'} e^{-i\beta k_y k_x/C} \int \frac{S^{\text{odd}}(k_x, k_y)}{k_y} e^{i(k_y y' + 2k_x y)} dk_y \\
S^{\text{even}}(k_x, y') = e^{-ik_y^0 y'} e^{-i\beta k_y k_x/C} \int \frac{S^{\text{even}}(k_x, k_y)}{k_y} e^{i(k_y y' + 2k_x y)} dk_y 
\end{cases}
$$

The $e^{-ik_y^0 y'}$ phase-modulation term here is, as in conventional pFT-y; however, the new phase terms $e^{i\beta k_y k_x/C}$ and $e^{i\beta k_y k_x/C}$, affecting the $S^{\text{even}}$ and $S^{\text{odd}}$ interferograms, evidence a coupling between the $k_y^0$ echo shifts and the $k_x$ sampling that needs to be removed from even and odd data sets before performing a pFT-y. In practice, we apply this zigzag correction, involving a row-by-row multiplication of these a priori known $\beta$-phase terms, in conjunction with a removal of the $e^{i\beta k_y k_x/C}$ and $e^{i\beta k_y k_x/C}$ phase imperfections that may affect signals collected under ±Gz gradients (23,26,27). The full procedure is summarized and exemplified in Figure 2. In the present study, the POCS (projection onto convex sets) partial Fourier reconstruction (28,29) was the pFT algorithm chosen to enhance resolution along either the readout or low-bandwidth axes.

Experimental

Phantom and animal-based acquisitions were carried out on a 7T/120 mm horizontal magnet using a quadrature volume coil and a DD2 Agilent console (Agilent Technologies, Santa Clara, California, USA). Animal protocols and maintenance were done in accordance with guidelines of the Institutional Committee on Animals of the Weizmann Institute of Science (protocol 10790514). Spin-echo multi-shot (SE-Multishot) images and SE-EPI experiments were carried out using sequences taken from the scanner's library; all SE-EPI acquisitions required reference "navigator" scans to correct for ghosts along the...
Partial Fourier Transform Single-Shot xSPEN MRI

FIG. 3. Representative results arising from a lime phantom incorporating a titanium screw (a). (b–d) Spin-echo multi-shot image arising from the green axial slice indicated in (a). (e–g) 2D imaging results delivered for the same slice by different single-shot sequences with identical FOV and resolution settings. (f,g) Images from a same acquisition involving partial sampling of the readout dimension, processed with and without POCS reconstruction. (h,i) Idem but with and without pFTx reconstruction along the xSPEN dimension. Both (g) and (i) have the same resolution as (e) but higher SNR, as evaluated from averaged ratios of the yellow/red squares denoting noise/signal regions shown in panel (e). Acquisition parameters: FOV = 40 × 40 mm²; thickness = 4 mm; repetition time = 2 s; T₁ = 22.02, 15.88, and 13.76 ms for (e), (f), and (h); time-bandwidth products 2G₁T₁ = 64, 64 and 40 for (e), (f), and (h); chirp bandwidths = 5.8, 8.0, and 5.8 kHz for (e), (f), and (h), respectively. Matrix sizes for images in (b–d) were 64 × 64; xSPEN image sizes were as indicated. EPI, echo-planar imaging; FOV, field of view; pFT, partial Fourier transform; RO, readout; SE spin echo; SNR, signal-to-noise-ratio; xSPEN, cross-term spatiotemporal encoding.

RESULTS

Figure 3 illustrates the advantages resulting from the pFT procedures just discussed, when performed on a 7T preclinical scanner. In these experiments, a lime was analyzed, onto which a nonferromagnetic titanium screw of a kind usually employed in orthopedic prostheses was inserted axially for exacerbating the field inhomogeneities. Figure 3a shows a photograph of the screw plus fruit, together with a SEMS sagittal image showing the effects of the screw as well as a challenging slice on which further axial analyses where implemented. These compared a SEMS image (usually used as our gold standard) (Fig. 3b) and images collected with SE-EPI with fully refocused SPEN and with the xSPEN sequence introduced in (1). This progression clearly shows the latter’s higher robustness and faithfulness (Figs. 3c–3e). Using this single-shot xSPEN image collected with the original sequence as starting point, Figures 3f through 3i illustrate the kind of improvements that can be achieved by implementing pFT procedures. Figures 3f and 3g show images obtained upon reducing the number of points collected along xSPEN’s readout segments from 64 to 40. Although a simple FT x procedure yields a 0.625 reduction in readout points clearly improves the sensitivity. An even larger sensitivity improvement is observed for identical P values if the pFT is implemented along the low-bandwidth dimension. Indeed, although Figure 3h once again shows that resolution is sacrificed upon reducing the sampled xSPEN lines from 64→40, the procedure in Figure 2 can restore the lost resolution while nearly tripling SNR vis-à-vis the original single-shot xSPEN image (Fig. 3i vs. 3e).

Figure 4 demonstrates another aspect of pFT’s sensitivity improvements, this time focusing on tradeoffs between resolution and SNR. Shown in the first row are images recorded for the phantom and slice introduced in...
Figure 3b, using the original xSPEN sequence as function of increasing matrix size. This quickly trades SNR for resolution (Figs. 4a–4d), reflecting in part the decreasing voxel sizes, but foremost the diffusion and relaxation penalties incurred upon seeking to increase resolution along the low bandwidth dimension. Images reconstructed using pFTy clearly can increase SNR vis-a-vis conventionally acquired xSPEN counterparts (Figs. 4e–4h). Moreover, the higher the resolution desired, the larger the SNR benefits arising from relying on a pFT.

**FIG. 4.** Sensitivity benefits arising from partial Fourier processing along the xSPEN dimension (pFTy), as judged by the SNR figures arising from the indicated yellow/red squares on the phantom introduced in Figure 3. (a–d) Images acquired with conventional xSPEN, showing how SNR degrades with increasing image resolution due to longer T_a and associated diffusion losses. (e–h) pFT, reconstructed counterparts showing how SNR gains improve with resolution. Acquisition parameters field of view = 40 × 40 mm²; thickness = 4 mm; repetition time = 2 s; T_a = 22.02, 33.02, 44.03, 76.8, 13.76, 27.52, and 48 ms for (a–h); time-bandwidth products = 64, 96, 128, 40, 60, 80, and 80 for (a–h); and chirp bandwidths = 5.8, 5.8, 5.8, 3.3, 5.8, 5.8, 5.8, and 3.3 kHz for (a–h), respectively. Matrix sizes were as indicated (arrows indicate the extent of the augmentation brought about by the pFT procedure). pFT, partial Fourier transform; SNR, signal-to-noise ratio; xSPEN, cross-term spatiotemporal encoding.

**FIG. 5.** Sensitivity benefits arising from xSPEN’s pFTy, illustrated with in vivo mouse head scans. (a) Reference spin-echo multi-shot image acquired in 2 min 40 s without respiration trigger, and indicating the regions used to evaluate signal (yellow) and noise (red). Images with lower and with improved SNR acquired by single-shot xSPEN MRI without (b) and with (c) pFT to deliver the same resolution. Field of view = 24 × 24 mm²; slice thickness = 2.5 mm; repetition time = 2 s; T_a = 32.6 and 20.4 ms; time-bandwidth products = 80, 50 and chirp bandwidths 4.8, 4.8 kHz for (b) and (c), respectively. Matrix sizes as indicated. pFT, partial Fourier transform; SE spin echo; SNR, signal-to-noise ratio; xSPEN, cross-term spatiotemporal encoding.
These advantages are recapitulated in Figure 5, with in vivo experiments comparing SEMS data against single-shot xSPEN images targeting a mouse head. Notice the absence of distortions in regions that typically challenge single-shot applications, for example, near eyeballs and in the ears. Notice as well the large ($\frac{\text{SNR}}{a^2}$) improvements brought about by the pFTy procedure for the $r = 0.625$ and $300 \mu m^2$ in-plane resolution targeted here. Figure 6 illustrates a similar advantage, but for a series of scans collected at 3T on a human volunteer and focusing on the frontal orbital cortex. Due to the susceptibility gradients introduced by the sinuses and eye sockets, single-shot EPI exhibits substantial distortions over various head regions (Fig. 6a). xSPEN yields distortion-less images for these regions, but the strong diffusion-driven losses arising when seeking in-plane resolutions better than $2 \times 2 \text{ mm}^2$ render this approach of limited value—even if restricting the FOV to limit the overall acquisition times (data not shown). By contrast, pFTy enables xSPEN to successfully target this resolution: by sampling only 62.5% of the readout lines, this procedure achieves acceptable SNR and yields undistorted, single-shot zoomed images, free from folding and/or susceptibility artifacts (Fig. 6b).

**DISCUSSION**

Single-scan xSPEN MRI shows remarkable resilience to field inhomogeneities yet suffers from SNR penalties due to its non-Fourier nature and diffusion and $T_2$ losses. These losses can be taxing when seeking improvements along the spatiotemporally encoded dimension, for which resolution is given by $D = \frac{2 \times \text{FOV} \times T_a}{a^2} G_z (1)$. $\delta y$ can thus be improved by restricting FOV$_y$, or by increasing the slice thickness $L_z$, albeit at the expense of losing in- or out-of-plane information. Additional parameters available for increasing resolution are $G_z$, the gradient that in xSPEN stays on for the course of the scan, and the acquisition time $T_a$. Owing to xSPEN's refocusing demands, $T_a$ will be proportional to each voxel's position-dependent echo time TE, and hence impart an $e^{-\alpha \text{TE}/T_2}$ attenuation for which $\alpha$ is a factor ranging between 2 and 3, and depending on the voxel's $y$-position. Improving resolution by increasing either $G_z$ or $T_a$ will incur in diffusion losses. Based on the Bloch-Torrey model (30,31), these losses can be approximated by an exponential attenuation varying as the square of the gradient and the cube of the free evolution time. On the basis of this, and disregarding for simplicity the effects of the refocusing pulses or of the $G_y$ encoding and $\pm G_x$ readout gradients, xSPEN's diffusion-driven attenuation will be proportional to $e^{-D s^2 G_z (a T_z)^3/12}$, with $D$ the diffusion coefficient.

pFT decreases these sensitivity losses without sacrificing resolution by collecting a fraction $p < 1$ of the points that would normally be required. This will result in shortened acquisition times that can be implemented by partially sampling either the readout ($x$) or the...
spatiotemporally encoded (y) dimensions. The first of these options restores the original x-axis resolution while acquiring a fraction of the original readout points. Disregarding for simplicity complications associated to ramp sampling or finite gradient slew rates, reducing the number of sampled readout points by a factor of \( p < 1 \) will shorten accordingly the associated acquisition time \( T_a \), leading to a reduction of the \( T_2 \)-driven relaxation losses by \( e^{-p \cdot \delta T_a/T_2} \). However, if this is to be done without a concomitant loss in the y-axis resolution, the relation given earlier for \( \delta y \) implies that \( G_y \) will have to increase by a factor \( 1/p \). The ensuing diffusion-related attenuation factor will therefore be reduced to \( e^{-p \cdot \delta y \cdot G_y \cdot (a \cdot T_x)/12} \); because \( p < 1 \), this is clearly an improvement over the original attenuation. Compare this with the case of pFTy, in which the \( T_a \) reduction is achieved by sampling fewer points along y-axis—that is, by applying fewer \( \pm G_y \) readout oscillations. The reduction in \( T_2 \)-driven attenuation losses will remain as for pFTy; however, the fact that the \( G_y \) can now be kept at its original strength without incurring in a \( \delta y \)-degradation means that the diffusion-driven attenuation factor will be reduced to \( e^{-p \cdot \delta y \cdot G_y \cdot (a \cdot T_x)/12} \). Therefore, although both pFTx and pFTy will improve SNR over xSPEN’s original realization, pFTy will lead to a larger improvement due to the \( p^2 < p < 1 \) factor arising in the diffusion-weighting exponent. This advantage of pFTy over pFTx is compounded by xSPEN’s lack of Fourier transform along the xSPEN dimension, which makes the sensitivity of the overall method drop as \([# \text{ sampled points}]/p\). By reducing this number by a factor \( p \), adopting the pFTy procedure enhances sensitivity by another factor \( 1/p \). All these expectations are confirmed by the data in Figure 3. They also explain the observations in Figure 4 whereby the higher the resolution being sought, the more there is to be gained by adopting the pFTy procedure. Indeed, in the latter case the increases in resolution called for the use of longer encoding and acquisition times that rapidly increased the diffusion-related attenuation exponent; the larger this exponent, the more remarkable are the benefits of the \( p^2 \) pFTy scaling in the final image SNR. Although an exact quantification of the SNR enhancement introduced by the pFT might benefit from synthetic replica procedures, the large factors evidenced by the experimental data demonstrate the method’s usefulness.

In addition to pure SNR considerations, a number of technical factors point to the convenience of choosing partial Fourier sampling along the spatiotemporal rather than the readout axis, particularly when considering xSPEN realizations on humans. One of these pertains to the limited \( p \) reductions that can be achieved in clinical scanners along the readout axis, where minimum readout times already are constrained by the maximal slew rates that physiological considerations allow one to achieve. Another limitation derives from the aforementioned need to increase the value of \( G_y \) by \( 1/p \) upon performing pFTx without decreasing the y-axis resolution. This gradient increase means that chirped pulses with larger bandwidths are needed to cover the original \( \text{FOV}_y \) and \( L_y \) dimensions, resulting in concomitant increases in xSPEN’s SAR values. In terms of data postprocessing, however, the reverse considerations apply: pFTx will barely change the original simplicity of the xSPEN processing, whereas pFTy requires both even/odd and zigzag phase corrections. Furthermore, to some extent there is an approximation in the assumption made in Figure 2 that these two corrections can be treated independently: a more rigorous analysis of even/odd mismatch problems incorporating the zigzag effect suggests that it may not always be feasible to factor out the phase terms \( e^{-i p k x k_y / C} \) from the integrals introduced in Equation [8]. When this is the case—and this naturally will depend on the nature of the even/odd mismatches—artifacts may arise in images processed, as described above. A general solution to this problem consists of replacing the continuous \( G_y \)-
driven xSPEN decoding by equivalent gradient blips, acting during the ramp times of the oscillating readout gradient train.

CONCLUSION

In summary, partial FT approaches acting along either the readout or the spatiotemporally encoded dimensions were introduced and shown to significantly improve the tradeoffs between resolution and SNR in single-scan xSPEN MRI. Details on how to implement these approaches were derived, and associated data processing considerations were introduced. In all cases, examples collected on preclinical and clinical scanners unambiguously demonstrate the advantages of the method without affecting xSPEN’s unique resilience to field inhomogeneities. From a practical standpoint, this should readily benefit the potential applications of this new single-scan technique. From a conceptual standpoint, new physical insight had to be introduced in connection to the pFTy, dealing with the application of orthogonal gradients to \( k \)-shift and to acquire a given imaging axis. These insights can in fact be extended to derive altogether new sampling schemes for single- and multi-shot xSPEN, as will be further detailed in upcoming studies.

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