isoPHASOR: localizing markers in a variety of scan types using its phase saddles

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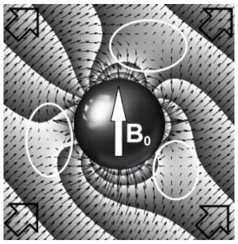
Target audience: Researchers in the field of interventional MRI aiming to depict pointine devices with positive contrast, while keeping image quality high, as in catheter tracking, micro-electrode depiction and the localization of brachytherapy seeds.

Purpose: In the past decade, many positive contrast methods were proposed, such as the White Marker method(WM)[1], Susceptibility Gradient Mapping (SGM)[2], center-out RAdial Sampled Off-Resonance imaging (co-RASOR)[3], pattern matching(PM)[4] and Quantitative Susceptibility Mapping(QSM)[5]. *The problem* is that most methods either depend on additional scans next to the anatomical scan (WM, SGM), require dedicated scans (coRASOR), depend on manual / error-prone /subjective subtasks as masking, unwrapping and background field removal (QSM), or they require simulations and a database (PM). *The aim of this work* is to derive a general formulation for depicting a known punctiform magnetic marker of interest from any scan type (FID, GRE, SE) of 3D MR-dataset, acquired with any type of trajectory (radial, cartesian, spiral, …).

The followed approach was to generalize coRASOR to non-radial scans. coRASOR highlights the center of a marker of interest by centrally focusing circular signal pile-up, arising when spherical symmetric objects are imaged with center-out radial scanning. The dependency on radial scans can be alleviated, by explaining the efficacy of coRASOR using the phenomenon of 'phase saddles'; three regions in the marker's vicinity in which the encoding k-vector is exactly canceled by the marker's induced field shift (fig1a). The preserved signal in these isophasic regions can be shifted to the marker's center, if the phase in these saddles is known, enabling a quantitative positive contrast filter compatible to a variety of scan types.

Theory: To calculate the relative phase in the three saddles, first their relative positions were determined. As they were found to lie in the plane spanned by $\vec{k}_{enc}$ and $\vec{B}_0$, their 2D polar coordinates $\{\theta_m, r_m\}$ in this plane were determined by solving $\nabla\varphi_{marker}(\theta_m, r_m, T_s) + 2\pi\vec{k}_{enc} = 0$, with $\varphi_{marker} = P\frac{3\cos^2(\theta)-1}{r^3}$. Here the perturbation $P \equiv \frac{\gamma B_0 \Delta\chi V}{4\pi} T_s$ depends on the marker's volume V and susceptibility $\Delta\chi$ relative to the medium, B_0 and the sampling time T_s relative to excitation (FID, GE) or Echo (SE), and $\vec{k}_{enc}$ is expressed in 2D polar form $\{\theta_{enc}, |k_{enc}|\}$. The formulas for the three phases φ_m are given in fig 1b.



b

$C(t) = \frac{1}{3}\sum_{j=0}^{2} exp(-i\varphi_m)$	$\varphi_m = \frac{8\pi\lvert k_{enc}\rvert}{3} sign(P) \sqrt[4]{\frac{3\lvert P\rvert}{2\pi\lvert k_{enc}\rvert}} \frac{3\,cos^2(\theta_m) - 1}{(1 - 2\,cos^2(\theta_m) + 5\,cos^4(\theta_m))^{3/8}}$
$cos^2(\theta_m) = \frac{1}{15}\left(2(4-A)\,sin\left(\frac{2\pi m}{3} - \frac{1}{3}arcsin\left(1 + \frac{54A}{(A-4)^3}\right)\right) + 7 - A\right)$	$A = sin^2(\theta_{enc})$

Fig 1a) *The phase distribution induced by a magnetic marker cancels the applied k-vector of spatial encoding (diagonal arrows) at exactly three positions (ellipses), located in the plane spanned by the vectors $\vec{B}_0$ and $\vec{k}_{enc}$ The preserved signal in these saddles can be used to highlight the marker by applying a phase correction to the raw data with the negative value of the relative phase in these saddles in respect to the marker.* ***1b)*** *The analytic formulation of this k-space filter.*

Methods: The filter was tested on a numerical phantom with a small perturber centrally located in the FOV. Three different acquisition schemes were simulated including Gradient Echo, Spin Echo and a center-out scan (kooshball). To further increase the method's contrast and the spatial resolution, the corrected data-points in k-space were respectively normalized to unity and zero-padded before applying the inverse Fourier Transform. A first experimental validation was performed by detecting brachytherapy seeds located in a piece of porcine tissue, which was scanned at 1.5T, $[1mm]^3$ with center-out radials with WFS of 0.243 voxels.

Results: Figure 2 shows the proposed filter's compatibility to a variety of 3D acquisition schemes, yielding selective positive contrast, especially when combined with high-pass filtering and zero-filling. Figure 3 shows experimental results for brachy-seed depiction. The boxes added in the detailed image show the results for coRASOR, showing that isoPHASOR generates finer, more localized contrast. Although not visible in the figure here, the proposed filter suppresses the background anatomy more than coRASOR.

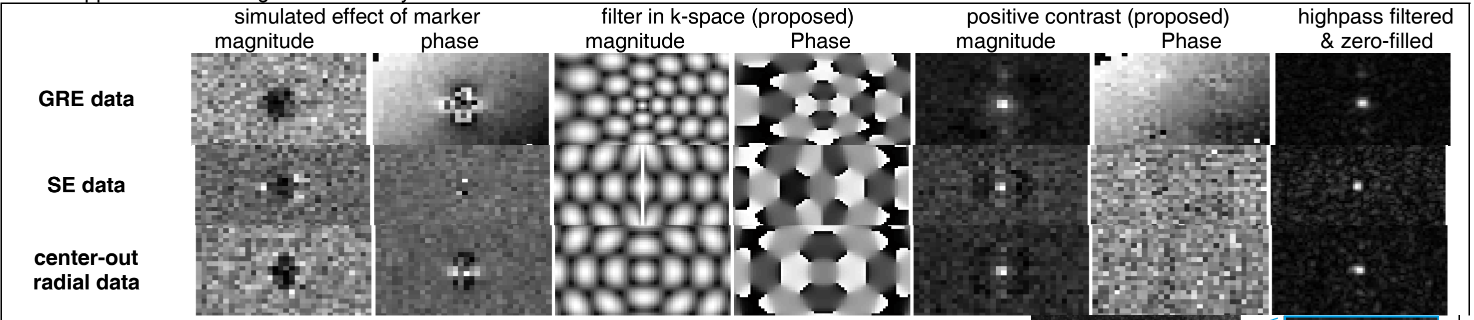


Fig 2) *Numerical validation of the versatility of the proposed method, by simulating the effect of a marker with a relative susceptibility of 400 ppm and radius 1.5mm scanned at 3T for a GRE acquisition, an SE acquisition and center-out kooshball data. Shown are the midsagittal planes with B_0 vertical, and the read direction horizontal.*

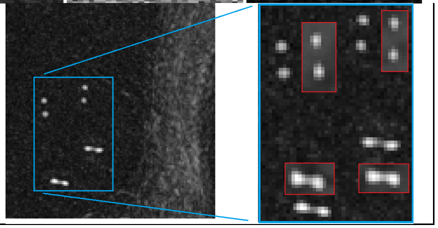


Fig 3) *The proposed method applied to brachyseed depiction in heterogenous porcine tissue. The detail in the right shows the result of coRASOR, showing that isoPHASOR results in finer contrast. Not evisible in this figure, is that isoPHASOR is less sensitive to other other anatomic structures than coRASOR. Moreover, isoPHASOR does not need tuning or optimization, as the optimal strength of the correction factor follows directly from the closed form equations.*

Discussion and conclusion: Proposed is a positive contrast filter for depicting punctiform objects that is compatible with a variety of different scan trajectories. The formulation more or less unifies several other k-space filters, including the optimal coRASOR phase ramp for center-out scanning, and the Fourier Transform of the complex signal at a given sampling time for GRE pattern matching. The method, however, is limited to depict objects with sufficient magnetic strength to locally cancel the applied phase gradient of the spatial encoding. The explicit formulation based on the scan trajectory and the marker strength exempts the user from further analyzing or simulating the interaction between the encoding and the marker induced field shift. Directly applicable to raw datasets, the method circumvents error-prone preprocessing, making the method both fast and robust.

References: **1.**Seppenwoolde J-H et al, MRM;50:784–790 (2003) **2 .**Dahnke H. et al, MRM;60:595–603(2008) **3.** P.R.Seevinck et al, MRM, 65:146–156(2011) **4.**K. Wachowicz et al, Med Phys, 33, 4459(2006) **5.** Dong et al, MRM, 10.1002/mrm.25453