# Phase sensitive PC-bSSFP: simultaneous quantification of $T_1$, $T_2$ and spin density $M_0$

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**Introduction**: The fast and simultaneous quantification of MR parameters with a single sequence (IR-bSSFP [1]) has been proposed several years ago. The method is not suitable for 3D imaging due to long magnetization recovery interruptions. The used bSSFP-sequence is highly sensitive to off-resonance effects resulting in banding-artifacts and leading to over and underestimation of the parameters. Especially at higher fields, off-resonances cannot be avoided anymore. Here we propose a new approach for simultaneous quantification of $M_0$, $T_1$ and $T_2$ based on phase-cycled bSSFP in 3D. The new proposed method yields its dynamics from the signals phase and offers intrinsic off-resonance compensation. This work presents the new theory and shows an experimental validation.

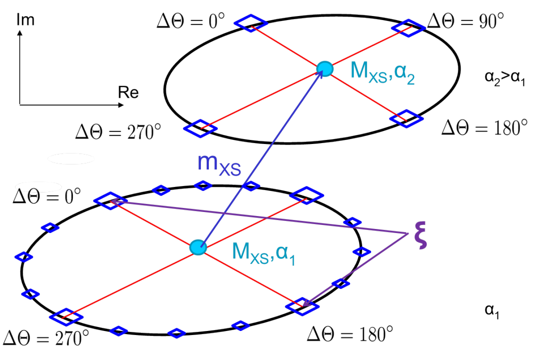
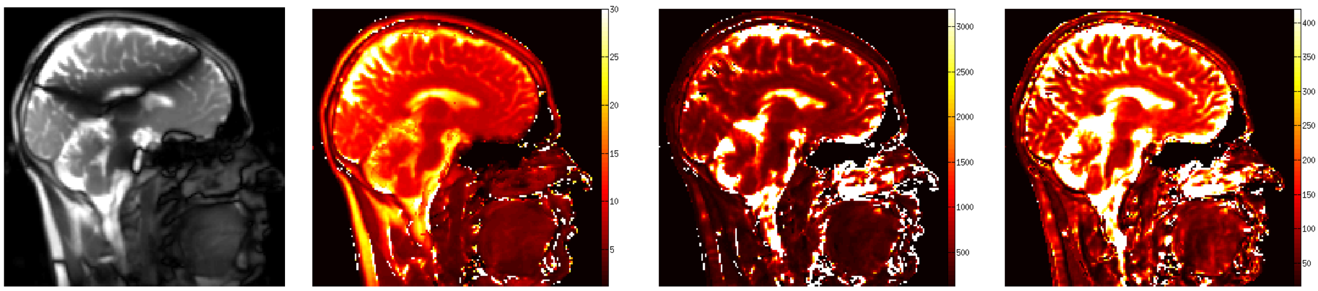



**Fig. 1:** Two complex ellipses are shown. The lower one at flip-angle $\alpha_1$ is fully sampled by 16 phase-cycles in opposite to the upper one at flip-angle $\alpha_2$ whos Cross-Solution is used to determine the slope $m_{\mathrm{XS}}$. The lower ellipse allows to determine the ratio $\xi$.

**Methods**: Experimental data-signal p from a phase-cycled bSSFP-sequence can pixel-wise fitted into a common ellipse equation: $\mathrm{p} = \mathrm{x}_0 + \mathrm{i}\mathrm{y}_0 + (\mathrm{x}\cdot\sin(\Phi) + \mathrm{i}\mathrm{y}\cdot\cos(\Phi))\cdot e^{i\gamma}$. Five data-points are required to determine an unambiguous fit. The common complex bSSFP steady-state equation can be recast into[3]:
$S_{bSSFP,\Theta} = M_{\mathrm{XS}}\frac{1-E_2\cdot e^{\mathrm{i}\Theta}}{1-b\cdot\cos\Theta}$ with $\Theta = \Delta\Theta + \Delta\omega\cdot\mathrm{TR}$, $\mathrm{b}=\mathrm{b}(T_1, T_2, \mathrm{TR}, \alpha)$, $M_{\mathrm{XS}} = M_{\mathrm{XS}}(M_0, T_1, T_2, \mathrm{TR}, \alpha)$, $\Delta\Theta$ as used phase-cycle. The shape of the function is similar to an ellipse equation and is a function of $M_0$, $T_1$, $T_2$, flip-angle $\alpha$ and TR. The ellipse shape allows to interpolate to any arbitrary off-resonance $\Delta\omega$ and hence to off-resonance free signals of measurements with $\Theta = \{0°, 180°\}$ for every pixel.
The ratio $\xi = \xi(\alpha_1, T_1, T_2, \mathrm{TR}) = S_{\mathrm{bSSFP},\Theta=180°}/S_{\mathrm{bSSFP},\Theta=0°}$ can be used as the first fit variable. The second fit variable is the slope $m_{\mathrm{XS}} = m_{\mathrm{XS}}(\alpha, T_1, T_2, \mathrm{TR})$ of demodulated magnetization [2, 3] $M_{\mathrm{XS}}$ between two flip-angles analogous to [2, 5]. The demodulated magnetization can be calculated from four data-points with perpendicular phase-cycles applying the Cross-Solution(XS)[3]. Both variables $\xi$ and $m_{\mathrm{XS}}$ only depend on $T_1$, $T_2$ as well as the parameters TR and $\alpha_1$. Therefore the parameters can be obtained by numerical fits. Spin density $M_0$ can be calculated from the demodulated magnetization $M_{\mathrm{XS}}$ as well as $\Delta\omega$ from signal equation.
**Experiments**: *In-vivo* measurements were performed on a healthy volunteer using a 1.5T clinical scanner. A bSSFP-sequence with non-selective super-balanced RF-pulses[4] was used. Two flip-angles of 33° and 50° were used as well as a TR-time of 8ms. 8 different phase-cycles were measured to overdetermine the ellipse. 4 more images were acquired for the second flip-angle. Total imaging time for a 192x192x44 matrix was approximately 14min. An exemplary raw data image is shown on the figure below.
**Results**: The data was analyzed using custom made MATLAB functions. The center slice was used for analysis. Other slices lead to similar results. As proposed the obtained $M_0$-, $T_1$- and $T_2$-maps do not suffer from banding-artifacts, see in the figure below. The obtained $T_1$- and $T_2$-times show good agreement for lower values.



(a) raw data image with severe banding-artifacts (b) $M_0$-map(arb. units) of a human head (c) $T_1$-map(ms) of a human head (d) $T_2$-map(ms) of a human head

**Conclusion**: In this work we have shown that phase sensitive PC-bSSFP measurements can be used to obtain $T_1$, $T_2$, $\Delta\omega$ and $M_0$. The method is a 3D and suitable for higher field strength. In contrast to DESPOT2[5], all measurements can be done simultaneous with one imaging sequence, no $T_1$-information is required a prior. A thorough analysis about accuracy and robustness as well as optimal flip-angles is subject of current research. Parallel imaging methods may be applied for speed up.
**References**: [1] Schmitt et al., 2004 MRM, 51:661–667 [2] M.Ott el al., 2011 ESMRMB [3] Q-S. Xiang and M.N. Hoff 2010 ISMRM [4] O. Bieri, 2011 MRM, in press [5] S. Deoni et al, 2003, MRM 49, 515-526
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