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.

Methods: Experimental data-signal $p$ from a phase-cycled bSSFP-sequence can pixel-wise fitted into a common ellipse equation:

$$p = x_0 + iy_0 + (x \cdot \sin(\Phi) + iy \cdot \cos(\Phi)) \cdot e^{-t \cdot \omega}.$$  

Five data-points are required to determine an unambiguous fit. The common complex bSSFP steady-state equation can be recast into [3]:

$$S_{bSSFP,\Theta} = \frac{M_{SS}}{1 - e^{-t \cdot \omega}}$$  

with $\Theta = \Delta \Theta + \Delta \omega \cdot TR$, $b = b(T_1, T_2, TR, \alpha)$, $M_{SS} = M_{SS} (M_0, T_1, T_2, TR, \alpha)$, $\Delta \Theta$ 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 $\Theta = (0^\circ, 180^\circ)$ for every pixel.

The ratio $\xi = \xi (\alpha_1, T_1, T_2, TR) = S_{bSSFP,\Theta=180^\circ} / S_{bSSFP,\Theta=0^\circ}$ can be used as the first fit variable. The second fit variable is the slope $m_{SS} = m_{SS} (\alpha, T_1, T_2, TR)$ of the demodulated magnetization [2]. The demodulated magnetization can be calculated from four data-points with perpendicular phase-cycles applying the Cross-Solution(XS) [3]. Both variables $\xi$ and $m_{SS}$ 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 $M_{SS}$ 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 $33^\circ$ and $50^\circ$ 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 in the figure below. 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.

![image](https://example.com/image.png)

(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 priori. 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.


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