T_1- and TR-Independent B_1^+ Mapping by Bloch-Siegert Shift for 7T Human Cardiac ^{31}P-MRS

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PURPOSE: Accurate quantification of metabolite ratios in human in vivo cardiac ^{31}P-MRS relies on saturation correction, which requires accurate knowledge of excitation flip angles in the VOI. However, at ultra-high field (7T) peak B_1^+ and SAR limits currently make composite or adiabatic B_1^+ insensitive pulses infeasible in the human heart.[1] Thus B_1^+ must be estimated, or separately measured to find the flip angle (FA). Long T_1s (typically 1s-6s) and 3D Chemical Shift Imaging (CSI) make magnitude B_1^+-mapping methods, which require complete recovery of longitudinal magnetisation, infeasible for cardiac ^{31}P-MRS. Dual-TR methods have been proposed,[2] which require knowledge of precise metabolite T_1s, but metabolites are under exchange with neighbours. A Bloch-Siegert (B.Siegert) phase based method is proposed for ^{31}P-MRS B_1^+ mapping, independent of metabolite T_1s or sequence TR.[3]

METHODS: An off-resonance, variable-length Fermi Pulse[3] (8ms $T_0 = 2.30\text{ms}, a = 0.630\text{ms}$ or 4ms $T_0 = 1.15\text{ms}, a = 0.315\text{ms}$) was placed between the excitation pulse and readout of a 3D UTE CSI sequence.[4] B_1^+ can be related to the phase accumulated over the duration of the off-resonance Fermi pulse by the equation $\phi_{BS} = B_{1,peak}^2 \int_0^T \gamma^2 B_{1,norm}^2(t) / 2\omega(t) dt = B_{1,peak}^2 K_{BS}$. K_{BS} is constant for a specific offset and pulse envelope.[3] A Siemens 7T system with a 10cm Tx/Rx surface coil was used throughout. Spectra were fitted using a Matlab implementation of the AMARES algorithm[5], and voxels were treated as independent throughout the analysis. The B.Siegert effect was demonstrated in a 2x2x2cm^3 single-peak phosphate phantom[4(SI)], using an unlocalised FID acquisition. (Fig.1) The 8ms Fermi pulse was swept over ±10000Hz. B_1^+ was computed using a full recovery "sin α" method, and expected ϕ_{BS} compared with that measured.

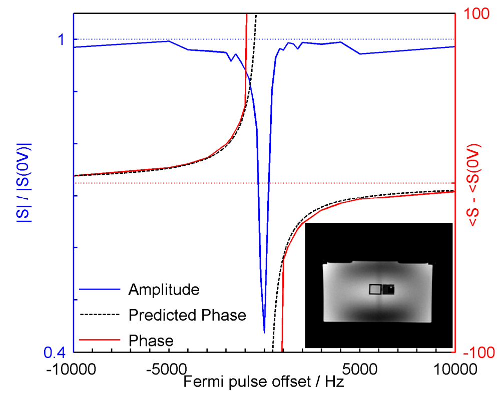

Fig. 1 Fitted phase and amplitude in 2x2x2cm^3 K_2HPO_4 phantom as a 8ms Fermi pulse is swept from -10KHz to +10 KHz. "Predicted phase" shows $\phi_{BS}(B_{1,\text{peak}} = 266\text{Hz})$ separately determined via a fully relaxed sin α approach.

B.Siegert mapping was validated in a uniform phantom (Fig. 2a), containing 0.04M $K_2HPO_{4(aq)}$ with a separately measured $T_1 = 13.4$s, against a reference method that fit the partial saturation equation to the multiple flip angle experiment. Both methods used the same 2.4ms shaped excitation pulse and acquisition weighted CSI parameters: FOV=150x320x320mm^3, resolution=16x8x8, averages at k_0=5. The B.Siegert B_1^+ was computed from the phase difference of the scans with the 8ms Fermi pulse placed at ±2000Hz. TR=1s, TA = 2x8min. The multiple FA method used 30V steps from 30V to 280V, a TR=10s, with a total scan time of 70min per 30V step (total ~11hrs).

B.Siegert mapping was compared with a previously published dual TR method in a healthy volunteer's quadriceps (Fig. 2b).[2] Both methods used the same excitation and acquisition weighted CSI parameters: FOV=200x200x200mm^3, resolution = 8x8x8, averages at k_0 = 14, TA = 2x7min. In the B. Siegert in vivo scans the 8ms Fermi pulse was centred around the isolated and non-exchanging α-ATP peak, TR = 1s, and B_1^+ was computed from from the phase difference with the pulse placed at ±2000Hz. The validation TRs used were 250, 600, 1000 and 1500ms; a literature value of $T_{1,\alpha-\text{ATP}} = 1.8$s was used to calculate the B_1^+.[6]

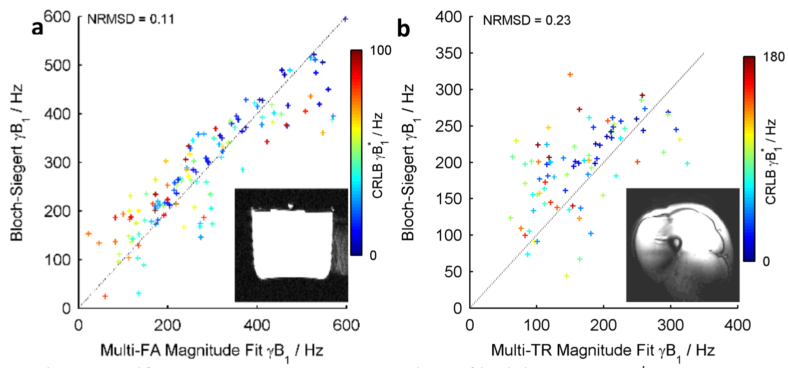

Fig. 2 **a**. Uniform K_2HPO_4 phantom, comparison of individual voxel B_1^+s. Calculated from Multi-FA validation method vs. B.Siegert ±2000Hz phase difference.
b. Quadriceps Multi-TR method ($T_{1,\alpha-\text{ATP}} = 1.8$s) vs. B.Siegert ±2000Hz difference. Colours ∝ CRLB B_1^+ ∝ SNR. CRLB above 100 & 180Hz respectively were masked.

Cardiac B.Siegert mapping was attempted in a single healthy volunteer. Two 15min acquisition weighted CSI scans were acquired: FOV = 240x240x200mm^3, 16x8x8, averages at k_0=13, TR=1s, with the 4ms Fermi pulse at ±2000Hz. B_1^+ maps were computed from the phase difference of the α-ATP peak, and masked by the Cramér Rao Lower Bound of the calculated B_1^+ (CRLB B_1^+ > 100Hz are excluded).

RESULTS: In the uniform phantom (Fig. 2a) there was excellent agreement between B.Siegert mapping and the long TR multi-FA magnitude validation method (Normalised Root Mean Square Deviation (NRMSD) = 0.11). A wider scatter was observed in quadriceps muscle (NRMSD= 0.23). In vivo, a small (15%) improvement in accuracy is gained from fitting multiple off resonance points (±2000, ±3000, ±4000Hz) but at the cost of a three-fold increase in scan time. α-ATP SNR = 9.3 is observed in the single cardiac experiment in the interventricular septum (IVS). The map is smoothly varying over the IVS and right ventricle, with a range of measured values between ~100 and 250Hz.

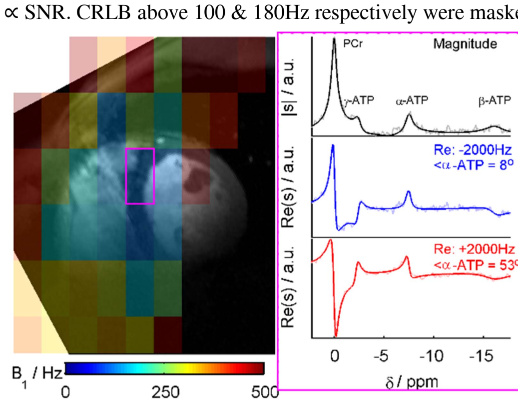

Fig. 3 γB_1^+map (Hz) overlaid on a mid-ventricular SA localiser. The excerpt shows spectra from the highlighted voxel with the Fermi pulse at ±2000Hz, centred on α-ATP (7.7ppm). Spectra were acquired in 15mins per offset (2).

DISCUSSION: The accuracy of B.Siegert mapping compared to current gold-standards has been demonstrated in phantom and in skeletal muscle. The feasibility of this approach has been shown in cardiac scans, further work is required characterise the effects of B_0 inhomogeneity and the scan-scan reproducibility. The later could perhaps be addressed using a single acquisition and fitting B_1^+ from the phase difference of multiple peaks (e.g. PCr and α-ATP), however at γB_1^+ observed in the IVS (150Hz) and with the current experiment parameters, this difference is only ~ 3 degrees.

CONCLUSION: Accurate B_1^+ mapping by the B.Siegert shift has been shown to be viable for human cardiac ^{31}P-MRS. A T_1- and TR-independent B_1^+ determination method opens up the route to fast cardiac T_1 and chemical exchange measurement protocols.

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