IN VIVO TRIPLE QUANTUM FILTERED POTASSIUM (^{39}K) MR IMAGING OF HUMAN THIGH MUSCLE

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TARGET AUDIENCE Physicists and physicians interested in non-proton MRI.

PURPOSE Potassium ions are of fundamental importance for the physiology of living organisms. The first *in vivo* potassium (^{39}K) MR images of human muscle and brain have been published recently[1, 2]. The aim of this study was to evaluate the feasibility of triple-quantum-filtered (TQF) ^{39}K MR imaging and to measure biexponential transverse relaxation time constants T_2^* of ^{39}K in human thigh muscle with this technique.

METHODS All measurements were performed on a 7-T whole-body MR scanner (MAGNETOM 7 T; Siemens Healthcare, Erlangen, Germany). For sequence optimization T_2^* relaxation time constants of five different agar phantoms (conc.: 1%, 2%, 3%, 4%, and 5%) containing 154 mmol/l KCl were determined by fitting the model equation $\mathrm{sqrt}(a[0.6\ \exp(-T_E/T_{2f}^*) + 0.4\ \exp(-T_E/T_{2s}^*)]^2 + N^2)$ to the signal intensity of magnitude images obtained at 45 different echo times T_E with an anisotropic, density-adapted, multi-echo (3) radial sequence[3] (repetition time T_R = 200 ms, T_E = 0.4-175 ms, total acquisition time T_{AQ} = 16:40 min, readout time T_{RO} = 2.5 ms, nominal resolution $(\Delta x)^3$ = 5×5×10 mm^3). T_E was defined as the time elapsed between the middle of the last radiofrequency pulse and the beginning of readout (RO). The optimum evolution time τ_1 and T_E for a TQF image was calculated using $\tau_{1opt} = \ln(T_{2s}^*/T_{2f}^*)/(1/T_{2f}^* - 1/T_{2s}^*)$ (Tab. 1).

Agar conc. [%]	T_{2f}^* [ms]	T_{2s}^* [ms]	$\tau_{1,opt}$ [ms]
1	10.7 ± 0.9	24 ± 3	15 ± 1
2	5.6 ± 0.3	20 ± 1	9.8 ± 0.4
3	3.5 ± 0.2	15.6 ± 0.7	6.8 ±0.2
4	2.6 ± 0.1	13.1 ± 0.6	5.3 ± 0.2
5	2.5 ± 0.1	12.1 ± 0.4	4.7 ± 0.1

Tab. 1: Short (T_{2f}^*) and long (T_{2s}^*) transverse relaxation time constants of ^{39}K measured in phantoms with different agar concentrations. The errors are calculated from the confidence interval of the plot. These relaxation times were used to calculate the evolution time τ_1 for maximum signal intensity in ^{39}K TQF images.

TQF images (Fig. 1b) of these phantoms were obtained using a three-pulse TQF sequence[4, 5] in combination with anisotropic *k*-space readout[3] (T_R = 100 ms, $T_E = \tau_1$ = 4.7 ms, mixing time [between middle of second and third radiofrequency pulse] τ_2 = 50 µs, *nex* = 24, T_{AQ} = 34:53 min, T_{RO} = 5 ms, $(\Delta x)^3$ = 14×14×28 mm^3). In addition, an ultra-short echo time (UTE) contrast with minimized T_2^*effects and the same resolution and readout bandwidth, but smaller s number of excitations was used (fig.1a; T_R = 100 ms, T_E = 0.35 ms, *nex* = 6, T_{AQ} = 5:49 min). Figure 1c displays the signal ratio of TQF to UTE image data corrected for the factor sqrt(6) to take into account the different T_{AQ}. Noise outside the target volume was suppressed by a binary mask created from the UTE image with an appropriately chosen threshold value. Signal oscillations [1] hamper the determination of the transverse relaxation time constants of human thigh muscle *in vivo*. Hence optimal τ_1 and T_E were estimated using a non-selective TQF sequence where both parameters were varied simultaneously (Fig. 2). Then UTE and TQF images ($T_E = \tau_1$ = 1.5 ms, other sequence parameters were the same as in phantom experiments) were acquired from the thigh muscle of a healthy volunteer (27 y, f). Both images as well as their signal ratio, corrected for the longer T_{AQ} of the TQF image, are shown in Figs. 1 d-f. The used binary mask was again defined by a threshold value in the UTE image. To enhance SNR and reduce Gibbs' ringing artifacts all images were Hamming filtered.

RESULTS The SNR of phantom TQF images (Fig. 1b) was maximum (≅ 15) for the phantom containing 4-% agar; the SNR of the 1-% agar phantom image was < 10. In UTE images (Fig. 1a) the SNR dropped gradually from ~45 to 40 with increasing agar concentration. *In vivo* SNR was ~7.5 in the TQF image (Fig. 1e) of human thigh muscle, while SNR was ~13 in the UTE image (Fig. 1d).
For the 4% agar phantom the signal intensity of the TQF image was 2.5% of the UTE image intensity corrected for different T_{AQ} (Fig. 1c). For the other phantoms the intensity ratio was lower than that of the phantom measured with optimally adjusted sequence. In the thigh muscle the averaged signal ratio was 3% (Fig. 1f).
Fitting the equation $\mathrm{sqrt}((a[\exp(-T_E/T_{2f}^*) - \exp(-T_E/T_{2s}^*)]^2)^2+N^2)$ to the measured, non-selective TQF data (Fig. 2) yields values for short and long transverse relaxation time constants, T_{2f}^* = (0.5 ± 0.1) ms and T_{2s}^* = (8.6 ± 0.3) ms, respectively, of ^{39}K in human thigh muscle. The method was also applied to the 4-% agar phantom data and resulted in T_{2f}^* = (1.2 ± 0.2) ms and T_{2s}^* = (13.0 ± 0.5) ms.

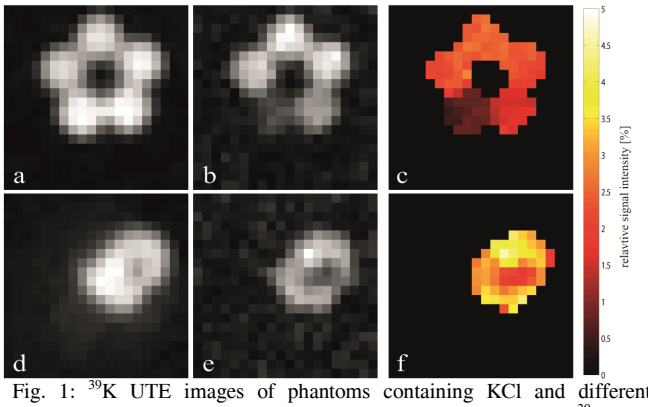

Fig. 1: ^{39}K UTE images of phantoms containing KCl and different concentrations of agar **(a)** and of human thigh muscle *in vivo* **(d).** ^{39}K TQF images of phantom ($T_E = \tau_1$ = 4.7 ms) **(b)** and muscle ($T_E = \tau_1$ = 1.5 ms) **(e)**. Images **(c)** and **(f)** show the relative signal ratio of TQF *vs*. UTE image corrected for differences in acquisition times T_{AQ}.

DISCUSSION The slow transverse relaxation determined by the non-selective TQF technique agrees with the results of the phantom experiments listed in Tab. 1. However, the fast component seems to be compromised by a systematic error since the shortest applicable echo time was 0.65 ms.
In correspondence to theory, the efficiency of the TQF was best for the 4% agar phantom, where the sequence was optimized to, and dropped for the other agar concentrations. The efficiency of 5.8% predicted by theory was not achieved. The filter efficiency was slightly higher *in vivo* than in the phantoms experiments, but without the correct values of transverse relaxation times a theoretical assessment is impossible. This was also the reason why - for better comparison - in both cases relaxation effects in the UTE image were not corrected for. Therefore, the signal ratio of TQF *vs*. UTE image data is underestimated, in particular for phantoms with high agar concentration.

CONCLUSION The first *in vivo* ^{39}K TQF images of human thigh muscle were obtained with acceptable resolution and measurement time. The achieved signal intensity was in the expected range. The slow component of transverse relaxation (time constant T_{2s}^*) of ^{39}K in human thigh muscle could be determined *in vivo*.

ACKNOWLEDGEMENT The authors thank Barbara Dillenberger for producing the agar phantoms and Christine Gnahm for providing reconstruction as well as evaluation software.

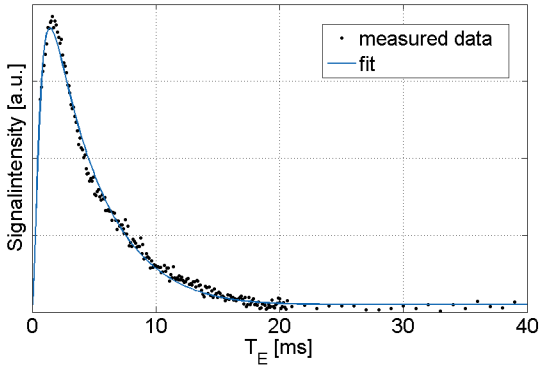

Fig. 2: ^{39}K signal intensity *vs*. T_E using a non-selective TQF sequence by varying τ_1 and T_E simultaneously. The fit results in T_{2f}^* = (0.5 ± 0.1) ms and T_{2s}^* = (8.6 ± 0.3) ms.

REFERENCES [1]Umathum *et al*., Radiology (2013); [2]Atkinson *et al*., Magn Res Med. (2013); [3]Nagel *et al*., ISMRM (2012); [4]Jaccard *et al*., J Chem Phys (1986); [5]Benkhedah *et al*., Magn Res Med. (2012)