MR sub-sampling strategies for transcranial MRgFUS applications

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Introduction

For transcranial MRgFUS applications, temperature measurements over the fully insonified 3D field of view are required to assess treatment and monitor heating in near field tissue-bone interfaces. This can be achieved by utilizing k-space subsampling in conjunction with e.g. parallel imaging[1], constrained reconstruction[2] or model based reconstruction algorithms[3]. Here we present a comparison between three different k-space subsampling schemes for 3D segmented EPI data acquisition.

Methods

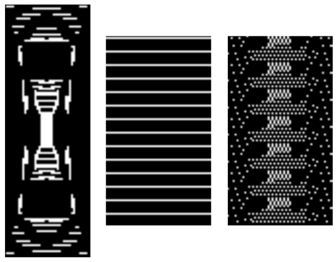
Subsampling schemes Three different subsampling schemes were implemented in a 3D Segmented EPI sequence on a 3T MRI scanner (Tim Trio, Siemens Healthcare, Erlangen, Germany).

1) Variable density subsampling (VDSS), taking advantage of the fact that most of the energy of k-space is located in the center, applied a variable density pattern in the phase encode-slice encode plane (k_y-k_z), while fully sampling the read out direction (k_x). The k_y-k_z plane was divided into 2D regions, where the central region was fully sampled every time, and the outer regions were sampled with increasing reduction factors (R), ranging from 3 to 13 (Fig. 1a). The echo train was applied centrically, i.e. the center most region of k-space was sampled with the last echo in the echo train.

2) Even subsampling (ESS) was applied in the k_y direction, while the k_x and k_z directions were fully sampled (Fig. 1b). Here the echo train was applied sequentially (center of k-space was sampled at the echo train center).

3) Variable density-even subsampling (VD-ESS) sampled the data in the same manner as in the ESS scheme, but varied the subsampling factor in the k_z direction, from R=16 for the lowest and highest k_z, to R=3 for the central k_z (Fig. 1c).

Variations of the VDSS and ESS schemes were also implemented in a gradient recalled echo (GRE) sequence (i.e. with EPI=1). Reconstructed temperatures were compared to a fully sampled "truth".



a) b) c)

Figure 1. a) VDSS; the central region is fully sampled, and the outer regions are sampled with R ranging from 3 to 13. b) ESS; even subsampling in the k_y direction. c) VD-ESS; Sampling density in the k_z direction varies as R=16-14-8-3-8-14-16.

Temperature induced phase shift From proton resonance frequency shift theory[4], it can be seen that a temperature increase of ΔT induces a frequency shift Δf of order $\Delta f = \Delta T B_0 \gamma \alpha$, where B_0 is the field strength, γ the gyromagnetic ratio, and α the temperature constant. This frequency shift results in a location shift of the focal spot (in number of voxels) of order $\Delta f / BW_{PE}$, where BW_{PE} is the bandwidth in the phase encode direction.

Experiment HIFU heatings were performed using a phased array transducer (256 elements, 1 MHz, 13 cm radius of curvature, 2x2x8 mm FWHM, Imasonic, Besancon, France) in an agar gel phantom imbedded with a plastic skull flap and pork muscle (Fig. 2). Phase aberration correction was applied[5]. MR and US parameters used can be found in table 1. All data was zero filled interpolated to 0.5 mm isotopic voxels to minimize partial volume effects, and all subsampled data had a total reduction factor of 7 and was reconstructed using the previously described TCR algorithm[2].

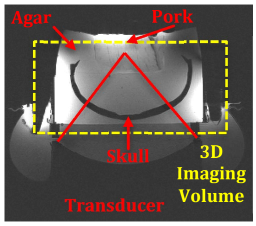


Figure 2. Transverse view of experiment set up.

Results, Discussion, and Conclusions

Fig. 3 shows temperature rise as a function of time for the hottest voxel, and Fig. 4 shows maximum skull heating throughout the experiment, both for the EPI=7 experiment. RMSE over a 3x3x5 voxel region during the heating was 1.45, 0.39, and 0.28 °C, for the VDSS, ESS, and VD-ESS schemes, respectively. Figure 5 shows temperature rise as a function of time for the hottest voxel for the GRE experiment.

Fig. 3 and 4 show that the VDSS scheme underestimates the temperatures, while the ESS and VD-ESS schemes perform well. In ESS and VD-ESS k-space is sampled sequentially, and temperature induced frequency shifts cause a linear phase shift across k-space, and results in a small shift of the focal spot in the image (hottest voxel's 11°C corresponds to 0.15 voxels). In the VDSS scheme, where k-space is sampled centrically, the temperature induced frequency shift results in a linear phase shift of opposite polarities in different parts of k-space (corresponding to ±0.19 voxels in the image). This induces a blurring effect that reduces the phase shift at the focal spot center, and leads to an underestimation of the reconstructed temperatures. When all of k-space is sampled with the same TE, as in the GRE experiment, the blurring effect does not occur. Further, echo shifting is considerably harder to implement in the VDSS scheme, as it has to be done simultaneously in 2D.

We have investigated three different k-space subsampling schemes. Sequential sampling (as in ESS and VD-ESS) leads to a small shift of the hot spot, and echo shifting is straightforward. For centrically sampled schemes (as in VDSS) the opposite polarities of the temperature-induced phase shift in different parts of k-space leads to blurring which cannot easily be corrected, and echo shifting is complicated by the need to be performed in 2D. For these reasons sequential sampling is preferred for segmented EPI sequences, whereas for non-EPI sequences k-space can be sampled centrically.

References 1. Huang ISMRM 2012 #561. 2. Todd MRM 62:406-19. 3. Todd MRM 63:1269-79. 4. Ishihara MRM 34:814-23. 5. Almquist Focused Ultrasound Surgery Foundation Symposium 2012 #148 (P-91-BR). **Acknowledgements** This work was supported by The Focused Ultrasound Surgery Foundation, Siemens Healthcare, The Ben B. and Iris M. Margolis Foundation, and NIH grants F32 EB012917-02, and R01s EB013433, and CA134599.

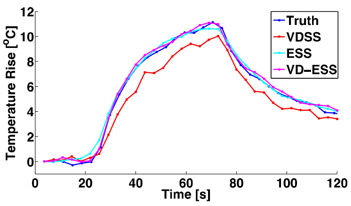
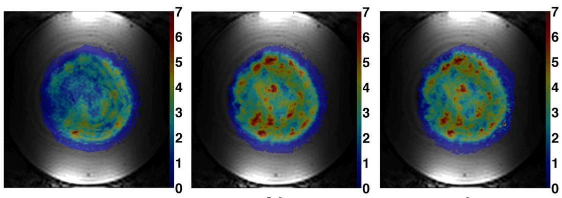


Figure 3. Temperature rise as a function of time for EPI=7 experiment.



a) b) c)

Figure 4. Maximum skull heating, overlaid on magnitude of agar phantom, as measured on the skull interface for a) VDSS, b) ESS, and c) VD-ESS, for EPI=7 experiment.

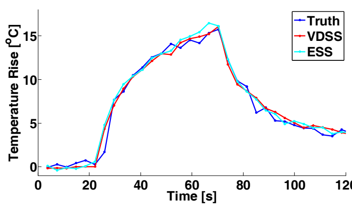


Figure 5. Temperature rise as a function of time for the GRE (EPI=1) experiment.

Parameter / Experiment	TR [ms]	TE [ms]	BW [Hz/px]	Flip Angle [°]	Echo spacing [ms]	T_{acq} [s]	Matrix size	Voxel size [mm³]	US Power [W]	US Duration [s]
Truth	33	12.0	752	25	1.56	3.7	128x77x10	2x2x3	80	48.1
VDSS	33	18.5	752	25	1.96	3.7	128x126x42	2x2x3	80	48.1
ESS/VD-ESS	33	12.0	752	25	1.56	3.7	128x98x54	2x2x3	80	48.1
GRE Truth	33	12	752	15	1.60	3.7	128x100x8	1x1x3	28	48.1
GRE VDSS	33	20.1	752	15	2.44	3.7	128x100x8	1x1x3	28	48.1
GRE ESS	33	12	752	15	1.60	3.7	128x100x8	1x1x3	28	48.1