A Method for Fast Longitudinal Relaxation Rate Mapping and for Image Enhancement: Equilibrium Signal Intensity-Mapping

P. Surányi[1,2], P. Kiss[1,2], B. Ruzsics[1], B. C. Brott[3], T. Simor[1,2], and G. A. Elgavish[1,2]

[1]Department of Biochemistry and Molecular Genetics, University of Alabama at Birmingham, Birmingham, AL, United States, [2]Elgavish Paramagnetics Inc., Hoover, AL, United States, [3]Department of Medicine, Division of Cardiovascular Disease, University of Alabama at Birmingham, Birmingham, AL, United States

Introduction Inhomogeneity of magnetic fields, both B_0 and B_1, has been a major challenge in magnetic resonance imaging. Field inhomogeneity leads to image artifacts and unreliability of signal intensity (SI) measurements. This work proposes, and shows the feasibility of, generating Equilibrium Signal Intensity Maps (SI_{Eq} maps) that can be utilized either to speed up relaxation rate measurement and/or to enhance image quality and relaxation-rate-based weighting in various applications.

Methods The SI_{Eq}-mapping method consists of generating a baseline, voxel-by-voxel control R_1-map (using IR with multiple TIs) without the use of a contrast agent. Applying nonlinear curve-fitting to the SI vs. TI dependence, the SI_{Eq} parameter is determined for each voxel of the imaged region of interest. A practical equation for longitudinal relaxation in inversion recovery imaging that takes into account effects of saturation and preparation pulse errors {Kaldoudi et al 1993}:

$$\mathbf{SI = SI_{Eq}\cdot (1 - \mathit{A}\cdot exp^{(-TI\cdot R_1)} + exp^{(-TR_{IR}\cdot R_1)})}$$

where SI_{Eq} is the signal intensity at equilibrium, the third term accounts for saturation (TR_{IR}=recycle time between successive 180º pulses), and *A* is a parameter dependent on the accuracy of the 180º inversion pulse. SI_{Eq} is the aggregate of several parameters, such that

$$\mathbf{SI_{Eq} = C\cdot\rho_0\cdot exp^{(-TE\cdot R_2)}}$$

where C is an instrumental constant (influenced by local field inhomogeneity of both B_0 and B_1, receiver gain, and the electronics of the instrument) and ρ_0 and R_2 are spin density and the transverse relaxation rate (in gradient echo imaging R_2* should be used) in the given voxel, respectively. SI_{Eq} is typically regarded as just a fitting parameter of the process of calculating R_1 and is generally not utilized. In this work we propose that, after determining it accurately, SI_{Eq} can be used to later determine R_1 from a single image acquired with an appropriately chosen TI. Additionally, SI_{Eq}-maps can be used to enhance SI-images (**CO**rrected **SI** **M**aps (COSIM)) to achieve more robust R_1-weighting following CA administration.

COSIM=SI/SI_{Eq} A 1.5T MR scanner was used. In canines (n=4) myocardial infarction was induced and 48h after the administration of 0.05mmol/kg Gd(ABE-DTTA), a contrast agent with slow tissue kinetics, in vivo R_1-mapping (Figure 1) was carried out using an inversion-recovery (IR) prepared, fast-gradient-echo sequence with varying inversion times (TI). To test the SI_{Eq} mapping method without the confounding effects of motion and blood flow, in another group of dogs (n=2), ex-vivo R_1-mapping was carried out after the administration of 0.2mmol/kg Gd(DTPA) using an IR-prepared fast-spin echo sequence. $R_{1,full}$-maps and SI_{Eq} maps were generated from the data from both sequences by three-parameter non-linear curve fitting of the SI vs. TI dependence. $R_{1,full}$-maps served as the reference standard. From single IR images, COSIMs were generated as described above. Additionally, R_1 values were calculated from each single-TI image separately, using the SI_{Eq} value and a one-parameter curve fitting procedure ($R_{1,single}$). Voxelwise correlation analysis was carried out for the COSIM and the $R_{1,single}$-maps, both vs. the standard $R_{1,full}$-maps. Deviations of $R_{1,single}$ from $R_{1,full}$ were statistically evaluated.

Results In vivo, COSIM vs. $R_{1,full}$ showed significantly ($p<0.05$) better correlation(correlation coefficient(CC)=0.95) than SI vs. $R_{1,full}$ with a TI=700-800ms, which is 200-300ms longer than the τ_{null} (500ms) of viable myocardium. With such TIs, SI vs. $R_{1,full}$ yielded CCs of 0.86-0.88. $R_{1,single}$ vs. $R_{1,full}$ yielded peak CC of 0.96 at TI=700-900ms. Mean deviations of $R_{1,single}$ from $R_{1,full}$ were below 5% for TIs between 500ms and 1000ms. Ex vivo, where τ_{null} is 300ms, the advantage of correction with SI_{Eq} was not in the improvement of linear correlation, but more in the reduction of scatter. Peak CCs for SI vs. $R_{1,full}$ and COSIM vs. $R_{1,full}$ at TI=500ms were 0.96 for both. The ex vivo CC for $R_{1,single}$ vs. $R_{1,full}$ at TI=500ms was 0.98. Mean deviations of $R_{1,single}$ from $R_{1,full}$ were below 5% for TIs between 400ms and 700ms.

Conclusions Once the corresponding SI_{Eq} map is obtained from a control stack, R_1 can be obtained accurately, even when using a single IR-image without the need for a stack of TI-varied images. This approach could be applied in various dynamic MRI studies where short measurement time, once the dynamics has started, is of essence. When using this method with IR-prepared T_1-weighted magnitude images, it is essential that the single TI be chosen such that the longitudinal relaxation in all voxels of interest would have passed the τ_{null}. SI_{Eq} maps are also useful in eliminating confounders from MR images to allow obtaining signal intensity values that represent more faithfully the relaxation parameter (R_1) sought.

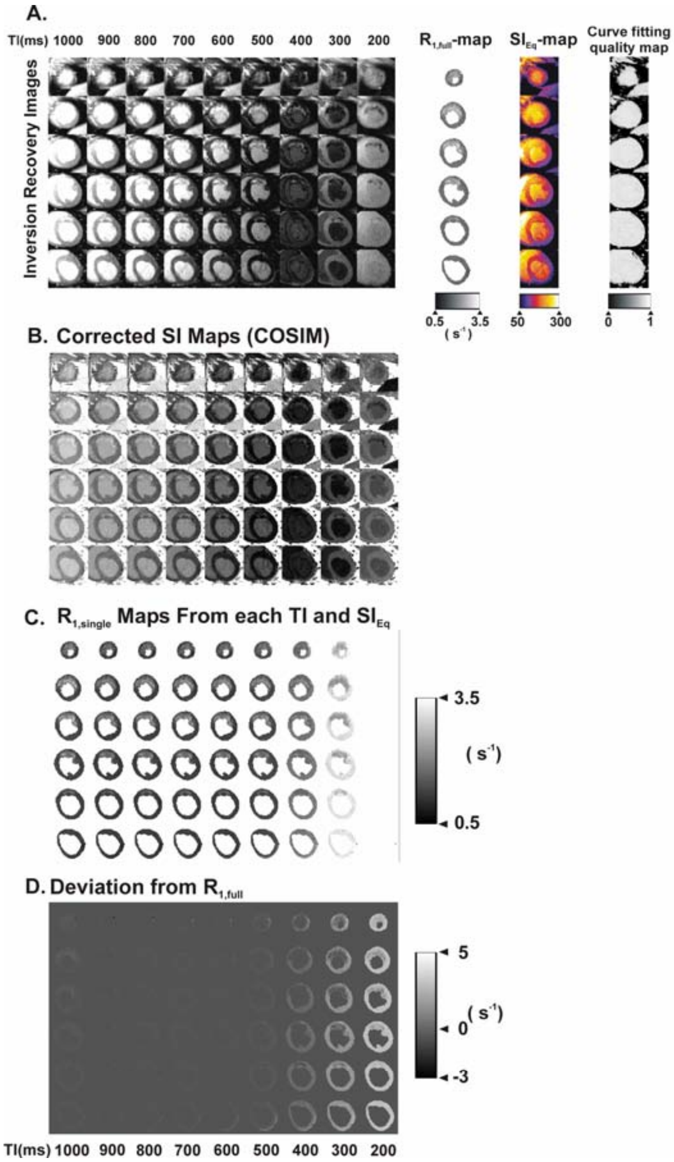

Figure 1A. Shown is a set of multi-TI IR images acquired in vivo in a dog heart 96h following MI and 48h following administration of Gd(ABE-DTTA), and the corresponding $R_{1,full}$-, SI_{Eq}-, and fit-quality-maps. In the raw IR-images, signal inhomogeneity is apparent. Due to its proximity to the cardiac coil on the chest wall, the anteroseptal region appears in most images much brighter than the inferolateral wall (far from coil) of the left ventricle. This inhomogeneity is also reflected in the SI_{Eq} map. **1B**. For the same experiment, the COSIMs for each TI are shown. Excellent R_1-weighting (infarct appears brighter than viable myocardium) can be observed in images acquired with TI≥500ms. The inhomogeneity of signal, observed in the raw images in Figure 1A, is almost completely eliminated in the COSIMs. **1C.** $R_{1,single}$ maps calculated from each single-TI image utilizing the SI_{Eq}-maps as detailed in the text. **1D.** Voxel-by-voxel deviation-maps of $R_{1,single}$ from $R_{1,full}$ for each TI, as compared to the reference $R_{1,full}$-map (calculated using multi-TI R_1-mapping) shown in Figure . For TIs between 600 and 1000 ms the error is very small (gray, i.e. close to zero) in all myocardial regions. Note that in this particular experiment which used Gd(ABE-DTTA), the τ_{null} for viable regions (those not accumulating the CA) was about 500ms (TR_{IR}=2100ms).