R2* Measurement Using Absolute SNR-Weighted Least Square Regression

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INTRODUCTION Accurate R2* measurements are critical for many quantitative imaging applications. R2* is estimated via mono-exponential fitting of signal decay within a series of gradient echo (GRE) images sampled at increasing TE. Root-sum-of-square (RSS) remains the most common approach to combine surface coil array images at each TE prior to the data fitting procedure. Rapid signal decay can result in poor SNR at later TEs. RSS approaches rectify and bias noise resulting in systematic fitting errors [1]. We previously studied the efficacy of combining truncation model with array coil combination methods to improve accuracy of R2* measurements in low SNR settings. Although truncation was found to be an effective method to reduce measurement error for RSS reconstructed data, the optimal truncation threshold was determined through brute-forced search (computationally intensive) with *a priori* knowledge of the anticipated R2* value [2]. The objective of this work was to investigate a less computationally exhaustive approach for R2* measurements with RSS reconstructed data (and no prior knowledge of anticipated R2*). We compared the accuracy of R2* measurements performed using SNR weighted least square (WLS) regression to R2* measurements using SNR-based truncation method in phantom, animal, and human studies.

METHOD SNR measurement: For all TEs, we reconstructed RSS combined images in SNR units via pre-scan noise, data pre-whitening, and bias correction [3]. This approach allows absolute SNR measurement since voxel-wise noise characteristics are taken into account during SNR calculations.

Comparison Studies: R2* maps were calculated via voxel-wise ordinary least-square (**Method A**: OLS_{ALL}) fitting and weighted least-square (**Method B**: WLS_{ALL}) fitting of the mono-exponential signal decay for all data echoes. By using its absolute SNR measurement as the weighting term at each TE, WLS_{ALL} weighted strongly high SNR TEs and weakly low SNR TEs. Similarly, R2* maps were also calculated via ordinary least-square fitting for truncated data (**Method C**: OLS_{TRUNC}), where TEs with absolute SNR below a given threshold were excluded from R2* map calculations. Truncation thresholds were incremented from SNR=0 to SNR=20 (steps of 0.1 SNR units) for all studies. A minimum of two TEs were kept for all R2* estimations.

Data Acquisition: R2* phantoms were constructed by filling cylindrical 2L polystyrene bottles with water doped with 1.6 mmol/L (*Phantom I*) or 0.8mmol/L (*Phantom II*) $MnCl_2.H_2O$. *Ex vivo* studies were performed on a recently euthanized rabbit. Abdominal axial scans were performed on 6 healthy volunteers according to our IRB-approved protocol. Phantom and *ex-vivo* studies were conducted using a 3T clinical scanner (Siemens Magnetom Trio) with 8-channel head coil. Volunteer studies were conducted using a 1.5T clinical scanner (Siemens Avanto) and a 32-channel surface coil array. A MGRE sequence was used with parameters: TR (phantom/*ex vivo*/abdomen)=5000/1000/100ms, TE=2-65ms, BW=640 Hz/pixel, 5mm slices and 24 echoes. For phantom and *ex vivo* studies, we achieved a range of SNR levels by using flip-angles (FA) = 1^o, 2^o, 5^o and 10^o; reference standard R2* measurements were performed using 32 averaged datasets acquired using the body transmit/receive coil. For volunteer studies, FA=20^o was used and we achieved different SNR levels by evaluating peripheral and central (high and low SNR) regions of within the liver.

Data Analysis: For phantom and *ex vivo* studies, we computed voxel-wise absolute error (VAE) as the difference between reference standard R2* map and comparison R2* maps.

RESULTS *Phantom*: R2* values were found to be 155 s^{-1} for *Phantom I* and 80 s^{-1} for *Phantom II*. At FA =1^o, 2^o, 5^o and 10^o, OLS_{ALL}, WLS_{ALL}, and optimal OLS_{TRUNC} (lowest error for truncation thresholds) are displayed in **Fig.1** for both phantoms. VAE was reduced with increasing SNR (increased FA) and decreasing R2* value (Phantom I vs. II). Both WLS and truncation improved R2* measurement. While R2* estimations using optimal OLS_{TRUNC} were more accurate than WLS_{ALL}, optimal OLS_{TRUNC} required 40-80 iterations of truncation and was based on prior knowledge of anticipated R2* value. WLS_{ALL} improved R2* measurement accuracy without any prior knowledge of anticipated R2* and only required 1 iteration for computation.

Ex vivo: R2* values were found to be 160 s^{-1} for liver parenchyma and 50 s^{-1} for gallbladder. Mean VAE for OLS_{ALL}, WLS_{ALL}, and optimal OLS_{TRUNC} are displayed for both tissues at FA =1^o, 2^o, 5^o and 10^o in **Fig.2**. Error decreased with increasing SNR/FA and decreasing R2* value (liver vs. gallbladder). WLS algorithm improved R2* measurement but didn't outperform optimal $OLS_{TRUNC.}$ However, optimal OLS $_{TRUNC}$ required iterations of truncation with prior knowledge of anticipated R2* values.

Normal Volunteer Studies: For a representative volunteer study, we selected ROIs in the peripheral and central region of the liver parenchyma (high vs. low SNR), shown in **Fig. 3A**. R2* measurements for OLS_{TRUNC} at SNR threshold from 0 to 20 for are shown in **Fig.3B**. R2*s from peripheral ROI are relatively constant at all thresholds, while R2*s for central ROI increased as SNR thresholds increased. For all six normal volunteers, optimal OLS_{TRUNC} R2* values were selected at the threshold where R2* values for both ROIs are closest (as labeled in Fig.3b). R2* values from all three methods (across all volunteers) are shown in boxplot **Fig. 3C.** In peripheral ROI, R2* measurements from all three methods are similar and can be viewed as the "relative reference standard". In central ROI, R2* values for both WLS_{ALL} and optimal OLS_{TRUNC} were close to the relative reference standard but no prior knowledge of anticipate R2* value was needed required for WLS_{ALL} method.

CONCLUSION R2* measurement accuracy improved with increased SNR and slower signal decay rates. SNR weighted least square algorithm and SNR-based truncation are both effective methods in reducing R2* measurement error. In clinical settings, where prior knowledge of anticipated R2* values and the optimal SNR truncation threshold are generally unknown, the SNR weighted least square algorithm is a fast and reliable approach for accurate R2* measurement.

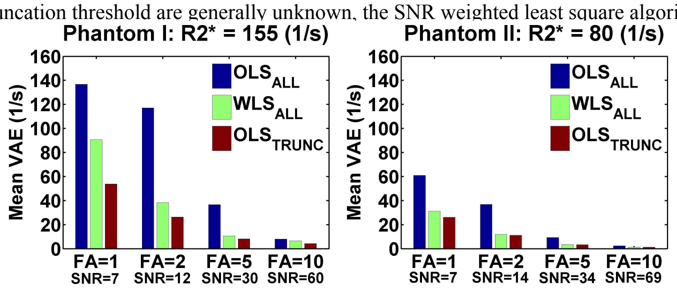

Fig.1 Phantom Studies: Mean VAE at FA= 1^o, 2^o, 5^o and 10^o for *Phantom I* and *Phantom II*. Error decreased with increasing SNR and decreasing R2* values. WLS_{ALL} and OLS_{TRUNC} improved R2* measurements. Accurate R2* measurement from OLS_{TRUNC} required prior knowledge of R2* values and iterations of truncation. Without prior information or R2* value, WLS_{ALL} is reliable approach to improve R2* measurement.

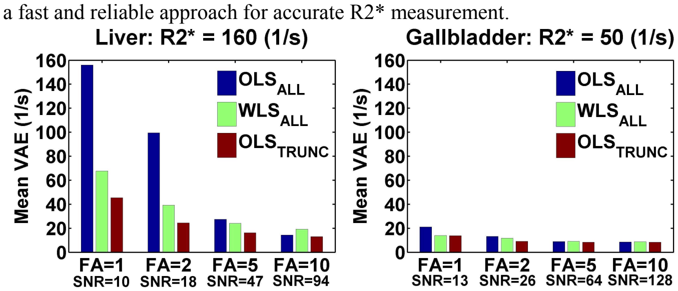

Fig.2 Ex vivo studies: Mean VAE at FA= 1^o, 2^o, 5^o and 10^o for liver and gallbladder. Higher SNR and lower R2* values reduces error. WLS_{ALL} and OLS_{TRUNC} improved R2* measurements. OLS_{TRUNC} provided a more accurate R2* measurements but is computationally intensive and required prior knowledge of anticipated R2* values.

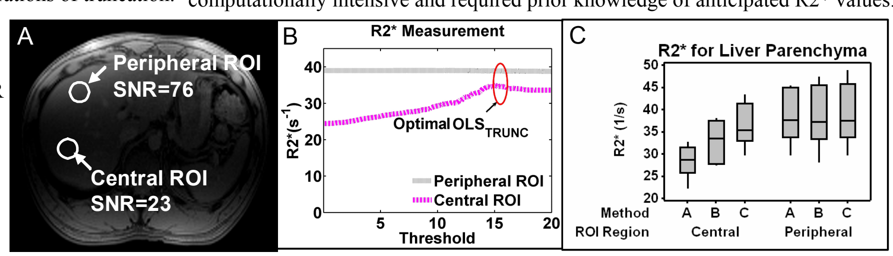

Fig.3 Volunteer Studies: **(A)** Axial abdominal slice, central and peripheral ROI for liver parenchyma. **(B)** OLS_{TRUNC} at SNR thresholds from 0 to 20. **(C)** Boxplots for R2* values from all methods (across all volunteers). In peripheral ROI, R2* for all methods are rather constant. In central ROI, optimal OLS_{TRUNC} and WLS_{ALL} both improved R2* estimation.

References: [1] Gilbert G, IEEE Med Imaging 2008; 26: 1428-1435. [2] Yin X, ISMRM 2009: 4636. [3] Kellman P, MRM 2005; 54: 1439-1447