IMPROVING NOISE ROBUSTNESS OF THE QUANTITATIVE (Q)BOLD MODEL.

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TARGET AUDIENCE: Researchers interested in new MRI contrast, modeling and data processing methods.

PURPOSE: The qBOLD model of He and Yablonskiy [1] describes the effect of deoxygenated blood of the capillary network on the signal decay assessed by gradient echo sampling of spin echo (GESSE) sequence. However, the oxygenation extraction fraction (OEF) and the deoxygenated blood volume (DBV) affect the signal decay very similarly, which allows a reliable estimation of OEF and DBV by fitting the qBOLD model to the GESSE signal only for very high signal to noise ratios (SNR>500) [2]. Other approaches quantify the blood volume by another independent methods like vesses size imaging or dynamic susceptibility contrast and use the qBOLD model only for estimating OEF. This approach is much more noise robust, but the independently assessed blood volume may not correctly represent the DBV of the qBOLD model leading to systematic wrong estimations of OEF.

In this work, we improve the fitting of the qBOLD model by obscuring the divergent global minimum of root mean squared errors (RMSE) and finding an effective global minimum by analyzing the local RMSE minima.

METHODS: An example GESSE signal decay was calculated by the qBOLD model for 3 Tesla, extravascular transverse relaxation rate (R2ex)=15/s, OEF=0.3, DBV=0.03 with the spin echo occurring at 30 ms and gradient echoes at every millisecond from -10 ms to +30 ms with respect to the time of the spin echo. Normal distributed noise was added to the signal resulting in an SNR of 100 (Fig.1). The noise of the example signal decay was not changed for later processing steps. RMSE was calculated similar to non-linear fitting between the example signal decay and all other signal decays for OEF=0-1 and DBV=0-0.1 (Fig.2,3,4). In Fig.2 the example signal and all other signals were free of noise. In Fig.3 the example signal with noise (SNR=100, Fig.1) was used. In Fig.4 also all other signal decays were added with normal distributed noise of the same magnitude as the example signal decay resulting an effective SNR of 71. Each of these signal decays was added with different random noise whereas the noise of the example signal decay was kept identically as shown in Fig.1. The RMSE of the local minima in Fig.4 was plotted with increasing OEF/decreasing DBV and fitted by a quadratic function whose minimum represents the best guess of the OEF and DBV values of the example signal decay. This approach was tested 100 time with recalculated noise and updated of the example signal decay.

RESULTS: The long band of low RMSE demonstrates how little the signal decays differ for a wide range of possible OEF and DBV combinations. However, for noise free signal decays the global minimum is zero and the example signal decay can be exactly reproduced (Fig.2). If the example curve is noisy, the band of low RMSE widens and the global minimum is not zero anymore and diverges from the actual parameters of the example signal decay (Fig.3). Adding random noise to the calculated signal decays for OEF=0-1 and DBV=0-0.1 results in an even wider band of low RMSE, but with no clear global minimum (Fig.4). Plotting and fitting the local minima along that band of low RMSE results in a robust estimation of OEF and DBV of the example signal decay. This approach (Fig.4,5) obtained OEF=0.32±0.05 and DBV=0.029±0.009 for the example signal decay with 100 times recalculated and updated noise which is closer to the actual example signal decay parameters and has less variability as non-linear fitting (Fig.3) which resulted OEF=0.33±0.12, DBV=0.036±0.021.

DISCUSSION: Adding noise to the signals decays of the RMSE calculation (Fig.4) obscures the divergent global RMSE minimum which occurs for the noisy example signal decay but non-noisy signals decays used for RMSE calculation (Fig.3). The added noise, however, worsens the RMSE, but can be recovered by analyzing the local RMSE minima by an quadratic fit function (Fig.5). Applying the quadratic fit function directly to the points of low RMSE of Fig.3 (not shown) only reproduces the divergent global RMSE minimum since it is not obscured by additional noise. The reliability of this approach

CONCLUSION: Due to the added random noise of the signal decays for RMSE calculation, non-matching global minima can be obscured (Fig.4) and better matching qBOLD parameters can be obtained by further analyzing the local RMSE minima (Fig.5). This approach will further be tested for the physiological range of OEF, DBV, R2ex and SNR parameters.

REFERENCES: **[1]** He X, Yablonskiy DA. Quantitative BOLD: mapping of human cerebral deoxygenated blood volume and oxygen extraction fraction: default state. Magn Reson Med. 2007 Jan;57(1):115-26. **[2]** Sohlin MC and Schad LR. Theoretical prediction of parameter stability in quantitative BOLD MRI: dependence on SNR and sequence parameters. Proc. of ISMRM 2009, 1623 **[3]** Christen T, Pannetier NA, Ni WW, Qiu D, Moseley ME, Schuff N, Zaharchuk G. MR vascular fingerprinting: A new approach to compute cerebral blood volume, mean vessel radius, and oxygenation maps in the human brain. Neuroimage. 2014 Apr 1;89:262-70.

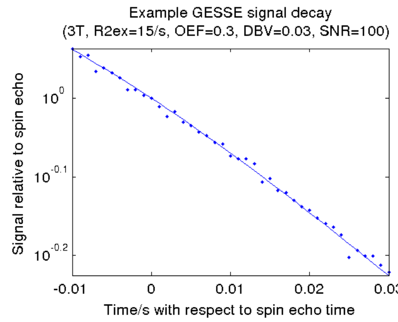

Figure 1: Example GESSE signal decay without noise (solid line) and with SNR = 100.

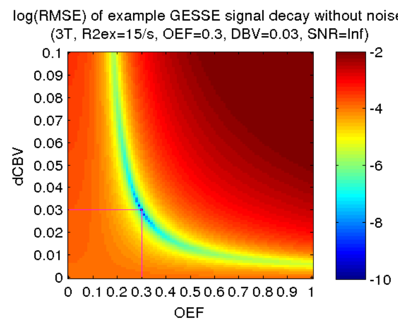

Figure 2: Logarithm of RMSE between noise free example signal decay (Fig.1) and all decays calculated for OEF=0-1 and dCBV=0-0.1. A long band of low RMSE is visible, but the minimal RMSE occurs at OEF=0.3 and DBV=0.03 which exactly matches the parameters of the example signal decay (Fig.1)

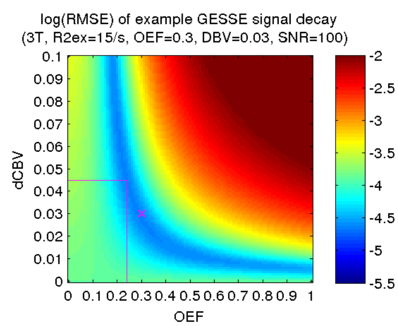

Figure 3: Logarithm of RMSE between example signal decay with noise (SNR=100, Fig.1) and all decays calculated for OEF=0-1 and dCBV=0-0.1. The band of low RMSE is wider than compared to Fig.2 and the global RMSE minimum occurs at OEF=0.24 and DBV=0.045. The RMSE position of OEF and DBV of the example signal is marked by X.

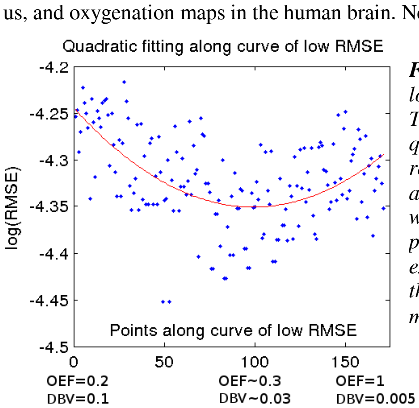

Figure 5: RMSE of local minima (Fig.4). The minimum of the quadratic fit function results in OEF=0.28 and DBV=0.032 which is closer to the parameters of the example signal decay than the global RMSE minimum in Fig.3.

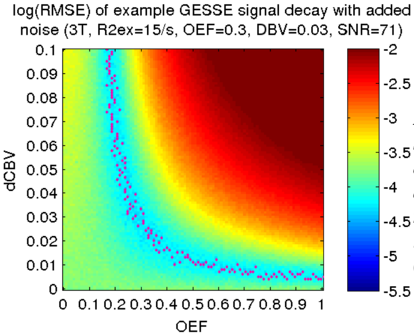

Figure 4: Logarithm of RMSE between example signal decay with noise (SNR=100, Fig.1) and all decays calculated for OEF=0-1 and dCBV=0-0.1 with added noise of the same magnitude as the example signal resulting an effective SNR of 71. The RMSEs of the local minima (dots) were plotted with increasing OEF/decreasing DBV in Fig.5.