Parallel transmit MRI safety modeling and pulse design

Sairam Geethanath[1], Shaihan J. Malik[1,2], Joseph V. Hajnal[1,2]

[1]Imaging Sciences Department, Imperial College London

[2]Imaging Sciences and biomedical engineering, Kings College London

Imperial College London

KING'S College LONDON

Introduction

The advantages of parallel transmit (pTx) MRI such as increased radio-frequency (RF/B_1) homogeneity and tailored excitation are well established (1). However, these are limited by the conservative limits on local Specific Absorption Ratio (L-SAR) due to the associated challenges in its evaluation such as subject dependency.

An approach to compute EM model based L-SAR and global SAR known as the Q-matrix formulation has been proposed recently (2)

Evaluation of L-SAR based on Q-matrices alone, called exhaustive search, is time-consuming due to the large number of cells involved in the electromagnetic (EM) models (order of 700,000 or more) for SAR evaluation. Hence, this cannot be applied for parallel transmit pulse design where SAR has to be computed in real-time.

These computational issues have been addressed by Virtual Observation Point (VOP) framework (3). The VOP algorithm is a clustering algorithm which allows estimating peak local SAR with no underestimation but controlled overestimation (defined by parameter μ). μ can also be tuned to minimize the number of VOPs for faster computation but with a penalty in increased over-estimation.

Figure1: The Visible Human Model (VHM), figure from ref (2)

Methods

Q-matrix generation: Q matrices for global and local SAR were generated for each of the 740,817 cells of the Visible Human Model (VHM).

These were compared with the corresponding matrices provided by the vendor for validation. SAR values calculated by the implemented model were compared with the vendor's implementation on the scanner for quadrature excitation

Implementation of VOPs: The VOP framework was implemented to enable fast calculation of local SAR as detailed in ref (3).

A 5% over-estimation of SAR was chosen to achieve Q-matrix compression and was tested with 1000 tries of random shims of unit norm. The implemented VOP framework was integrated with the scanner software

Optimization for RF shimming: The VOP framework was then used to retrospectively perform RF shimming on previously acquired B_1 maps of the human pelvis on 3.0 T scanner using the 8 channel pTx coil and the variable flip angle pulse sequence (TR = 30ms, nominal flip angle =80º)

The RF shimming optimization problem was solved using the magnitude least squares (MLS) approach constrained by L-SAR, G-SAR and forward power.

The problem was formulated as 2 different design approaches described by the constrained optimizations in equations [P_1] and [P_2].

Methods

$$\begin{gathered} \text{minimize } \|(|Ax|) - b\|_2 \\ \text{subject to} \\ \text{L-SAR} <= K_L \\ \text{G-SAR} <= K_G \\ \|x\|_2 <= K_P \end{gathered} \qquad [P_1]$$

$$\begin{gathered} \text{minimize (L-SAR + G-SAR)} \\ \text{subject to} \\ \|(|Ax|) - b\|_2 <= K_{MLS} \\ \|x\|_2 <= K_p \end{gathered} \qquad [P_2]$$

Here, A is the system matrix of transmit sensitivities, x is the vector of complex shims, b is the normalized target unit B_1 profile, $K_{L,}$ $K_{L,}$ K_L and K_L are the value of constraints for L-SAR, G-SAR, forward power and the MLS error respectively.

The results were compared with quadrature excitation to illustrate the utility of parallel transmit incorporating model based l-SAR information. Hence K_L and K_G were set to the L-SAR and G-SAR values of quadrature excitation while K_P to 4.2426 (l_2 norm of having an amplitude of 1.5 on all 8 shims) and K_{MLS} was set to the l_2 norm value of the inhomogeneity of the quadrature solution as compared to *b* in P_2.

The optimization problems were solved using CVX (4) and all implementations were performed using MATLAB, (Mathworks, Inc., MA, USA).

Results

Q-matrix validation: Figure 3 shows the Q-matrices for whole body generated by the vendor (a), and the current implementation (b), and the ratio between the two (c).

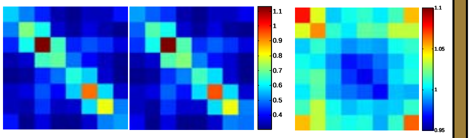

Figure 2: Whole body Q-matrix generated by the (a) vendor, (b) current implementation and (c) the ratio between the two

The RMSE difference between the two over the entire VHM model was 0.06. The values of predicted and observed SAR values are tabulated in table 1.

Table 1 Predicted and observed scanner SAR values for quadrature excitation

	Implemented	Observed on scanner
L-SAR (W/kg)	2.5995	2.6
G-SAR (W/kg)	0.1670	0.162

VOP for the VHM model: Implementation of a 5% over-estimation bound on SAR values for unit norm shims resulted in 72 VOPs thereby accomplishing a compression factor of 10289.125.

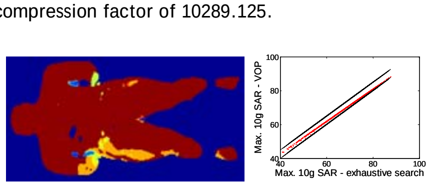

Figure 3: (a) A VOP-labelled coronal slice of the Visible Human Model (VHM) (b) Correlation between local SAR values computed by exhaustive search and VOP methods over 1000 random shim values (5% over-estimation)

Results

Figure 3(a) shows a VOP labeled coronal slice of the VHM (each colour is a different VOP) while figure 3(b) shows the VOP-predicted SAR values as compared to the exhaustive search and being within the 5% bound of the maximum L-SAR.

RF shimming: Figure 4 depicts the solutions of [P_1] and [P_2]. Table 2 provides complimentary information related to SAR levels and RF inhomogeneity of the solutions. The average time for solving P_1 and P_2 was 23 ± 0.7 seconds over 5 trials.

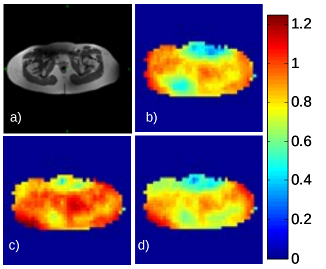

Figure 4: (a) MR anatomical image of the pelvis (b) Corresponding quadrature normalized- B_1 map (c) Normalized- B_1 map solution for P_1 (d) Normalized- B_1 map solution for P_2

It can be observed through figure 4 and table 2 that VOP based optimization provides control over local SAR while mitigating RF inhomogeneity.

Table 2: Evaluation of the solutions of pTx-VOP based optimization with respect to quadrature excitation for problems (a) P_1 and (b) P_2 with respect to MLS error, SAR and forward power

P_1	Quadrature	pTx –VOP optimized	% difference
MLSE	5.7248	3.1406	-45.14
L-SAR (W/kg)	3.2	2.5	-21.87
G-SAR (W/kg)	0.160	0.160	0
$\|\|x\|\|_2$	2.8284	3.4354	+21.46

(a)

P_2	Quadrature	pTx –VOP optimized	% difference
MLSE	5.7248	5.7139	-0.19
L-SAR (W/kg)	3.2	1.5	-53.13
G-SAR (W/kg)	0.160	0.107	-33.13
$\|\|x\|\|_2$	2.8284	2.6515	-6.25

(b)

Conclusions & future work

The implemented Q-matrix formulation is in good agreement with the vendor's results for the same EM model as indicated by figure 2 and table 1. The VOP framework has been demonstrated to result in significant compression, bounded SAR over-estimation and hence resulting in practical execution times for pulse design optimization. The results of SAR constrained RF shimming also validate the utility of obtaining solutions with superior B_1 homogeneity or lower SAR as compared to quadrature excitation

Implementation of the Q-matrix formulation and integration with the scanner enables building a library of EM models to better address SAR issues due to diversity in physical attributes of subjects. The VOP framework allows for model based SAR information to be incorporated into parallel transmit pulse design for applications such as RF shimming and tailored excitation.

References

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