Loco-regional hyperthermia treatment planning: optimisation under uncertainty

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Citation for published version (APA):
Chapter 8

SAR inter-subject variability in 7T parallel transmit MRI of the head

Purpose: The use of patient-specific RF shim sets to mitigate $B_1^+$ inhomogeneity in high-field MRI requires on-line, patient-specific SAR monitoring. Numerical simulation is currently the most effective way to do so, however, this requires the formulation of a dielectric patient model. In this study, generality in the SAR distribution during MRI of the head is studied to investigate whether a generic model may be chosen in combination with a safety factor to account for variation within the population.

Methods: Electric and magnetic fields are simulated for an 8 channel parallel transmit array loaded with 6 different head models. The head models derive from detailed manual segmentations. Generic SAR behaviour is studied through comparison of the largest eigenvalue distributions associated with the local power kernel matrices. Two numerical RF shimming experiments were performed: a constraint free experiment and an experiment with local and global SAR constraints. In the latter case, local and global SAR were evaluated based on a generic model. For both cases the ability of different generic models to predict actual SAR levels was evaluated.

Results: Generic SAR behaviour is indeed observed. The largest eigenvalue distribution is observed to be comparable between models and clearly reflects the contribution of the different elements. RF shimming without constraints slightly improves the $|B_1^+|$ homogeneity at the cost of a substantial increase in the local and global SAR. Imposing constraints on local and global SAR during optimization, where SAR levels are estimated based on a generic SAR model, is an effective strategy provided that the generic model is carefully selected. In that case a safety factor of 1.4 appears to be sufficient for the studied population.

Conclusions: Generic SAR behaviour causes the use of a generic SAR model to be a practically feasible alternative to patient-specific SAR models. Based on the results acquired for the studied population, a moderate safety factor is sufficient to account for under-estimation of the local SAR in reality. The use of a generic SAR model has been shown to be effective in $|B_1^+|$ shimming with SAR constraints.
8.1 Introduction

High static field (>3T) magnetic resonance imaging offers excellent anatomical detail and new possibilities for functional imaging. At the same time, as the Larmor frequency increases, the radiofrequency (RF) fields that are needed to realize transverse magnetization penetrate less into the human body. Due to the decreasing wavelength, interference patterns become more pronounced as well (101; 102; 103; 104; 105; 106). These combined effects result in inhomogeneous magnetization and hence an unwanted spatial modulation of the intensity in the acquired images.

RF inhomogeneity is mitigated in practice by parallel transmit arrays allowing RF shimming. The contribution of every transmit element of the array to the $B_1^+$ field can be mapped and in this way a patient specific set of phases and amplitudes, a RF shim set, can be determined that results in an optimal homogeneous excitation of spins.

With the RF magnetic fields, electric fields are associated that give rise to local and systemic heating. This is a safety concern and heating, as measured in practice by the specific absorption rate (SAR), therefore needs to be monitored and kept within safe limits.

The use of patient specific shim sets is associated with an increase in SAR relative to quadrature excitation of the transmit array (107; 108; 109). However, in general, no one-to-one mapping of $|B_1^+|$ homogeneity and local and global SAR levels will exist. In order to determine whether a shim set can safely be applied, there is a need for on-line monitoring of SAR (110).

Although there are several techniques available to map the $B_1^+$ field (50; 111; 51), the associated electric fields within the scanned sample cannot be measured directly. To overcome this problem, numerical simulation can be used to compute the electric fields due to excitation of the different elements of the coil (112; 113; 102; 104). However, numerical simulation of electromagnetic fields requires the formulation of a dielectric model of the patient in the scanner. In order to account for the patient specific dielectric anatomy, such a model would be based on the segmentation of previously made images (114). Routine clinical application requires this procedure to be automated in order to be of practical use. It is likely however that the segmentation algorithm needs to be supervised to some extent making it too time consuming.

In this study, two RF shimming scenarios with SAR monitoring are investigated for a 7T 8-channel parallel transmit head coil. Because of the aforementioned reasons, these scenarios are not based on a patient specific SAR model but on the use of
a generic SAR model.

The first RF shimming scenario is based on patient specific $B_1^+$ maps and no SAR constraints are imposed during the shimming procedure. Global and local SAR levels are evaluated afterwards based on a generic model. The nominal flip angle, pulse duration and the duty-cycle (the pulse time over the repetition time) then need to be chosen such that the local and global SAR are within their limits. This shimming scenario results in optimal homogeneity, possibly at the cost of increased scanning time or signal loss due to a reduction of the flip angle.

In the second scenario, a generic SAR model is used during shimming to constrain the local and global SAR. In this way, for a certain signal level, a shim set resulting in maximum homogeneity is found with maximum local SAR and average head SAR values within the defined limits (115; 116). Imposing SAR constraints can come at the cost of reduced homogeneity but preserves scanning time and signal level.

In both scenarios, safety evaluations depend on the assumption that there are strong similarities in SAR behaviour between individuals. Based on this assumption, the use of a generic model in combination with a safety factor is appropriate. This safety factor accounts for the over- and, more important, under-estimation of local and global SAR by the generic model.

In this study, eigenvector/eigenvalue analysis of the matrices that relate shim settings to SAR is used to demonstrate whether similar heating patterns can be expected for different individuals.

In both scenarios, discrepancies will exist between the SAR predicted by the generic model and the actual SAR. These discrepancies will be analysed to establish the necessary safety factor for the studied population. This provides further information about the practical use of generic SAR models in clinical RF shimming for specific patients.

8.2 Theory

8.2.1 Determination of power absorption matrices

In order to relate a RF shim set to a local SAR value we use the $Q$ matrix concept. The SAR value depends on the electric field distribution as follows

$$\text{SAR} = \frac{\sigma}{2\rho} \vec{E}^* \cdot \vec{E}. \quad (8.1)$$
Here $\vec{E}$ is the total electric field (\(^*\) denotes the complex conjugate) with the shim set $\vec{v}$ applied, $\sigma$ (S/m) is electric conductivity and $\rho$ (kg/m\(^3\)) is the density. This field, written here in column-vector notation can be computed from

$$
\vec{E} = \vec{E}_{\vec{v}} = \begin{pmatrix}
E_1^x & \ldots & E_N^x \\
E_1^y & \ldots & E_N^y \\
E_1^z & \ldots & E_N^z
\end{pmatrix}
\begin{pmatrix}
A_1 e^{i\phi_1} \\
\vdots \\
A_N e^{i\phi_N}
\end{pmatrix}
$$

(8.2)

where $N$ is the number of elements of the transmit coil, $A_i$ is the amplitude of the signal that excites element $i$, $\phi_i$ is the relative phase of this signal and $E_i^{x,y,z}$ are the electric field components when only element $i$ is excited. Combining equations 8.1 and 8.2 we then find

$$
\text{SAR} = \nu H \left( \frac{\sigma}{2\rho} \vec{E}^H \vec{E} \right) \vec{v}.
$$

(8.3)

By introducing a matrix $Q$ we finally find

$$
\text{SAR} = \nu H Q \vec{v}.
$$

(8.4)

where $Q = \frac{\sigma}{2\rho} \vec{E}^H \vec{E}$. The matrix $Q$ relates any shim set to a local SAR value. This concept is easily extended for the evaluation of a SAR average. For the N-gram average SAR it holds that

$$
<\text{SAR}>_{Ng} = \frac{1}{N_v} \nu^H \sum_{i=1}^{N_v} Q^i \vec{v}
$$

(8.5)

where $N_v$ voxels constitute N-gram of tissue. Similarly for the whole head

$$
<\text{SAR}>_{\text{head}} = \frac{1}{V_{\text{head}}} \nu^H \sum_{V_{\text{head}}} Q^i \vec{v}.
$$

(8.6)

A number of interesting observations can be made from the matrix $Q$ through calculation of its eigenvalues and eigenvectors. The eigenvalues are denoted by $\lambda_1, \ldots, \lambda_N$, arranged in descending order, with corresponding eigenvectors $\vec{u}_1, \ldots, \vec{u}_N$. The first eigenvalue $\lambda_1$ gives the highest possible SAR value within a voxel for a given power level. The eigenvector $\vec{u}_1$ gives the corresponding shim set. By considering the largest eigenvalue in MRI safety evaluations, the need to choose a certain shim set, potentially biasing the evaluation, is no longer present. In addition, the
Figure 8.1: Surface models of the six subjects included in this study. The figure gives an impression of the differences in shape and size of the different heads.

eigenvalue – eigenvector pairs can be used to develop classifiers (28) to reduce the dimensionality of numerical shimming problems e.g. by discarding voxels with low heating potential.

8.3 Methods

8.3.1 Voxel based head models

Six voxel based human anatomical models were used in this study. Four models were retrieved from the virtual family and classroom model databases (117). These models include two Caucasian adult models (a 34 year old male named Duke and a 26 year old female named Ella), a model of an 11 year old Caucasian (Billie) and a model of a 14 year old Caucasian (Louis). In addition the Japanese adult female (Hanako) and male model (Taro) were included (118). All models originate from detailed manual segmentations and are voxelized at 2mm isotropic resolution. Figure 8.1 shows surface models of the six subjects to give an impression of the differences in head shape and size. An overview of the segmented tissue types is given in table 8.1. Figure 8.2 shows the segmented anatomy for the Ella model in a transver-
8.3.2 Electromagnetic simulations

Electromagnetic field modelling was based on the finite difference time domain method (37). An implementation of the algorithm that can be executed on a graphical processing unit was used to allow for calculation using a $2 \times 2 \times 2 \text{mm}^3$ voxel size within a practical time frame. In order to assure convergence of the computed steady-state response, 100,000 time-steps at 95% of the Courant stability limit were taken. This corresponds to over 100 periods at the frequency of interest. The computational domain was truncated with 15 perfectly matched layers at each side of the rectangular domain. The auxiliary differential equation implementation was used for this purpose (79).

8.3.3 Coil modelling

The considered parallel transmit array was an eight channel volume coil consisting of strip line type elements (figure 8.3) (119). Each element consists of two ground conductor plates two centimeters apart from two strips that are connected to a differentially fed coaxial cable. At the inner- and outer ends of the pairs of plates, capacitors are placed that are used to tune the coil. In order to tune and match the coil elements, the capacitor values of the capacitances in each coil element and the impedance of the connected source were varied. For each element four capacitors were modelled: two identical capacitors at the outer- and inner ends of the coil elements. Although physically all coil elements are identical, numerically two types can be distinguished: elements at 0, 90, 180 and 270° that are voxellized without stair
<table>
<thead>
<tr>
<th>Tissue type</th>
<th>$\sigma$ (S/m)</th>
<th>$\epsilon_r$ (-)</th>
<th>Tissue type</th>
<th>$\sigma$ (S/m)</th>
<th>$\epsilon_r$ (-)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air</td>
<td>0</td>
<td>1.00</td>
<td>Mandible</td>
<td>0.0825</td>
<td>13.4</td>
</tr>
<tr>
<td>Artery</td>
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<td>65.7</td>
<td>Marrow</td>
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<td>5.76</td>
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<td>65.7</td>
<td>Medulla oblongata</td>
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<td>52.0</td>
</tr>
<tr>
<td>Bone</td>
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<td>13.4</td>
<td>Mid brain</td>
<td>0.552</td>
<td>52.0</td>
</tr>
<tr>
<td>Cartilage</td>
<td>0.552</td>
<td>46.8</td>
<td>Mucosa</td>
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<td>52.0</td>
</tr>
<tr>
<td>Cerebellum</td>
<td>0.972</td>
<td>59.8</td>
<td>Muscle</td>
<td>0.770</td>
<td>58.2</td>
</tr>
<tr>
<td>Cerebrospinal fluid</td>
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<td>72.8</td>
<td>Nerve</td>
<td>0.418</td>
<td>37.0</td>
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<td>Commissura ant/post</td>
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<td>43.8</td>
<td>Pharynx</td>
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<td>Connective tissue</td>
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<td>48.0</td>
<td>Pineal body</td>
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<td>62.5</td>
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<td>52.0</td>
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<td>46.8</td>
<td>SAT</td>
<td>0.0395</td>
<td>5.64</td>
</tr>
<tr>
<td>Ear (skin)</td>
<td>0.640</td>
<td>49.9</td>
<td>Skin</td>
<td>0.64</td>
<td>49.9</td>
</tr>
<tr>
<td>Esophagus</td>
<td>0.971</td>
<td>68.7</td>
<td>Skull</td>
<td>0.0825</td>
<td>13.4</td>
</tr>
<tr>
<td>Esophagus (lumen)</td>
<td>0.630</td>
<td>52.0</td>
<td>Spinal cord</td>
<td>0.418</td>
<td>37.0</td>
</tr>
<tr>
<td>Eye (lens)</td>
<td>0.647</td>
<td>49.0</td>
<td>Teeth</td>
<td>0.0825</td>
<td>13.4</td>
</tr>
<tr>
<td>Eye (sclera)</td>
<td>0.975</td>
<td>58.9</td>
<td>Tendon ligament</td>
<td>0.537</td>
<td>48.0</td>
</tr>
<tr>
<td>Eye (vitreous humor)</td>
<td>1.52</td>
<td>69.0</td>
<td>Thalamus</td>
<td>0.691</td>
<td>60.1</td>
</tr>
<tr>
<td>Fat</td>
<td>0.0395</td>
<td>5.64</td>
<td>Thymus</td>
<td>0.851</td>
<td>62.5</td>
</tr>
<tr>
<td>Grey matter</td>
<td>0.691</td>
<td>60.1</td>
<td>Thyroid</td>
<td>0.850</td>
<td>62.5</td>
</tr>
<tr>
<td>Hippocampus</td>
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<td>60.1</td>
<td>Tongue</td>
<td>0.744</td>
<td>58.9</td>
</tr>
<tr>
<td>Hypophysis</td>
<td>0.851</td>
<td>62.5</td>
<td>Trachea</td>
<td>0.552</td>
<td>46.8</td>
</tr>
<tr>
<td>Hypothalamus</td>
<td>0.851</td>
<td>62.5</td>
<td>Trachea (lumen)</td>
<td>0</td>
<td>1.0</td>
</tr>
<tr>
<td>Intervertebral disc</td>
<td>0.552</td>
<td>46.8</td>
<td>Vein</td>
<td>1.32</td>
<td>65.7</td>
</tr>
<tr>
<td>Larynx</td>
<td>0.552</td>
<td>46.8</td>
<td>Vertebral</td>
<td>0.0825</td>
<td>13.4</td>
</tr>
<tr>
<td>Lung</td>
<td>0.502</td>
<td>40.5</td>
<td>White matter</td>
<td>0.413</td>
<td>43.8</td>
</tr>
</tbody>
</table>

Table 8.1: An overview of the tissue types included in the voxel models with the applied dielectric properties.
Figure 8.3: Schematic drawing of the 8-channel parallel transmit coil. The coil consists of 8 strip line type elements and can be tuned by four capacitors at the inner and outer ends of the strips.
casing and elements at 45, 135, 225 and 315° that are voxellized with stair casing effects. These elements were considered separately.

### 8.3.4 Eigenvalue analysis

The distribution of the largest eigenvalue ($\lambda_1$) was computed for each head model. A comparison of these distributions gives an indication whether there is similar SAR behaviour in the six models. Furthermore, the eigenvectors corresponding to the maximum largest eigenvalue were compared to indicate whether the worst-case SAR was achieved for the same shim set.

### 8.3.5 RF shimming

Based on the assumption of generic SAR behaviour, RF shimming was performed with and without local and global SAR constraints in a “leave-one-out” type of numerical experiment. One of the models was taken as the generic head model and was used to estimate local and global SAR for the other models. These SAR levels were compared to the actual SAR that followed from evaluation of the shim settings on a patient-specific SAR model. Shimming was based on patient specific $B_1^+$ maps, as this resembles the clinical situation where it is possible to acquire these maps. To prevent a selection bias, every model was selected in turn as a generic model. In case of shimming with SAR constraints, the local and global SAR were evaluated for the generic model.

RF shimming was performed for a region-of-interest defined in figure 8.4. $|B_1^+|$ homogeneity was measured within a 2cm thick transversal slab. Tissues types other than brain tissue (e.g. skull, fat, muscle) were excluded in the computation of the normalized standard deviation that was chosen as a measure of homogeneity.

The following parameters were evaluated for all shim sets

- Maximum 10g-average: $\max(<\text{SAR}>_{10g})$ (W/Kg).
- Average head SAR: $<\text{SAR}>_{\text{head}}$ (W/Kg).
- Inhomogeneity: IH (%).

All shim sets were normalized to a power level for which a nominal 90° flip angle within a region-of-interest (ROI) was achieved. SAR evaluations are based on a 5% duty-cycle ($\tau_{\text{pulse}}/\text{TR}$). As a reference shim set, for all subjects quadrature excitation
was evaluated. Quadrature excitation is realized by setting the phase of channel $i$, $\phi_i = -(360/N)i$ with all amplitudes equal.

**Constraint-free RF shimming**

In order to minimize the heterogeneity of the $|B_1^+|$ distribution the following objective function was defined

$$IH(v) = \sqrt{\frac{1}{N_v} \sum_{ROI} (\mu - |B_1^+|)^2 \overline{\mu}}$$

(8.7)

where $\mu$ is the average $B_1^+$ magnitude over the ROI containing $N_v$ voxels (typically 40,000 voxels). Solutions to this nonlinear optimization problem were computed with the CFSQP toolkit (65). To accelerate the optimization procedure, the objective function was evaluated on a graphical processing unit by making use of the Thrust template library (120) and CUDA (121). To reduce the risk of convergence to a local minimum, the optimization algorithm was run 100 times with different random initial shim settings.

**RF shimming with local and global SAR constraints**

An extended version of the numerical shimming problem, in which the objective function given by equation 8.7 is minimized, was formulated by including constraints for local and global SAR. To formulate a meaningful optimization problem,
an minimum average flip angle of 90° was required. In summary, the applied constraints are

\[
\gamma \tau_{\text{pulse}} < |B_1^+|_{\text{ROI}}(\psi) = \frac{\pi}{2}
\]

\[
< \text{SAR}_{10g}(\psi; \vec{x}) \leq < \text{SAR}_{10g,\text{constraint}}
\]

\[
< \text{SAR}_{\text{head}}(\psi) \leq < \text{SAR}_{\text{head,constraint}}
\]

(8.8)

where \(< \cdot >\) denotes a volume average, \(\gamma\) is the gyromagnetic ratio, \(\tau_{\text{pulse}}\) is duration of the RF pulse (a block pulse). Local and global SAR constraints are based on IEC regulations (122) and are 10W/kg and 3.2 W/kg, respectively. The pulse duration \(\tau_{\text{pulse}}\), relevant to the first constraint, was set to 1 ms. This corresponds to an average \(B_1^+\) magnitude in the ROI of 5.87 µT.

### 8.4 Results

#### 8.4.1 Eigenvalue analysis

Figure 8.5 shows cross-sections of the \(\lambda_1\) distributions for the six models. Similar distributions are found for all models. One of the features that the distributions have in common are the hot-spots observed at the back and front part of the heads. For the front part of the head, \(\max(\lambda_1)\) varied from 0.81 - 1.0 (normalized to the maximum value for the six models) while for the back part of the head, a slightly larger variation was observed, from 0.71 – 1.0 (table 8.2). Comparison of the eigenvectors by amplitude (figure 8.6) shows 1) a strong similarity between the shim sets corresponding to worst-case local SAR and 2) that the distance of the coil elements to the head dominantly determines the amplitudes in the shim set. This also explains the different behaviour for the Hanako and Taro model that is the result of the more “round” shape of the head.

#### 8.4.2 RF shimming

Table 8.3 presents the \(B_1^+\) and SAR statistics for the six models applying quadrature excitation of the coil. It is observed that for all models a nominal flip angle of 90° was realized without exceeding of the local and global SAR limits.
Figure 8.5: Transversal, sagittal and coronal cross-sections of the $\lambda_1$ distribution for the six models. Results are normalized by the maximum value found in the population.
<table>
<thead>
<tr>
<th>Model</th>
<th>$\max(\lambda_1)_{\text{front}}$</th>
<th>$\max(\lambda_1)_{\text{back}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ella</td>
<td>0.88</td>
<td>1.0</td>
</tr>
<tr>
<td>Duke</td>
<td>0.99</td>
<td>0.91</td>
</tr>
<tr>
<td>Billie</td>
<td>0.88</td>
<td>0.83</td>
</tr>
<tr>
<td>Louis</td>
<td>1.00</td>
<td>0.71</td>
</tr>
<tr>
<td>Hanako</td>
<td>0.81</td>
<td>0.74</td>
</tr>
<tr>
<td>Taro</td>
<td>0.89</td>
<td>0.78</td>
</tr>
</tbody>
</table>

Table 8.2: The maximum first eigenvalue for the six models ($\max(\lambda_1)$) normalized by the maximum value for the front part of the anatomy and the back part.

Figure 8.6: Eigenvectors (amplitude) corresponding to the maximum first eigenvalue in the front part of the head (a) and back part of the head (b).
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Ella</th>
<th>Duke</th>
<th>Billie</th>
<th>Louis</th>
<th>Hanako</th>
<th>Taro</th>
<th>IEC Norm</th>
</tr>
</thead>
<tbody>
<tr>
<td>IH($</td>
<td>B_1^+</td>
<td>)$ (%)</td>
<td></td>
<td>20.2</td>
<td>14.3</td>
<td>13.9</td>
<td>9.2</td>
<td>17.6</td>
</tr>
<tr>
<td>10g-SAR$_\text{max}$ (W/Kg)</td>
<td></td>
<td>6.0</td>
<td>5.0</td>
<td>5.5</td>
<td>4.6</td>
<td>8.1</td>
<td>5.1</td>
<td>10.0</td>
</tr>
<tr>
<td>$&lt;\text{SAR}&gt;_{\text{head}}$ (W/Kg)</td>
<td></td>
<td>1.7</td>
<td>1.4</td>
<td>1.8</td>
<td>1.2</td>
<td>1.9</td>
<td>1.5</td>
<td>3.2</td>
</tr>
</tbody>
</table>

Table 8.3: SAR and $B_1^+$ statistics for the six models applying quadrature settings. Results are based on a 5% duty-cycle ($\tau_{\text{pulse}}/\text{TR}$) and are normalized to realize a nominal flip angle of 90° within a 1ms pulse. Inhomogeneity (IH) is measured by the standard-deviation of $|B_1^+|$ over the mean $|B_1^+|$ value.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Ella</th>
<th>Duke</th>
<th>Billie</th>
<th>Louis</th>
<th>Hanako</th>
<th>Taro</th>
<th>IEC Norm</th>
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</thead>
<tbody>
<tr>
<td>IH($</td>
<td>B_1^+</td>
<td>)$ (%)</td>
<td></td>
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<td>12.2</td>
<td>10.4</td>
<td>8.2</td>
<td>14.9</td>
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<td>11.4</td>
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<td>2.6</td>
<td>4.0</td>
<td>2.0</td>
<td>3.4</td>
<td>2.9</td>
<td>3.2</td>
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Table 8.4: SAR and $B_1^+$ statistics for the six models after constraint-free shimming. Results are based on a 5% duty-cycle ($\tau_{\text{pulse}}/\text{TR}$) and are normalized to realize a nominal flip angle of 90° within a 1ms pulse. SAR values that are above the IEC norm are printed bold.

Table 8.4 shows the $B_1^+$ and SAR statistics for the six models after constraint-free maximization of the $|B_1^+|$ homogeneity in the ROI. A substantial increase in the local (×2.0-3.5) and global (×1.7-2.2) SAR in comparison to quadrature excitation is observed. The global SAR limit is exceeded in two models (Billie and Hanako) while the local SAR limit is exceeded in all six models. A moderate improvement in $|B_1^+|$ homogeneity was found, on average 21% (min. 11% – max. 35%).

Figure 8.7 shows the maximum 10g-SAR and average head SAR after constraint-free shimming according to the generic models for the different shim models (x-axis) relative to the actual SAR. Over-estimation up to 80% is observed and under-estimation of the SAR of approximately 40%.

Figure 8.8 shows the under- or over-estimation of the maximum local and average head SAR by a generic SAR model after RF shimming with SAR constraints. SAR evaluations during shimming were performed on the generic model. Over-estimations up to 50% were found for both the local and global SAR. The global SAR was under-estimated up to 30% and the local SAR up to 40%.

In figure 8.9 the $|B_1^+|$ homogeneity after shimming with SAR constraints is shown for the different generic SAR models. For the purpose of comparison, the figure shows the $|B_1^+|$ homogeneity for quadrature excitation and after constraint-free shim-
Figure 8.7: Relative average head SAR (a) and maximum 10g-SAR (b) for the different models. Along the horizontal axis are the models for which constraint-free shimming was performed. The used generic SAR model is indicated and the bars denote the relative difference between the SAR as predicted by the generic model and the actual SAR as predicted by the patient specific SAR model. Negative values represent an under-estimation of the actual SAR level by the generic model where as positive values represent an over-estimation.
Figure 8.8: Relative average head SAR (a) and maximum 10g-SAR (b) for the different models. Along the horizontal axis are the models for which RF shimming with local and global SAR constraints was performed. SAR evaluations were based on different generic SAR models as indicated in the plot. Bars denote the relative difference between the predicted SAR according to the generic model and the SAR computed for the shim model. Negative values represent an under-estimation of the real SAR level by the generic model where as positive values represent an over-estimation of the real SAR level.
ming as well. The figure illustrates that constraint-free shimming realizes maximum homogeneity while imposing constraints comes at the cost of a slight increase in heterogeneity. RF shimming with constraints still improves $|B_1^+|$ homogeneity compared to quadrature excitation (with exception of the Louis model where constraint-free shimming realizes a relatively small improvement).

### 8.5 Discussion

In order to limit local and systemic heating during MRI, RF safety limits have been devised for local and global (volume average) SAR levels (122). As the electric fields that cause RF heating can not be measured, numerical simulation can be used to estimate local and global SAR in the imaged volume. Since it is not feasible in routine clinical practice to develop a SAR model for every patient undergoing MRI, the use of a generic SAR model is a practical alternative in RF safety evaluations.

However, the use of a generic SAR model assumes that, the observed SAR patterns for different individuals within the population will be very similar. If this assumption holds, the remaining differences may be accounted for by multiplying the SAR levels found with the generic model by a safety factor. This limits the risk of under-estimation of the SAR.

The purpose of this study was to evaluate the necessary safety factor for a population of patients when a generic SAR model is used to evaluate local and global SAR levels for specific individuals. First the assumption of generic SAR behaviour was tested by comparing the distributions of the largest eigenvalue of the local Q matrix for the six models included in the study.

The largest eigenvalue of the local Q matrices gives a worst-case estimate of the maximum local SAR for a certain power level. For the 10g-SAR, the maximum first eigenvalue was on average 0.91 (0.81 - 1.0) (normalized to maximum value in the population) for the back of the head and 0.71 - 1.0 for the front part of the head. The corresponding eigenvectors were shown to be similar and the distance to the different coil elements dominantly determines the amplitude of the elements of the eigenvectors.

One of the limitations of the eigenvalue/eigenvector analysis is that the eigenvector corresponding to the maximum eigenvalue does not necessarily represent a practically relevant shims set in terms of $B_1^+$ homogeneity. For this reason the eigenvalue/eigenvector analysis is likely to over estimate the upper bound for the SAR when only relevant shim sets are considered.
Figure 8.9: Inhomogeneity of the $|B_1^+|$ distribution for quadrature excitation, shimming without constraints and shimming with local and global SAR constraints. The figure illustrates that the selected SAR model has a small impact on the inhomogeneity.
Furthermore, the eigenvector corresponding to the largest eigenvalue for a particular voxel only gives the maximum achievable SAR in that voxel if these settings are within the working range of the amplifiers connected to the array elements. In this study the assumption was made that, for power levels realistic in this particular application, the amplitudes are well within this range and hence the presented analysis is appropriate.

Quadrature excitation was evaluated for all subjects. This shim set served as a reference for other shimming results. On average, the maximum 10g-SAR level was found to be 5.7W/kg (4.6 – 8.1W/kg). The anatomical localisation of SAR hot spots was found to be very similar. The average head SAR was on average 1.6W/kg (1.2 – 1.9W/kg).

Two RF shimming strategies were tested, for both strategies SAR evaluations were made on a generic model. Every model was selected in turn as this generic model.

Constraint-free shimming improved homogeneity for all subjects, however, a moderate increase in homogeneity was found to come at the cost of a more than two-fold increase in maximum 10g-SAR. For the selected pulse duration and duty-cycle, the IEC local SAR norm was exceeded for all subjects while the global SAR norm was only exceeded in two out of six subject.

By imposing constraints on the local SAR and global SAR during optimization, an improvement in \(|B_1^+|\) homogeneity can be achieved relative to quadrature excitation while at the same time the relevant SAR norms are respected. Relative to the \(|B_1^+|\) distributions resulting from constraint-free shimming, the homogeneity is slightly reduced.

Based on both shimming scenarios, the Ella model would be the most suitable generic model as the average over- and under-estimation is relatively small. To account for anatomical variation and the consequent under-estimation of 10g-SAR, a safety factor of \(1/0.7 \approx 1.4\) would be required based on the maximum of 30% under-estimation of the local head SAR by the generic model. Contrary to local and global SAR assessment, the choice of a generic model was found to be less critical for the \(|B_1^+|\) homogeneity.

Based on the established safety factor of 1.4, the additional scanning time would be given by \(\sqrt{1.4} \approx 1.2\) (preserving the nominal flip angle and the duty-cycle). If reliable patient specific SAR monitoring would be available, the average gain in scanning time is given by the average overestimation of the SAR multiplied by this factor. Implementation of such a procedure would however require additional scanning
time to reconstruct the total electric field (constraint-free shimming) or the complex electric field per element (shimming with SAR constraints). In addition to this, a patient specific density and electric conductivity map needs to be acquired to compute the SAR distribution from the electric fields.

In this study, the effect of anatomical variations, variations in scale and shape, on local SAR and global SAR predictions were investigated. A number of factors were not considered. One important factor is the variation in dielectric properties between individuals. These variations require the use of an additional safety factor and further research is needed to determine the magnitude of this factor and whether it is model independent. Another contribution to variation in SAR in clinical practice is expected to be found in differences in position and posture of the head with respect to the array. Finally, all models included in this study derive from healthy subjects. Certain types of pathology may be expected to introduce further variation that needs to be addressed in further research.

8.6 Conclusions

In MRI of the head, generic SAR models are a useful substitute for patient specific SAR models that are time consuming to realise. This is explained by the generic SAR behaviour observed between individuals. It is expected that a moderate safety factor can account for the variations in SAR observed within the population. RF shimming with a generic SAR model to impose SAR constraints reduces local SAR substantially at the cost of a small increase in $|B_1^+|$ inhomogeneity. Whereas the selection of a model as a generic model is critical in terms of SAR, i.e. certain models are better predictors than others, for the $|B_1^+|$ homogeneity this selection is less critical.