Random RF Shimming may conceal possible local SAR hotspots for asymmetric parallel transmit coils

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Synopsis

While general-purpose coils mostly have identical elements arranged symmetrically, purpose-built coils can be asymmetrical. This asymmetry may lead to a high variation in local SAR distributions of individual coil-elements. For an arterial spin labelling coil, we show that using 2,000,000 unconstrained random excitations to characterize the maximum local-SAR underestimates the local-SAR by 7%. We also show that for the investigated ASL coil, the neck elements, which are exclusively used for labelling, yield 33% less SAR than the head-imaging coils. Therefore, 50% higher power limits can be used for labelling part of an ASL sequence than the imaging part.

Introduction

Parallel-transmit (pTx) RF coils are used at higher field strengths to mitigate wavelength related artefacts. However, some combinations of weights applied to individual coil-elements may lead to increased local SAR. While general-purpose coils mostly have identical elements arranged symmetrically, purpose-built coils can be asymmetrical (Figure 1). This asymmetry may lead to a high variation in local SAR distributions of individual coil-elements and may make some coils more likely to be used.

Most arterial spin labelling sequences consist of two parts, i) labelling the spins in a lower slice in the neck, and ii) imaging the spins in a higher slab, in the head. To increase labelling efficiency, an ASL-coil was previously built with three elements around the neck, four around the head and one on the crown (Figure 1).

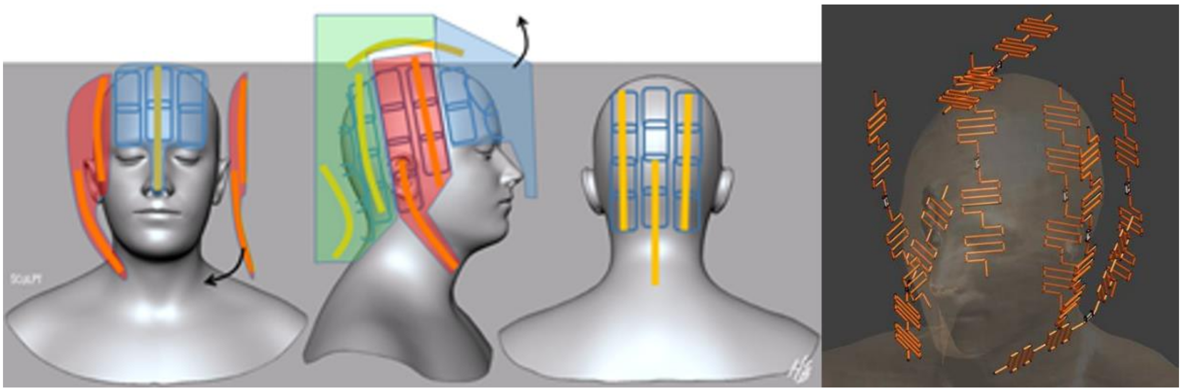

Figure 1: *RF coil array structure features three elements around the neck, four around the head and one on the crown. The coil was simulated on Sim4Life using the Duke body model of the Virtual Family[3]. The head of the model was discretized into ~17 million voxels with a grid resolution of approximately 1.25mm (not shown here).*

Random RF magnitude/phase combinations are commonly simulated to investigate local SAR, as these are expected to cover most real-life scenarios for a sufficiently large number of excitations (Nexc). However, using random excitations is unlikely to yield numerous cases with several coil-elements turned off, unless Nexc is impractically high.

In this study, we investigate the efficiency of using a random set of excitations to determine the operational SAR limits of an asymmetrical 8-element ASL-coil array.

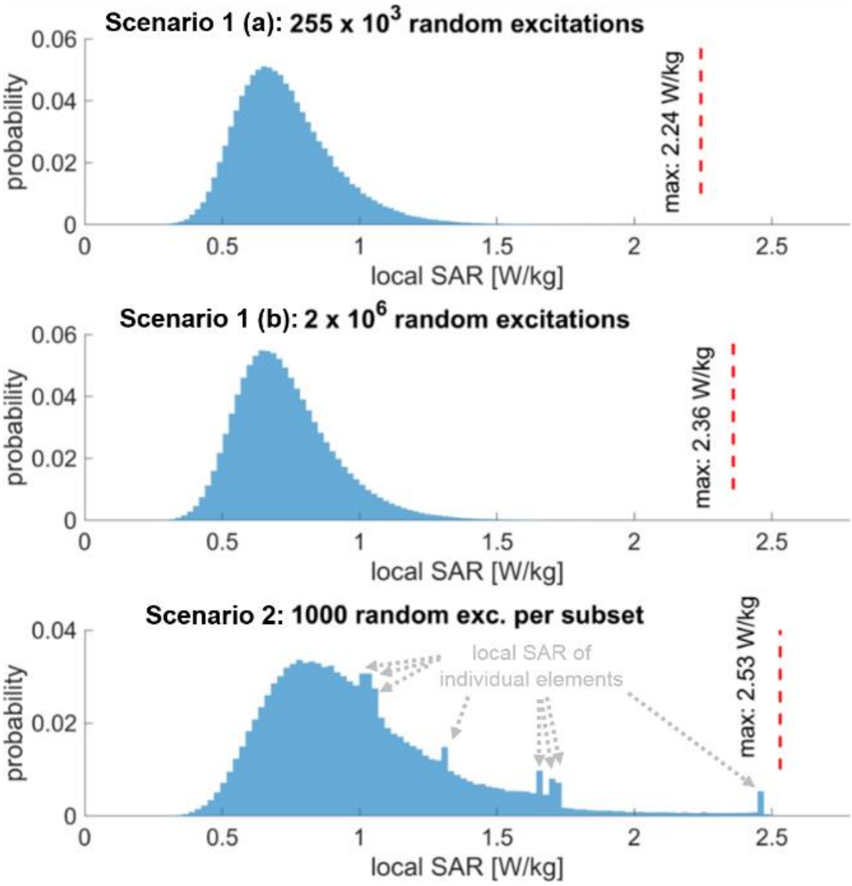

Figure 2: *Local SAR values observed in Scenario 1 – unconstrained random excitation with* ***a)*** *Nexc=255,000 and* ***b)*** *Nexc=2,000,000; and in Scenario 2 – subset of coils with* ***c)*** *255 different cases with 1000 excitations-per-case. For same number of excitations (Nexc=255,000), unconstrained random excitations underestimated local SAR by 13%. Even with Nexc=2,000,000 excitations, local SAR was underestimated by 7%. Increasing Nexc by ten-fold in Scenario 2 (Nexc=2,550,000) did not increase the observed maximum local SAR (not shown). In scenario 2, the 8 bins corresponding to local SAR of individual elements can be seen. Note that no coil yields the maximum local SAR when used alone.*

Methods

Electromagnetic simulations of the coil (details given in Figure 1) were performed in Sim4Life (ZMT, Zurich, Switzerland). Virtual observation points (N=3738) were used in local SAR calculations[1]. Random excitations were created by randomizing the amplitudes (A_lower≤amplitude≤1) and phases (0≤phase<2π) of each coil-element. The amplitudes were then scaled such that the total input power to the whole coil array was 1W.

Scenario 1: **Unconstrained random shimming**. Random excitations were created for Nexc=255,000 and Nexc=2,000,000 for A_lower = 0.

Scenario 2: **Subset of coils (Constrained random shimming)**. 1,000 random excitations were created for each subset of coil-elements (one-ON, two coils ON, …, one-OFF, all-ON), yielding a total of Nexc=255,000. Because only the three coil-elements around the neck will be used for labelling while the remaining five are used for imaging in an ASL sequence, we also investigated these two specific cases separately.

Scenario 3: **All-ON**. Calculations in scenario 2 were repeated as A_lower was increased from 0 to 1 (phase-only shimming) at increments of 0.1. Instead of turning elements off, their amplitudes were set equal to A_lower while the amplitudes for the selected subset were randomized between [A_lower, 1]. Phase was randomized for all elements.

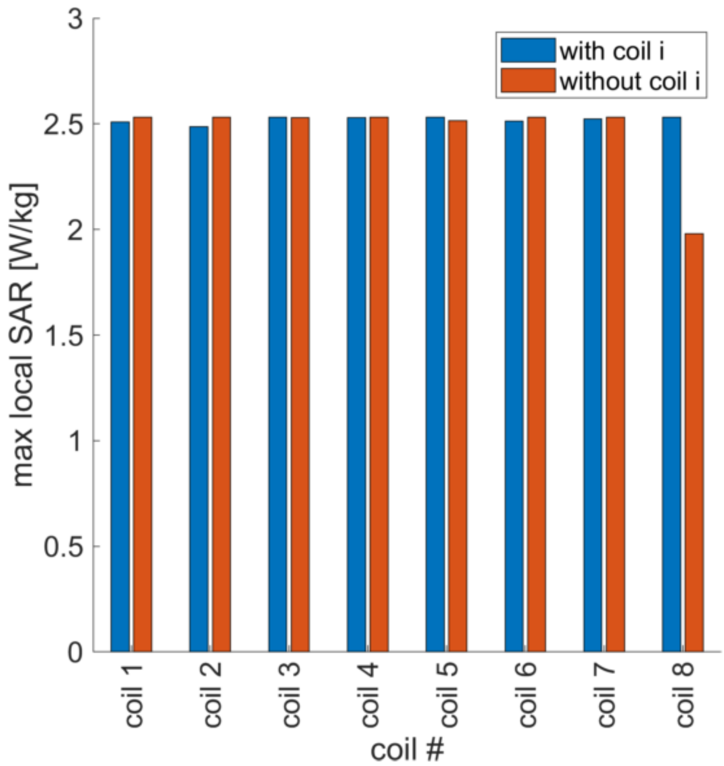

Figure 3: *The dataset in scenario 2 is parsed to show the maximum observed local SAR when a given coil-element is used (in combination with other elements, blue colour) versus when that coil-element is turned off (red). Comparisons show that using the crown element (8^{th} coil) increases the maximum local SAR by 28% compared to when it is turned off. Also notice that the crown element does not yield the maximum local SAR when used alone (Figure 1), and it is the constructive interference of the electric fields from multiple coils including the crown element that leads to the calculated maximum local SAR.*

Results and Discussion

The maximum local SAR was observed as 2.24W/kg (Nexc=255,000) in scenario 1 and as 2.53W/kg in scenario 2 (Figure 2). An increase of 13% was observed in calculated local SAR when elements were explicitly turned off for the same number of excitations. Using Nexc=2,000,000 (scenario 1) still yielded 7% underestimation (2.36W/kg). This difference highlights that unconstrained random excitations may not cover all possible scenarios, unless an impractical number of excitations is used, and may possibly result in an important underestimation of local SAR.

Note that explicitly diverting the power to a subset of coil-elements still does not guarantee that the global worst case is found. Increasing Nexc to 10,000 per subset did not yield any changes in our experience. Nevertheless, increasing Nexc further or developing an interval search algorithm that searches around the local SAR maxima might increase the likelihood of finding the global maximum of local SAR.

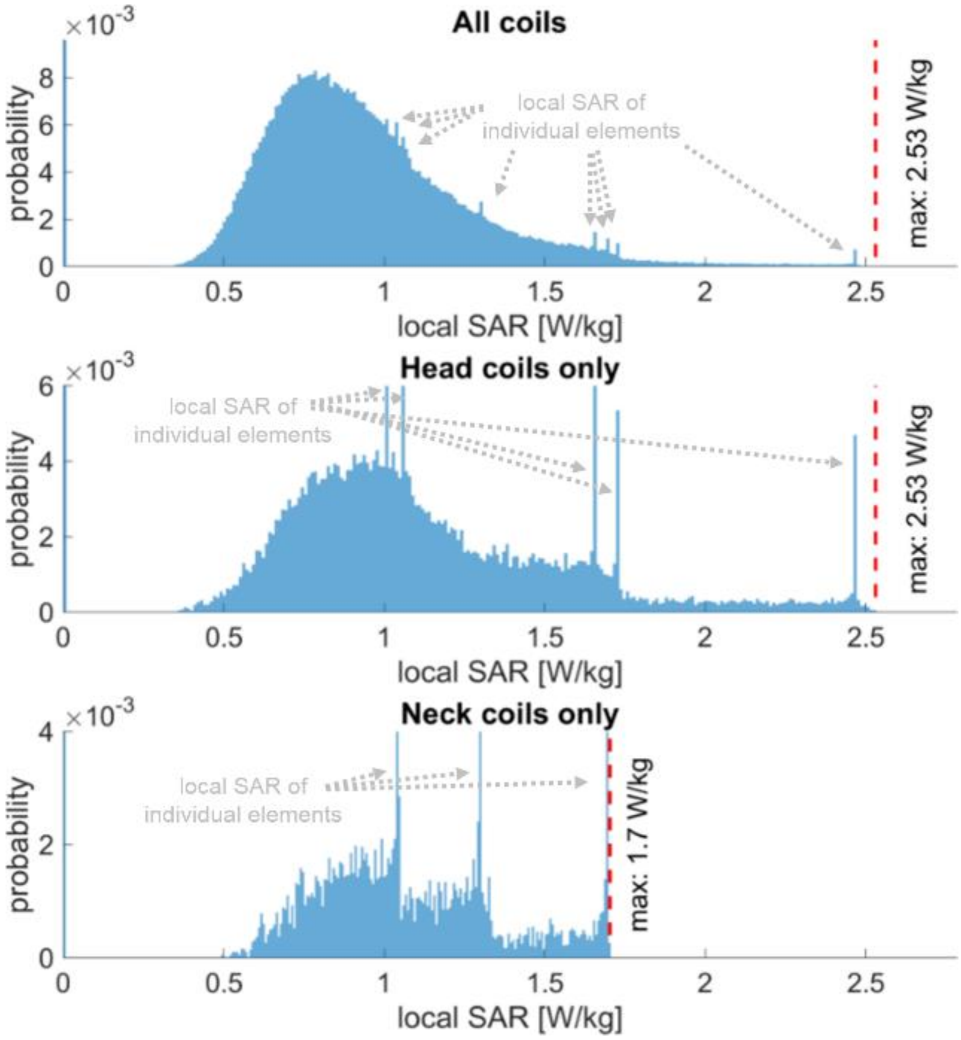

Figure 4: *Local SAR values observed when* ***a)*** *the dataset in scenario 2 is parsed to investigate* ***b)*** *all subsets that use only the five head coils and* ***c)*** *all subsets that use only the neck elements. Using only the neck elements yields 33% lower maximum local SAR, compared to using the head elements and using all elements. This allows using a 50% higher total input power setting for the same safety level when only the neck elements are used, e.g. for labelling in an ASL sequence. In all panels, the distinct bins indicate local SAR of individual elements.*

The crown coil led to 28% higher maximum local SAR when it was used (Figure 3). Consequently, maximum local SAR when the five head coil-elements were used, was equivalent to the overall maximum of 2.53W/kg, while maximum local SAR when only the three neck elements were used with other coil-elements turned off was 1.70W/kg (Figure 4). Labelling can be achieved by using only the neck elements, which yields 33% less maximum local SAR. Therefore, we could define an input power limit that is 50% higher for labelling than for imaging, instead of penalizing the neck coils with the effect of the crown-element by using a single SAR limit. Because labelling yields comparable SAR to imaging during a pseudo-continuous ASL sequence[2], this potential SAR-benefit may be used to increase labelling duration or reduce TR at 7T considerably. Also, note that the crown coil does not yield the maximum local-SAR when used alone (Figures 1, 3).

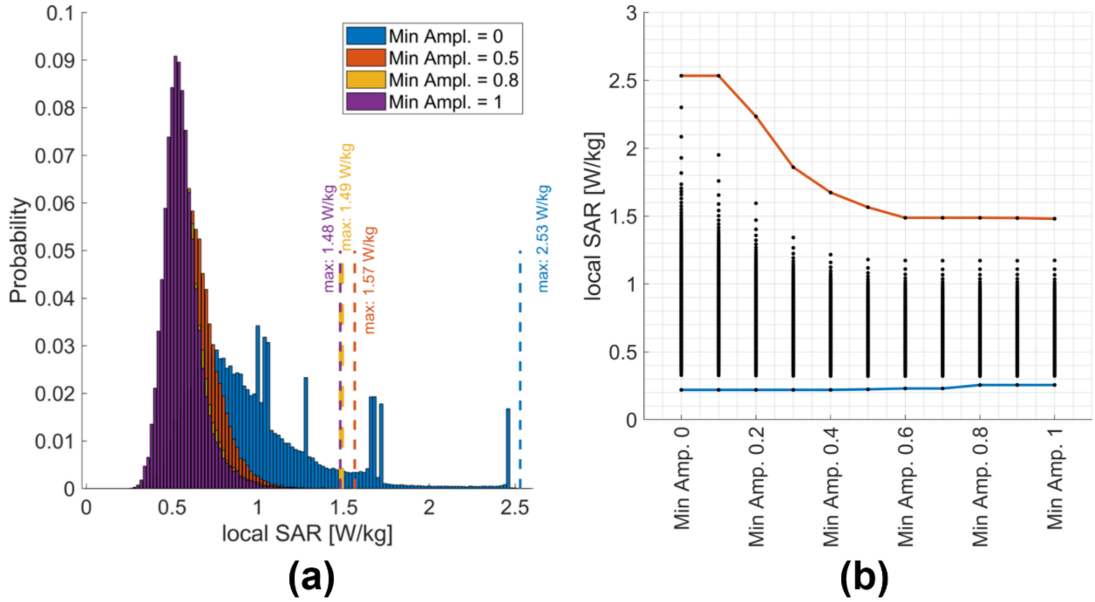

Figure 5: *Limiting the minimum amplitude (A_lower) that can be applied to any coil-element leads to a more balanced distribution of the input power across the coil-elements and may reduce the peak local SAR. Setting A_lower=1 (phase-only shimming) reduces the maximum local SAR by 42%. However, limiting the minimum amplitude to A_lower=0.6 of the maximum provides 41% reduction in SAR as well, while creating more degrees of freedom in determining coil-element weights for mitigating wavelength effects.*

Finally, phase-only shimming (all amplitudes set to 1) is considered a safer alternative to amplitude-and-phase shimming. This is confirmed in Figure 5 where the maximum local SAR is reduced by 42% for A_lower=1 compared to unconstrained amplitude-and-phase shimming. However, setting A_lower to 0.6 also yields a very similar reduction of 41% while allowing more freedom in designing the coefficients across the coil-elements for mitigating wavelength effects.

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