# Rapid RF Safety Evaluation for Transmit-Array Coils

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**Introduction:** Parallel-transmission (pTX) [1,2] facilitates greatly enhanced flexibility for RF-pulse design, and while it can be exploited to reduce the global and local energy deposition throughout the exposed body [2,3], it can also lead to localized E-field hot-spots [4]. To ensure safety various elaborate safety concepts have been proposed [5,6], which typically rely on accurate coil specific RF-simulations. However, obtaining the necessary simulations tends to be a computationally intensive and time-consuming endeavor [7]. In addition, validation measurements will be necessary to assure that the simulations accurately capture the behavior of the physical coil [8]. Moreover, when the newly acquired in-vivo data indicates that modifications to the physical coil are desirable, the entire simulation and validation cycle needs to be repeated. In this work, we present a new method for transmit-array safety evaluation based on a single 15min MR experiment. The novelty of the proposed method resided in its ability to account for, to first order, the geometrical decoupling of the E-fields. Consequently, the resulting power limits are sufficiently lenient to facilitate a plethora of in-vivo experiments. This enables a rapid iterative transmit-array coil design procedure, where the optimization processes is driven by representable and relevant in-vivo data without the need for a time-consuming simulation and validation process.

**Theory:** The specific absorption rate (SAR), a measure of the absorbed power per kg, produced by an N-channel transmit-array at point $\boldsymbol{r}$ is defined as $SAR(\boldsymbol{r}) = \frac{\sigma(r)}{2\,\rho(r)} \|\sum_n^N \boldsymbol{E}_n(\boldsymbol{r})\|_2^2$, where σ, ρ, *N*, and ***E*** are the conductivity, density, number of transmit-channels, and electric-field, respectively. Assuming constructive interference, the upper limit is confined to $SAR(\boldsymbol{r}) \leq \frac{\sigma(r)}{2\,\rho(r)} (\sum_n^N E_n(\boldsymbol{r}))^2$, where $E_n(\boldsymbol{r}) = |\boldsymbol{E}_n(\boldsymbol{r})|$. Adopting the AM-GM inequality [9] we find: $SAR(\boldsymbol{r}) \leq \frac{\sigma(r)}{2\,\rho(r)}\, N \sum_n^N E_n(\boldsymbol{r})^2$. When the heat capacitance ($C_p$) of the phantom is known, than $\frac{\sigma(r)}{2\,\rho(r)} \sum_n^N E_n(\boldsymbol{r})^2$ can be deduced from a single MR temperature measurement. To this end, a dedicated sequential RF-heating pulse is required. This pTX pulse consists out of a series of identical sub-pulses, each played without overlap on a different transmit-channel (Fig. 1**A**). Provided that the heating time ($\tau$) is relatively short compared to the heat diffusivity of the phantom, the source term in the heat equation $SAR_{seq}(\boldsymbol{r}) = \frac{\sigma(r)}{2\,\rho(r)} \sum_n^N E_n(\boldsymbol{r})^2$ can be retrieved by solving $\Delta T(\boldsymbol{r}) = \tau\, SAR_{seq}(\boldsymbol{r})/C_p$. Finally, the power limits for each channel are given by: $P_{in}\ IEC_{lim}/(N \times Max[< SAR_{seq}(\boldsymbol{r}) >])$, where the $P_{in}$, $IEC_{lim}$, $< SAR_{seq}(\boldsymbol{r}) >$, are the average injected power, relevant 10-gram SAR limit [10], and the 10-gram average of the measured SAR, respectively.

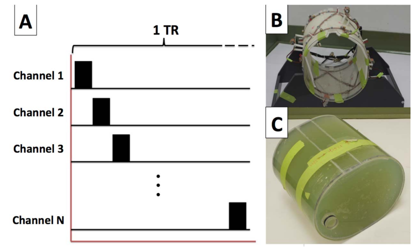


**Fig 1**: Sequential RF heating pulse (**A**). Coil (**B**) and phantom (**C**) used.

**Methods:** Experimental verification was performed on a Siemens 7T Magnetom scanner equipped with an 8-channel pTX-setup (Siemens, Erlangen, Germany). In this case an 8-element transceiver-array head coil used (**Fig. 1B**), based on the recently introduced triangular design [11]. The phantom closely matched the contours of the coil (**Fig. 1C**, Agarose, conductivity = 0.56 (S/m), relative permittivity = 52.5, heat capacity = 3.7 (MJ $m^{-3}$ $K^{-1}$), heat conductivity = 0.47 (W $m^{-1}$ $k^{-1}$), heat diffusivity 0.13 ($mm^2$ $s^{-1}$)). Phantom characteristics were measured using the 8570E dielectric probe (Agilent, Santa Clara, CA), and thermal properties were obtained with the KD2 pro probe (Pullman, WA, USA). Separate oil phantoms were attached to the phantom, to provide a stable phase reference. Temperature measurements were based on the proton chemical shift (PRF) [12]. Pre- and post-heating images were obtained using the VIBE sequence (TR = 12ms, TE = 10ms, FA= 5°, 3.4mm isotropic, total accusation time 40s), where the TE was chosen to match the T2* of the phantom, and the flip-angle set to approach the Ernst angle. Moreover, to ensure adequate signal levels throughout the phantom, the recently introduced $k_T$-points method was employed to homogenize the flip-angle throughout the imaging volume [13]. The accuracy was evaluated, by calculating the temperature variations measured between two consecutive pre-heating measurements. A dedicated sequence without any gradients was used for RF-heating (total time 6min). To facilitate optimal SNR reconstruction for the multichannel coil, a noise measurement was performed (VIBE now with FA= 0°). Subsequently the heat equations were solved to retrieve the SAR. In addition to the proposed method, to provide a frame of reference, a similar analysis was also performed for the circular polarized (CP) mode of the coil. All RF heating experiments were performed with the same average incident power per channel.

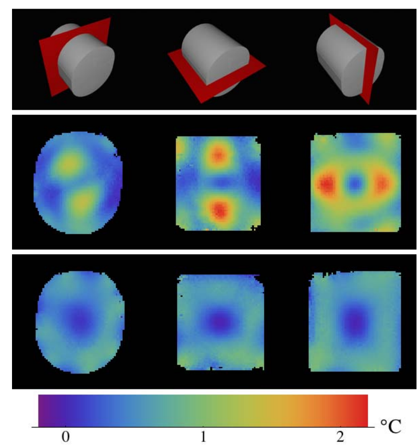


**Fig 2:** MR thermometry measurements. Slice orientations (top). Measured temperature maps obtained by RF heating using circularly polarized mode (middle), and sequential heating (bottom).

**Results:** Based on the phase images acquired without heating, an absolute maximum error of 0.1°C was found (standard deviation 0.04°C). Temperature measurements performed while heating with the CP-mode revealed the usual pattern (**Fig. 2** *top*). When driven sequentially (**Fig. 2** *bottom*), the peak temperature is substantially lower due to the absence of interference effects (1.5 °C vs 2.2 °C). Consequently, the maximum 10-gram SAR is also substantially lower (**Fig. 3**). For the proposed method a peak 10-gram SAR of 13W/g was found compared to 23W/kg for the CP-mode. However, the AM-GM inequality indicates that for this coil a safety factor of 8 must be applied when operating in pTX. Consequently, the allowed power per element is nearly 5 times smaller compared to a situation where the same coil would be driven exclusively in the CP mode.

**Discussion & conclusion:** With the here-introduced method, safe limits can be derived base on a singe 15min MR experiment. Note that, the presented technique is valid for any type of transmit-array and has already been used to evaluate radically different coil designs, including two 7T human torso coils. If the heat capacitance of the phantom is not exactly known, then the proposed approach can also be used to derive safe power limit based on a predefined maximum allowed temperature increase. The only perquisite is the ability to constrain the forward power on each channel independently. Considering the conservative nature of this method, advanced safety systems paired with coil specific simulations will still be necessary to reap the benefits provided by incorporating local SAR optimization in to the RF-pulse design process [3]. Nevertheless, it is now possible to thoroughly evaluate new transmit-array coil designs under relevant in-vivo conditions without a time-consuming conjoined simulation proses at every step.

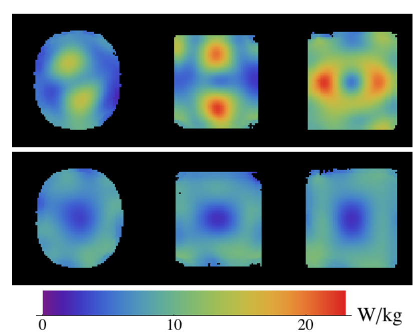


**Fig 3:** Ten-gram averaged SAR maps derived from the experimental data. Circularly polarized mode (top), and sequential heating (bottom).

**References:** [1] Katscher, et al., MRM; 49:144-150 (2002). [2] Zhu, MRM 51:775-784 (2004). [3] Lee, et al., MRM 67: 1566-1578 (2012) [4] Collins, et al., ISMRM p1092 (2007) [5] Greasslin, et al., MRM 68 1664-1674(2012) [6] Boulant, et al., ISMRM p 3850 (2011) [7] Koslov, et al., PIERS online 6:395-399(2010) [8] Cauchy-Schwarz Master Class, ISBN 978-0-521-54677-5 p15. [9] Alon, et al., ISMRM p491(2012) [10] IEC Standard, 60601-2-33. [11] Wiggins , et al., ISMRM p0309 (2012). [12] Poorter , et al., JMR B1203: 234-241 (1994). [13] Cloos, et al., MRM 67:72-80 (2012).