An algorithm for automatic optimisation of transmit array coil tune and match applied in a cardiac TEM coil at 7T

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Purpose: Transmit array coils using the transverse electromagnetic resonator ("TEM") design are attractive for ultra-high field 7T MRI in the body,[1] but require time-consuming manual tuning (i.e. adjustment of tune and match capacitors) for each subject. Tuning an 8-element array by hand takes ~30min. We have shown previously that coil tuning can be mechanised using piezo actuators fitted in the coil.[2,3] We now demonstrate how to *automate* coil tuning so that it is efficient, accurate and free from manual intervention.

Methods: Experiments used the posterior half of a 7T cardiac 8-channel TEM array coil[1] fitted with NEXACT piezo actuators (PI, Germany) with a single multiplexed controller. The coil was connected to a 7T scanner (Siemens, Germany). To monitor the coil characteristics, a pulse sequence was developed that pulses the coil with independent control over each element as instructed in real time over a network connection. The relative forward and reflected power was measured with a USB-6008 8-channel ADC (NI, USA) digitizing the output from 4x AD8302 gain and phase detectors (Analog Devices, USA) connected to the RF power amplifier monitor ports. All components were controlled from a PC by custom Matlab software to automate coil tuning as explained below.

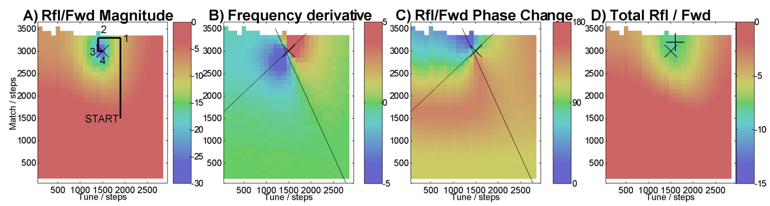

Fig. 1: Evaluating 4 possible optimisation metrics on a volunteer at isocentre for a single element of the array coil. Similar features were observed on all other channels and with a phantom at isocentre and outside the magnet. The path taken by the auto-tune algorithm is marked in (A). The lines of maximum gradient in (B) and (C) are marked on both plots. The S_{nn} minimum is denoted 'x' and in (D) the $\Sigma_m S_{nm}$ minimum is denoted '+'.

Results: Fig. 1 shows typical data from a volunteer evaluating 4 candidate optimisation metrics, sampled for each coil over its full (tune, match) range with the other coils well adjusted. The single channel forward/reflected power ratio S_{nn} (Fig. 1A) was measured to a precision of 0.02 dB with a 30ms, 30V hard pulse. In 2 volunteers, end-inspiration and end-expiration S_{nn} differed by <0.5 dB. All elements showed an "acceptable" region with S_{nn} < -15 dB (i.e. <3% reflected power) covering ~500 actuator steps in both tune and match. S_{nn} always varied smoothly and had a single minimum. Fig. 1B shows the frequency derivative $\partial Snn/\partial \nu$ determined by pulsing at $\nu_L \pm 0.3$MHz which displays a pronounced biphasic response centred around the S_{nn} minimum. Fig. 1C shows the phase change between forward and reflected RF, which also has a region of rapid change (in an orthogonal direction) around the S_{nn} minimum. Fig. 1D shows the total reflected power $\Sigma_m S_{nm}$, which varies smoothly and has a single but less pronounced minimum that lies close to the S_{nn} minimum. The performance of the actuators in our coil was also assessed. The actuators move with ~3% precision and the speed for motion in groups of N_s steps is $v=(500\ N_s)^{1/2}$ steps/s. Using N_s=100 gives adequate resolution for optimisation and speed (15s for a full range move).

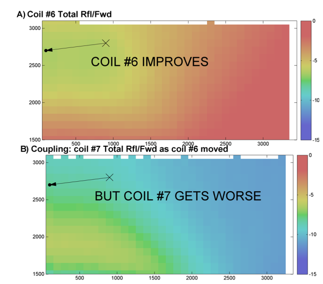

Fig. 2: Effect of adjusting coil #6 on total reflected power (ie. coupling).

These data inspired the following algorithm: optimising on S_{nn} with a sequential line search. Coil 1's match is stepped by +100 until a significant (5σ) increase in S_{nn} is observed. (If the first step reaches the actuator's end of travel or increases S_{nn}, the direction is reversed.) Coil 1's tune is then optimised. These steps are repeated until the position converges. Each other coil is then optimised. The whole procedure is repeated until all coils move 100 steps or less in tune and match and all S_{nn} < -15dB. We do not use gradients (avoiding small, slow steps) and avoid algorithms such as simplex whose oscillatory convergence would exacerbate stepping errors. Auto-tuning was tested on 4 volunteers with all actuators starting in the middle of their range. In all cases, the time taken was <5 min and the final S_{nn} were < –25 dB (checked with an RF Sweeper (Morris Instruments, Canada)).

Discussion: Auto-tuning in <5 min is preferable to manual adjustment of TEM coils because it is quicker and reduces the need to work close to the subject, improving comfort. Indeed, ~36% of time was spent moving the actuators, ~21% acquiring S_{mn} and ~43% was software overhead. We anticipate tuning in <2min as our software is refined. With a second controller, both halves of this 8-element array could be tuned simultaneously in <2 min, and using a controller per actuator would see tuning in a few seconds.

Auto-tuning is not only more convenient, it achieves better results by adjusting at isocentre (gaining 5-10 dB on some elements) and we have begun optimising using total reflected power $\Sigma_m S_{nm}$. Fig. 2 shows how $\Sigma_m S_{nm}$ reveals the complex interplay between elements; an adjustment that improves one element's reflected power may cause a greater power loss through coupling in a neighbour. The truly optimum adjustment will require elements to be favoured according to their contribution to B_1^+ in the study's region of interest.

Conclusion: Auto-tuning using piezo-electric actuators while monitoring forward and reflected power with directional couplers at the amplifiers is an effective and robust approach for tuning TEM coils at 7T. Auto-tuning is significantly faster than manual tuning.

References: 1. Snyder, *et al. Magn. Reson. Med.* **61**, (2009). 2. Snyder, *et al. Proc. ISMRM* (2011). 3. Snyder et al., US Patent 8299681.

Acknowledgements: Funded by the MRC; NIHR Oxford Biomedical Research Centre; Royal Society and Wellcome Trust [098436/Z/12/Z]; Merton College and NIH [NIH-NIBIB-1R41EB013543-01].