Use of the noise covariance matrix in array coil quality assurance

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Introduction

With the ever-increasing complexity of MRI RF receive arrays and the requirements placed on these by modern acceleration techniques, coil failure becomes both more probable and more problematic. Manufacturers' tools often only provide the briefest of summaries in their array coil quality assurance (QA) results. It is possible to obtain some information by inspecting images from individual array elements, but this is slow and becomes impractical when the coils are small and when there is no single slice that is "seen" by all the elements. The noise covariance matrix (NCM)[1] provides more information, both quantifying the noise from each individual element and providing information about the correlations between channels which degrade the final image SNR and are a strong indicator of coil failure. In this work we present examples of the NCM in failing arrays and propose criteria that all arrays should satisfy.

Methods

Ten phased array coils with number of elements ranging from four to 32 were set up with low-conductivity phantoms containing dimethyl silicon fluid and gadolinium on two different manufacturers' systems (GE, Waukesha, WI & Siemens, Erlangen, Germany). As far as possible, array elements were kept equidistant from the phantom surface to avoid any variation in loading of the array. Noise data were acquired as a 256x256 image as part of a QA protocol by either switching off the RF amplifier output in hardware or setting the transmitter voltage to zero in software. The complex, multi-channel *k*-space data were analysed off-line using MATLAB (The Mathworks, Natick, MA) to calculate the NCM using the expression:

$$R_{ij} = \frac{1}{N}\sum_{k=1}^{N} n_i(k) n_j^*(k) \,,$$

in which N is the number of noise samples (here 256x256) and $n_i(k)$ is the k^{th} noise sample from element i. The absolute value of the NCM was used for plotting and analysis. The SNR was measured by the multi-image method[3] on images reconstructed using both the true NCM (for maximum SNR) and the identity matrix (to provide a lower SNR limit)[1].

Results

An appreciable (>15%) drop in SNR was found in images acquired with arrays meeting at least one of the following conditions:

1) The variation of on-diagonal real elements in the NCM is >35% (Fig. 1);
2) The largest off-diagonal element is >25% of the largest on-diagonal element (Fig. 2).

Discussion

Variations in on-diagonal are due to channels either failing completely (no noise detected) or becoming noisier, for example due to a failing component. Large off-diagonal elements are seen when, for example nearest-neighbour mutual inductance is increased or there is high sample noise in a mutually sensitive volume. The above conditions hold for arrays in which the elements are identically sized and the phantom is placed such that it equally loads all elements[2]. If this is not the case, the diagonal may vary more than 35% even in a well-conditioned array. However, the quantitative assessment of the off-diagonal elements is still useful, and a threshold of variation of 80% for on-diagonal elements will be sensitive to elements which are completely non-functional. Alternatively, if the NCM is characterised at commissioning, it can be checked for longitudinal variations. The use of a phantom filled with a material with low conductivity is important as this helps to reduce spurious coupling between elements due to sample-based Johnson noise, making the NCM more sensitive to intrinsic array performance.

Conclusion

The characterisation of the NCM of a lightly-loaded phased array can provide a clear indication of failure. The acquisition and analysis of the NCM is quick and straightforward. The method also has the advantage that it can be applied to third party arrays, for which automated QA analysis tools are often not provided.

References

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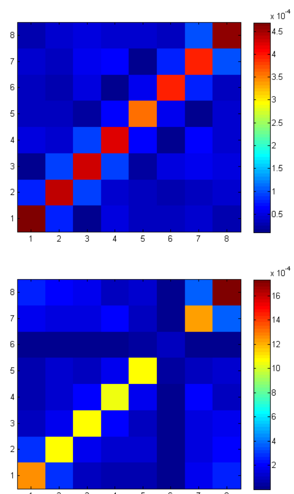

Fig 1. Eight channel brain arrays, showing a normal NCM on the top and an array with one non-functioning element on the bottom.

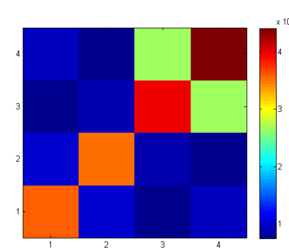

Fig 2. Failure in a four-channel bilateral carotid array caused by coupling between elements. The SNR drop due to the coupling between elements 3 and 4 on the left was 18% but this failure mode would not have been detected by inspecting individual images.

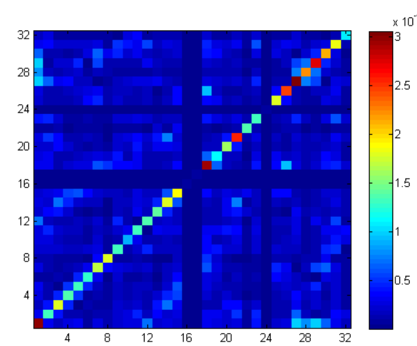

Fig 3. Failure in a 32-channel head array. Three elements have almost no output, which is easily seen in the NCM. There are other on-diagonal elements with high variance, due to couplings visible in the off-diagonal elements.