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Assessment of the SNR, g-factor and relative B1- fields of Medical Radiofrequency Arrays

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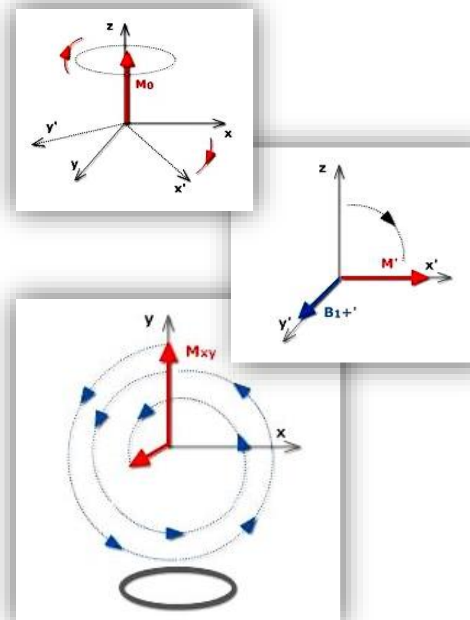
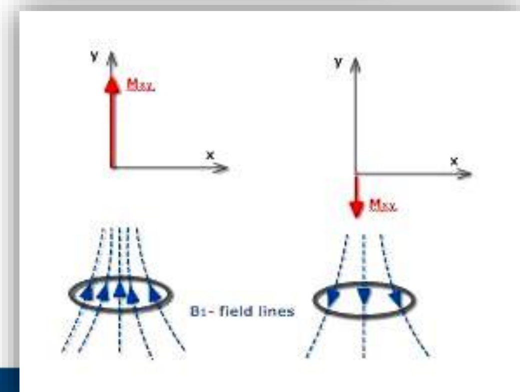
Contents of talk

- **Medical radiofrequency coils**
  - How are coils used in Magnetic Resonance Imaging?
  - Medical need vs. technical requirement
  - Examination of existing clinical coils for paediatric MR
- **Purpose of study**
  - Assessment of project design (‘Swiss Roll’ design)
  - Role of simulation in coil design and use of COMSOL Multiphysics
- **Results**
  - Signal to Noise Ratio (SNR); sum of squares and uniform noise images
  - g-factor and acceleration potential

Radiofrequency Arrays in MR Imaging

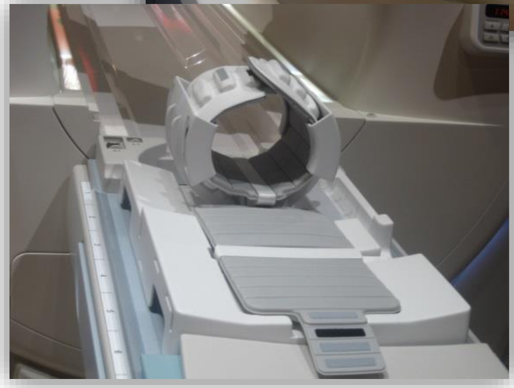
- **MR Imaging relies on NMR**
  - Net magnetic moment created in tissue (M_0) by static B-field
  - M_0 manipulated using RF fields
  - When fields removed M_0 orientation recovers
  - Oscillation of M_0 induces a voltage in the coil, tuned to Larmor frequency, ω_0
  - Signal localised using gradient fields – for each iteration one line of image k-space acquired
- **Receive Arrays**
  - Arrays comprise of multiple loops – mutual inductance occurs
  - Knowledge of coil sensitivities fewer lines of k-space are required, accelerating acquisition





Paediatric Magnetic Resonance Imaging

- **CT used as gold standard imaging for many diseases**
  - Increasing concerns regarding radiation exposure during childhood
  - Studies show repeated CT significantly increase lifetime cancer risk
- **MRI offers advantages over CT**
  - Non-ionising radiation
  - Soft tissue distinction – lesions, necrosis, appendicitis
- **Time and equipment costs**
  - Patient must remain still over protracted periods
  - Intubation, sedation and environment control important



Paediatric RF coils

- **The appropriate coil for a child is determined by:**
  - Size and temperament, medical condition
  - Sensitivity depth, surface conformity of design
  - The adult torso and cardiac coils can be used in some cases, but ‘wrap’ coils offer more flexibility

- **Project Design**
  - Flexible for surface conformity and sensitivity
  - Ability to wrap to different positions –accommodate different sizes
  - 4x8 channels to enable higher acceleration factors

Role of Simulation in Design

Conceptual Designs
patient subgroup identification
technical specification

COIL SIMULATION
Find best initial design
(1) Relative **sensitivity** maps
(2) Maximum **SNR** in region(s) of interest
(3) Acceleration **g-factor**

Initial Prototype
(proof of concept only)

Experimental comparison to technical specification

Design Adjustment

Simulated
Optimisation of topology

Further prototypes

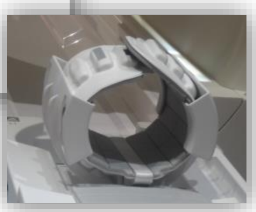
Final Design

Geometry: Coil and Load

- **Three coil geometries created**

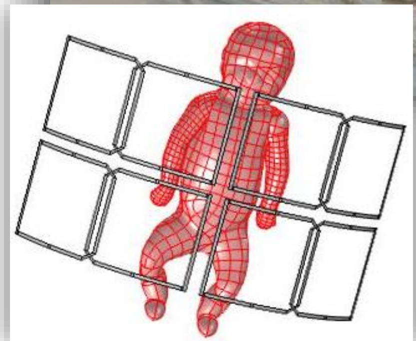
Small flexible coil

- 16 channels
- Can be wrapped to conform to surface
- Critically overlapped in both directions

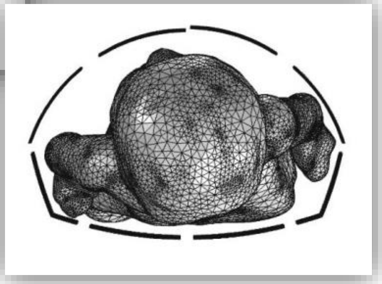


Cardiac array

- 8 channels, partially overlapped
- Rigid former with joints



Project Coil



- 32 channels, overlapped along bore axis
- Swiss-roll, wrapable design

Boundary conditions and Mesh

- **Tissue Properties**
  - Simple phantoms contained generic ‘muscle’ tissue
  - Baby model contains 11 age-adjusted tissues
- **Coil Materials:**
  - Coil track set as Copper (for materials library) – PEC
  - Capacitor lumped elements used to tune elements
  - Driving port included – V0 and Z_{ref} adjustable
- **Meshing**
  - Tetrahedral mesh specified for sample volumes – elements < 2cm
  - Swept mesh used at edge of solution volume
  - Cylindrical phantom resulted in a mesh an order of magnitude smaller

COMSOL Process I

(1) Element Tuning

- Ensure that the elements are tuned and matched at 63.86MHz

(2) Noise Correlation Matrix, Ψ , Extraction

- Assess the level of cross-talk between elements
- Calculated using COMSOL integration function over the load (sample) volume(s):

$$\Psi_{ij} = \int_{sample} \sigma(r)[E_i(r) \cdot E_j{}^*(r)]dV$$

(3) Normalisation of coil sensitivities

- Calculated for each element – counterclockwise B-field relative to bore axis

$$B_1^- = \frac{1}{2}(B_x - iB_y)$$

- Result for each element power-normalised in post-processing

COMSOL Process II

(4) Signal to Noise Ratio Calculation

- Clinically it is desirable to maximise Signal to Noise
- Analytically using signal and noise definitions maximum SNR for a loop (radius R) found at $r_M = \sqrt{5}R$
- Experimentally, absolute SNR calculations depend on reconstruction method
- **Numerically,** three ways to assess potential coil SNR:

i. **SUM OF SQUARES IMAGE →** standard reconstruction, optimal coil field combination for SNR (Roemer *et al.* 1989)

Calculated element-wise in MATLAB using separate coil fields and extracted NCM:

$$S(r) = \left| \sqrt{\sum_{i=1}^{N}\sum_{j=1}^{N} B_{1\ i}^{-}(r)\Psi_{ij}\, B_{1\ j}^{+}(r)} \right|$$

COMSOL Process III

- **SNR (con't)**

ii. **UNIFORM NOISE IMAGE →** this shows how the sensitivity profile varies over a sample under (ideal) uniform noise conditions.

$$UNI(r) = \left| \frac{\sum_{i=1}^{N}\sum_{j=1}^{N} B_{1\ i}^{-}(r)\Psi_{ij} B_{1\ j}^{+}(r)}{\sqrt{\sum_{i=1}^{N}\sum_{j=1}^{N} B_{1\ i}^{+}(r)\Psi_{ij} B_{1\ j}^{-}(r)}} \right|$$

iii. **ACCELERATION POTENTIAL →** calculation of the g-factor under different acceleration conditions shows the resultant loss of SNR

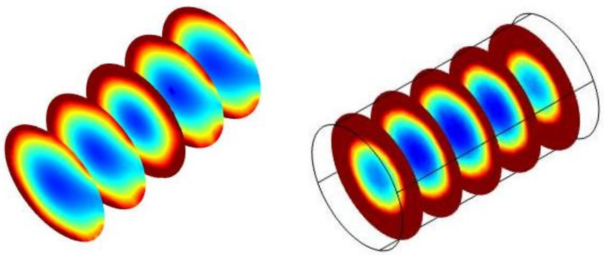
$$SNR_{SENSE,p} = \frac{SNR_{full,p}}{\sqrt{R}g_p}$$

Calculated in MATLAB using alias maps; each set of wrapped pixels requires a separate calculation:

$$g_p = \sqrt{[(W^H \cdot \Psi^{-1} \cdot W)^{-1}]_{p,p}(W^H \cdot \Psi^{-1} \cdot W)^{-1}{}_{p,p}}$$

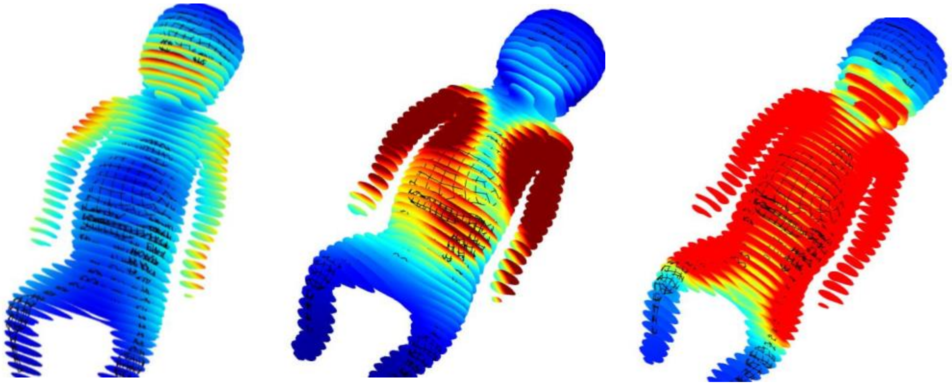
Results I: Signal to Noise Ratio

- Sum of Squares SNR – phantom experiments
  - Initial `best guess’ coil against closest existing coil
  - Higher potential SNR and greater sensitivity
- Sum of Squared SNR – baby model
  - Higher maximum SNR achieved using wrap coil
  - SOS SNR more uniform for project design
  - Larger field of view with higher SNR



Above (left) Flexible 16 channel coil SOS SNR image **(right)** project 32 channel coil

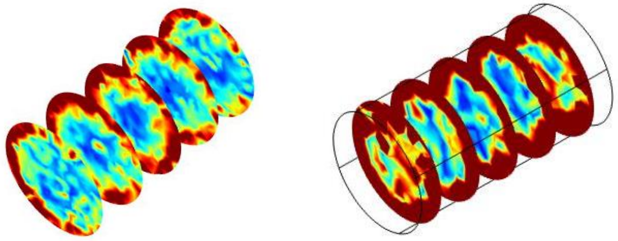
Coil	Cardiac	Flex	Project
Maximum SNR (phantom)	-	149.74	355.13
Maximum SNR (baby)	5.49	221.61	2933.38
Uniformity of SNR (heart)	1.47	49.63	68.85



Above: SOS SNR maps for (left-right) cardiac, flexible and project coil designs

Results II: Uniform Noise Images

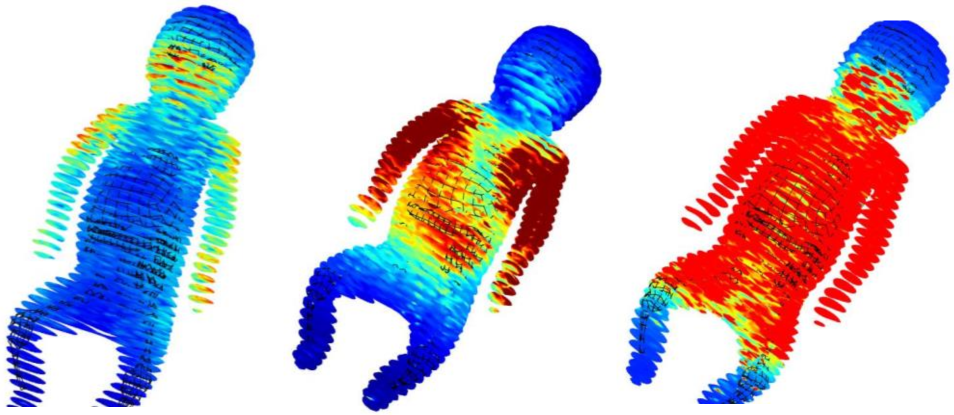
- Uniform Noise SNR – phantom experiments
  - Initial `best guess' coil against closest existing coil
  - Wrap coil shows less signal variation but lower values



Above (left) Flexible 16 channel coil UNI SNR image **(right)** project 32 channel coil

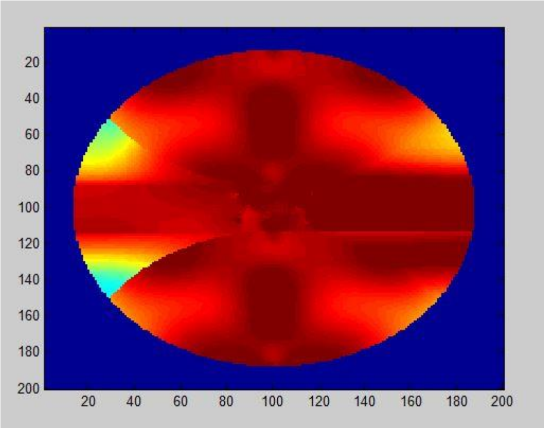
- Uniform Noise SNR – baby model
  - Higher maximum SNR achieved using wrap coil though similar maximum value in heart

Coil	Cardiac	Flex	Project
Maximum UNI (phantom)	-	149.74	354.95
Maximum UNI (baby)	5.48	221.74	2931.04
Maximum UNI (heart)	3.01	189.96	181.55



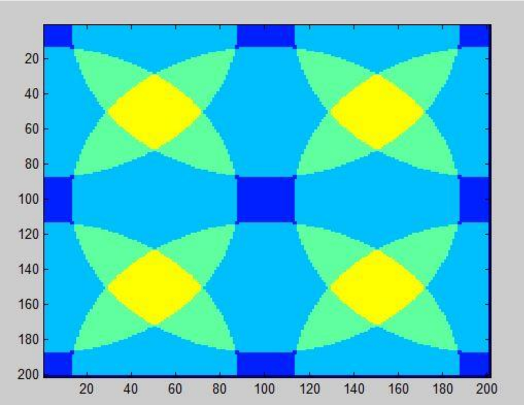
Above: UNI SNR maps for (left-right) cardiac, flexible and project coil designs

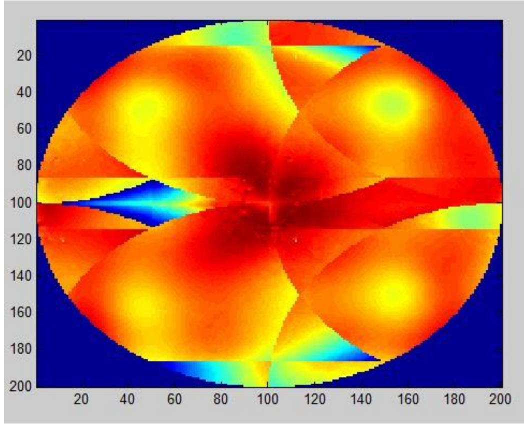
Results III: g-factor maps

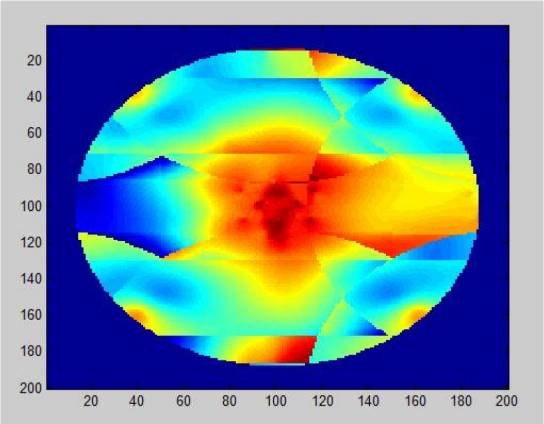


- **Inverse g-factor maps**
  - Initially done for wrap and project coils
  - 2x1 wrap and 2x2 acceleration considered on axial slice

Below (left-right): alias map for 2x2 acceleration, corresponding inverse g-factor maps for wrap coil and project coil respectively







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