Spatial Encoding in MRI with Nonlinear Fields

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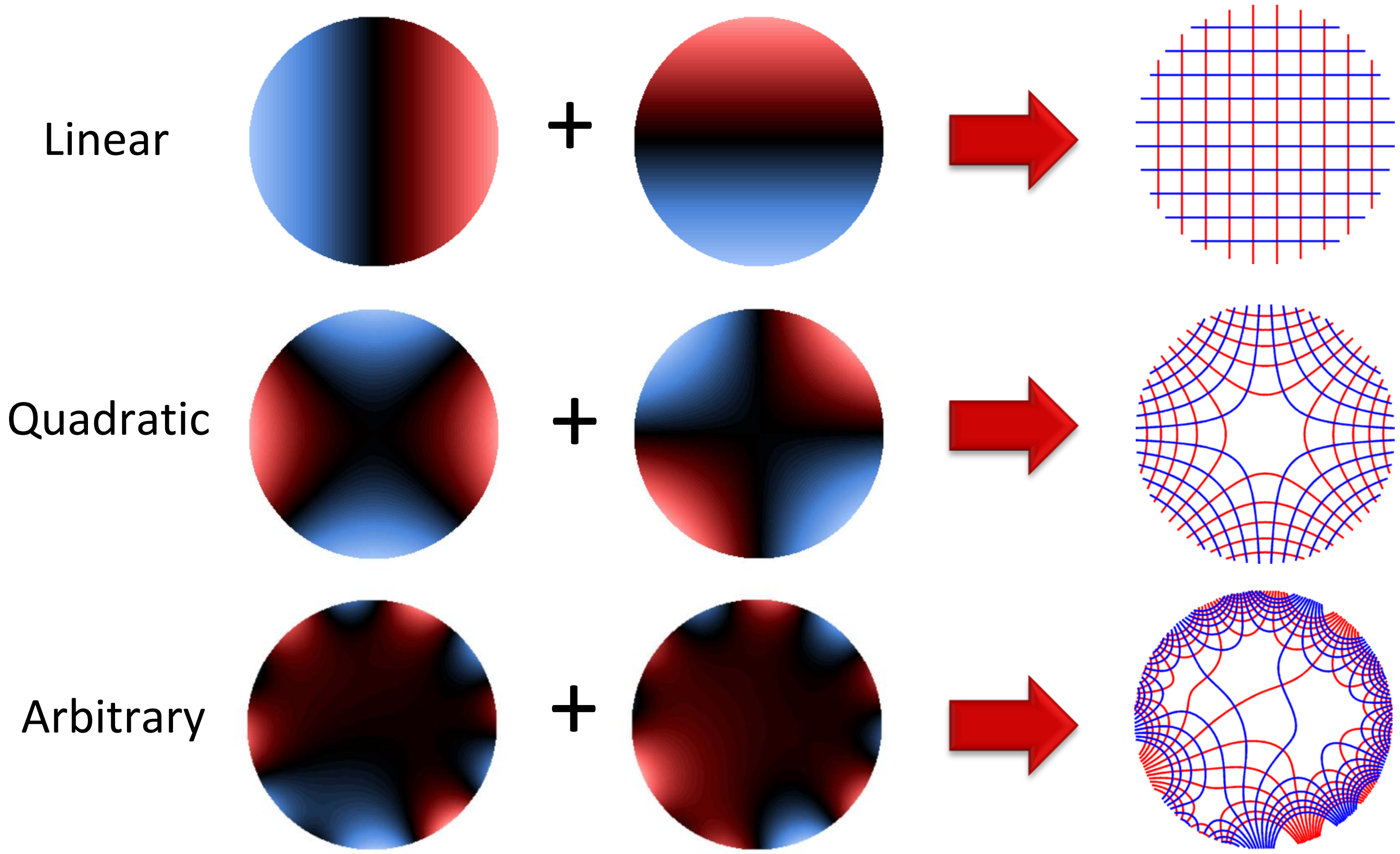
Overview

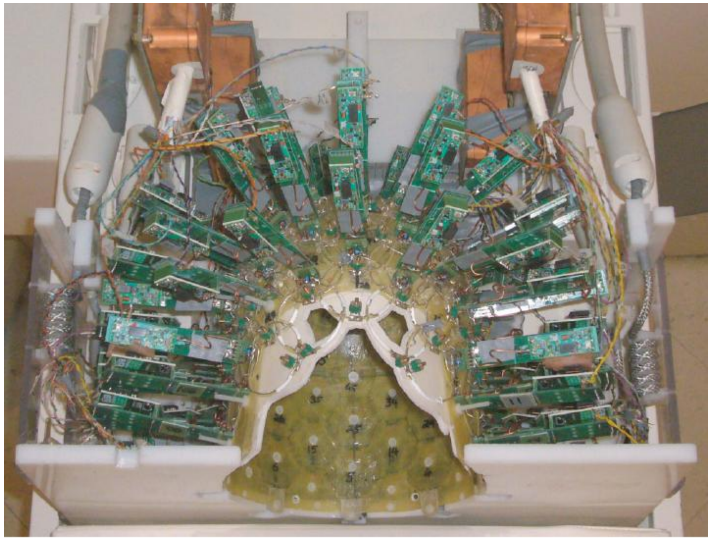
- Encoding with curved fields
  - What's different to normal?
  - Including first in vivo brain images
- Encoding with linear and curved fields simultaneously
  - How does the reconstruction work?
  - Experimental verification

More general 2D encoding



Why bother with curved fields?

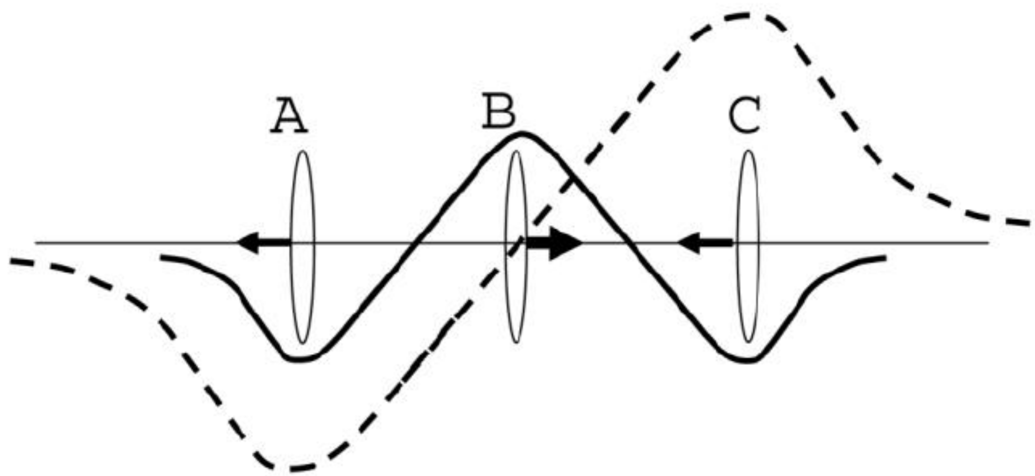
- Rectilinear fields are poorly suited to living organisms
  - RF coils are already matched to anatomy
    why not gradients?



96-channel RF coil (Wiggins et al, MRM 2009)

Why bother with curved fields?

- Reduce nerve stimulation caused by gradient switching

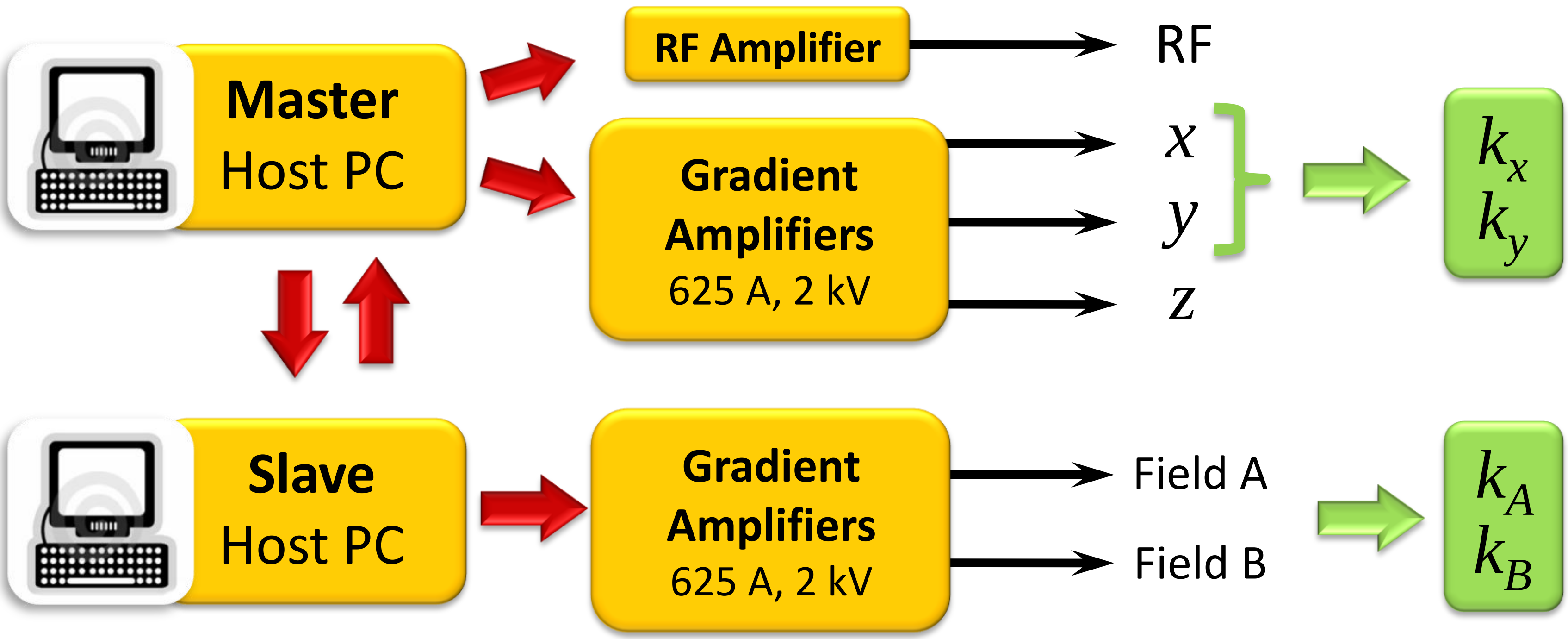


Multiple-region gradient encoding (Parker and Hadley, MRM 2006)

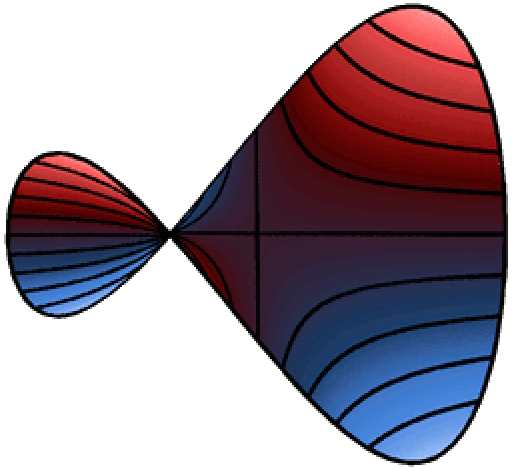
Why bother with curved fields?

- Because we can!
- Potential applications include:
  - Allow imaging where linear fields are too difficult/expensive (portable MRI)
  - New kind of image acceleration (more later…)
  - Real-time shimming
  - Phase preparation
    - PIPS, M. Zaitsev, proc ISMRM 2009
    - GradLoc – W. Witschey, proc ISMRM 2011 and MRM (in press)
  - Combination with MREG/OVOC to provide fast spatial encoding

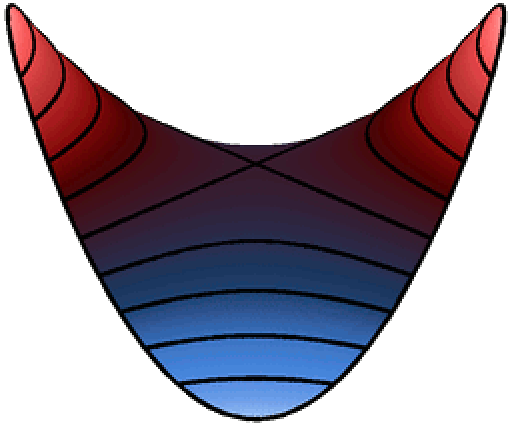
Hardware: Modified Siemens 3T Trio



The fields we decided to make



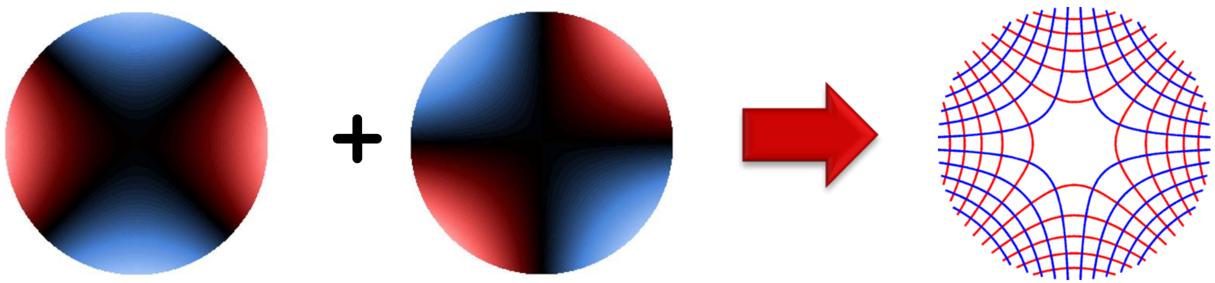
Field A

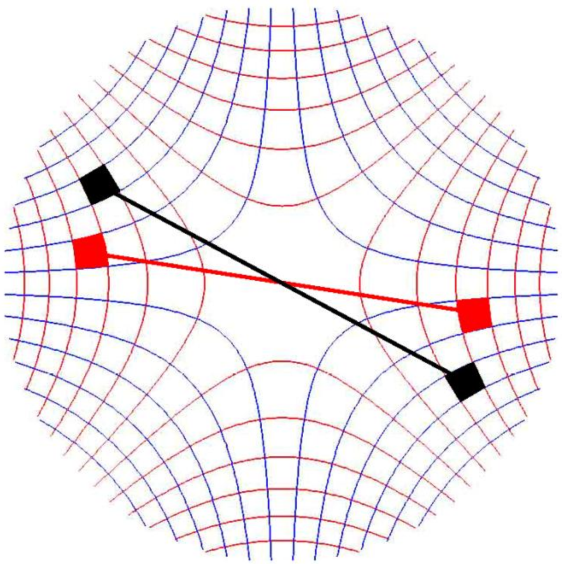


Field B

The hyperbolic paraboloid

Ambiguous encoding



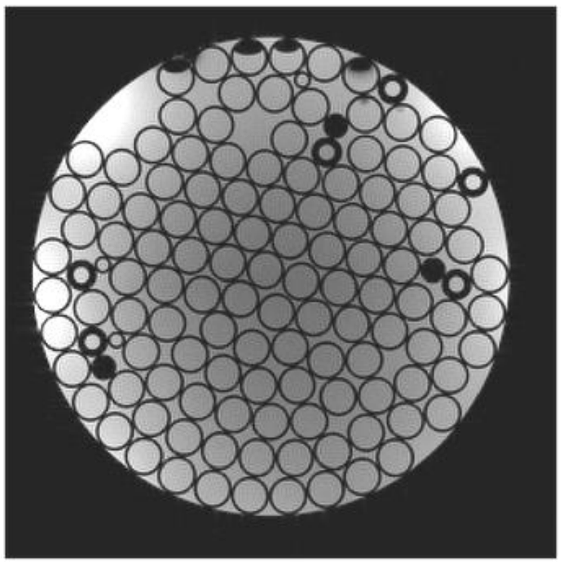


Voxels rotated 180˚ from each other receive identical encoding - they will overlap (alias) in the image

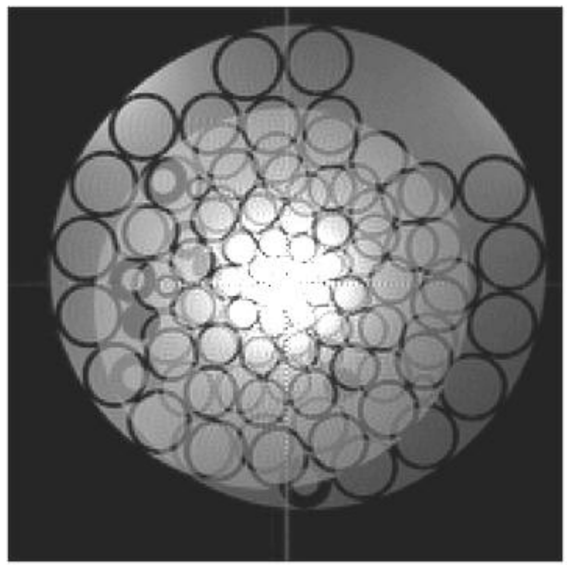
But we already know how to deal with aliasing

- Parallel Imaging (SENSE or GRAPPA) involves acquiring less data and therefore aliased images

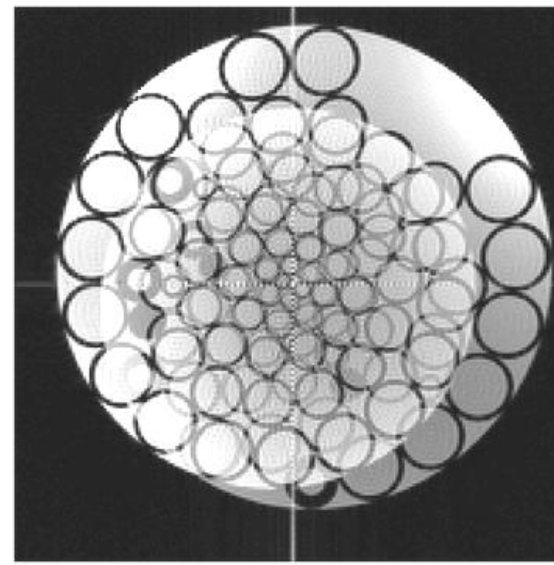
For our quadratic fields



Linear gradients



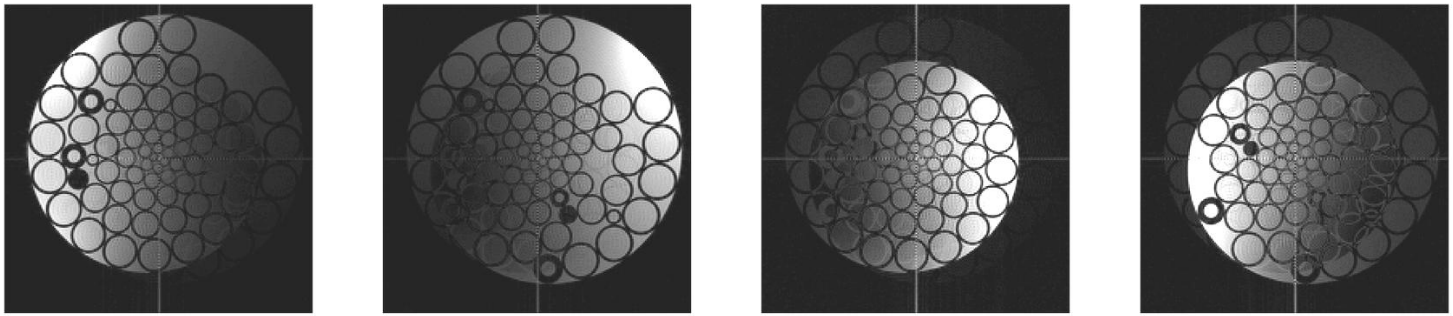
Quadratic gradients
After FFT



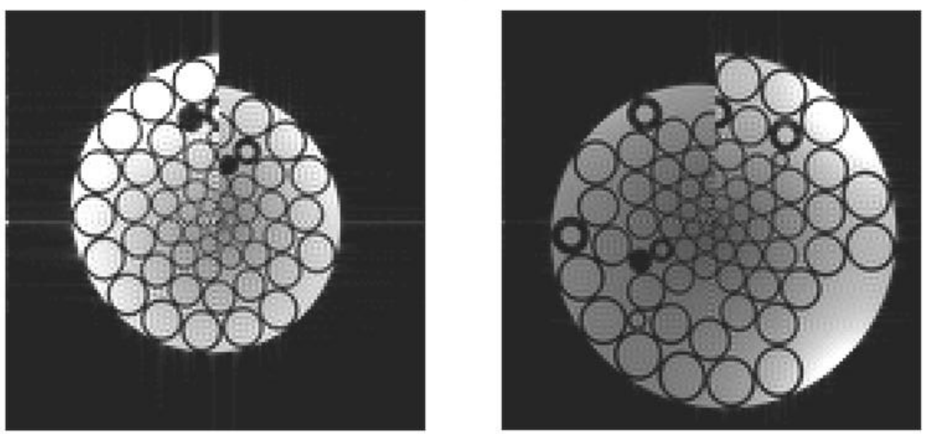
Quadratic gradients
After FFT and
intensity correction

SENSE-like unaliasing

Separate coil images



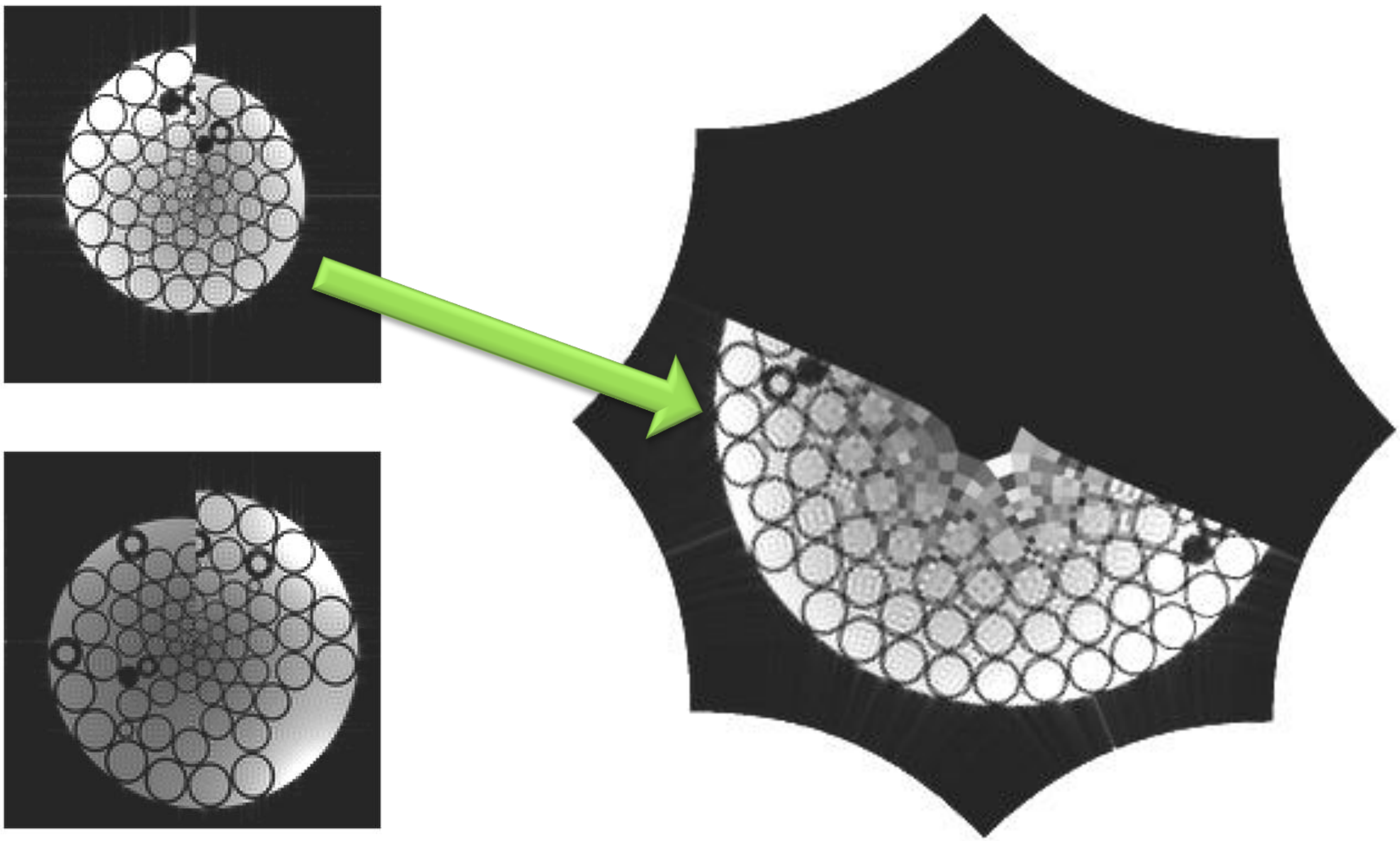
SENSE-like unaliasing



Unaliased images in encoding space

G. Schultz et al, MRM 2010

Make 'human readable'



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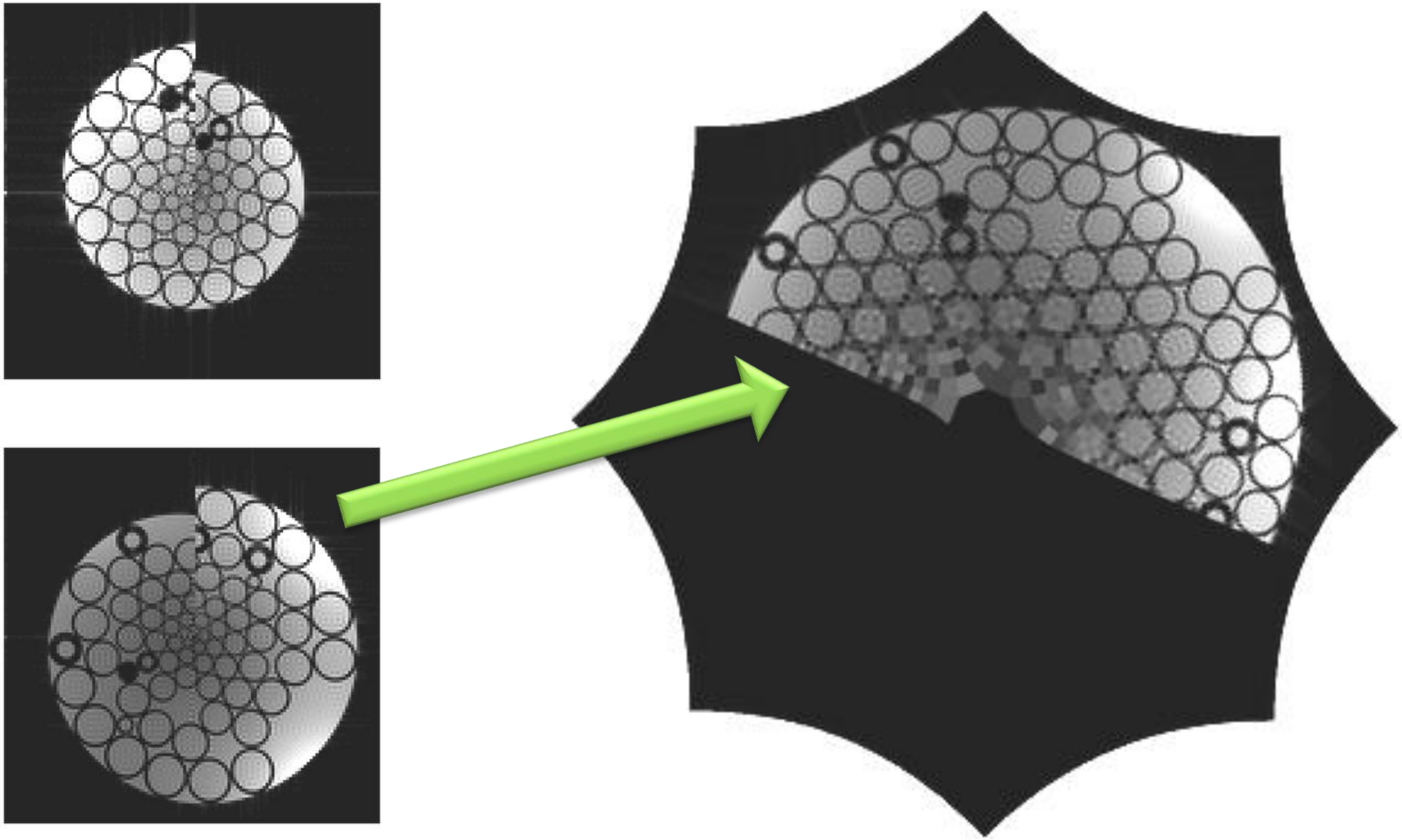
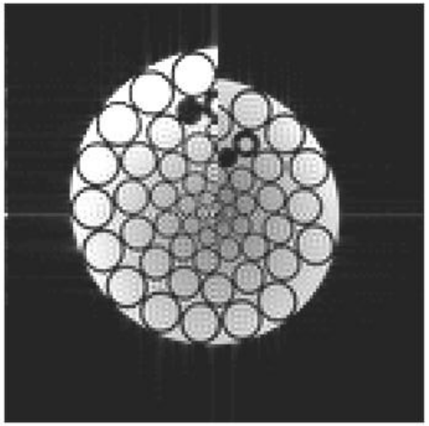
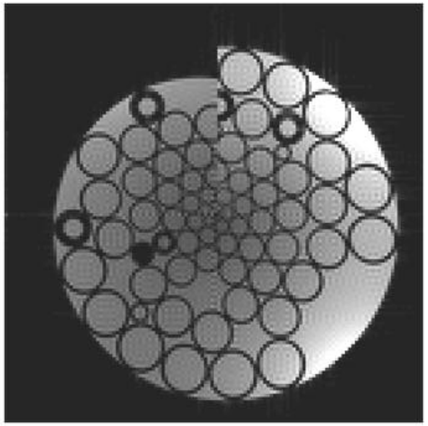
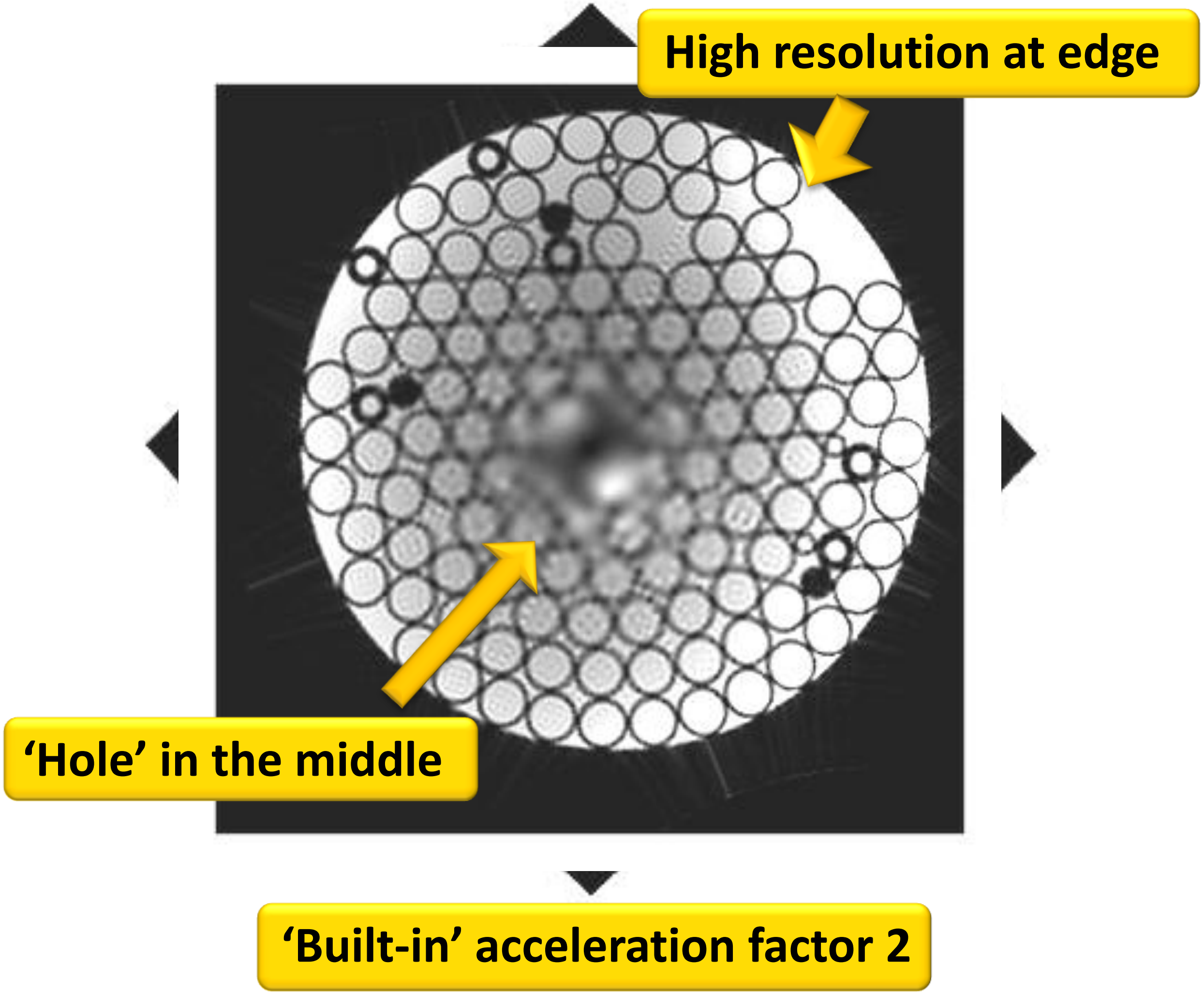


Make 'human readable'







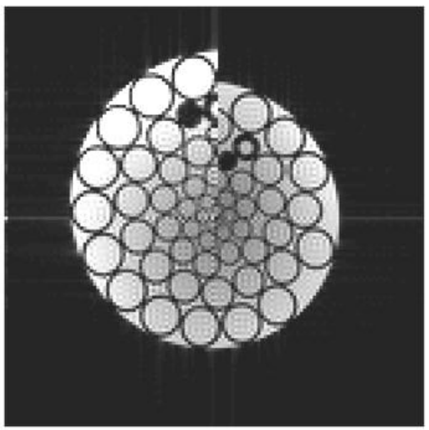
PatLoc

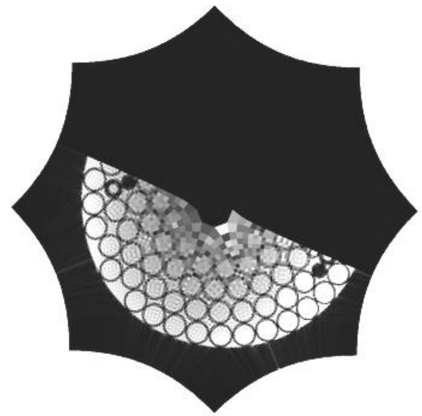
Parallel imaging technique

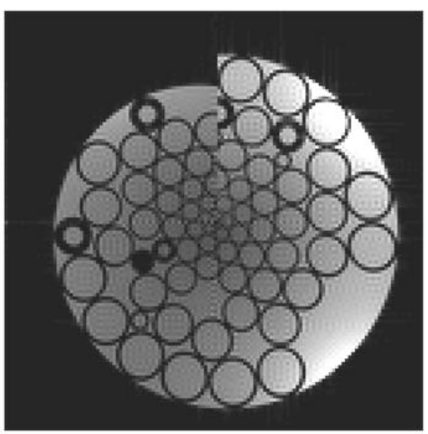
using localized gradients

Hennig *et al*, MAGMA 2008

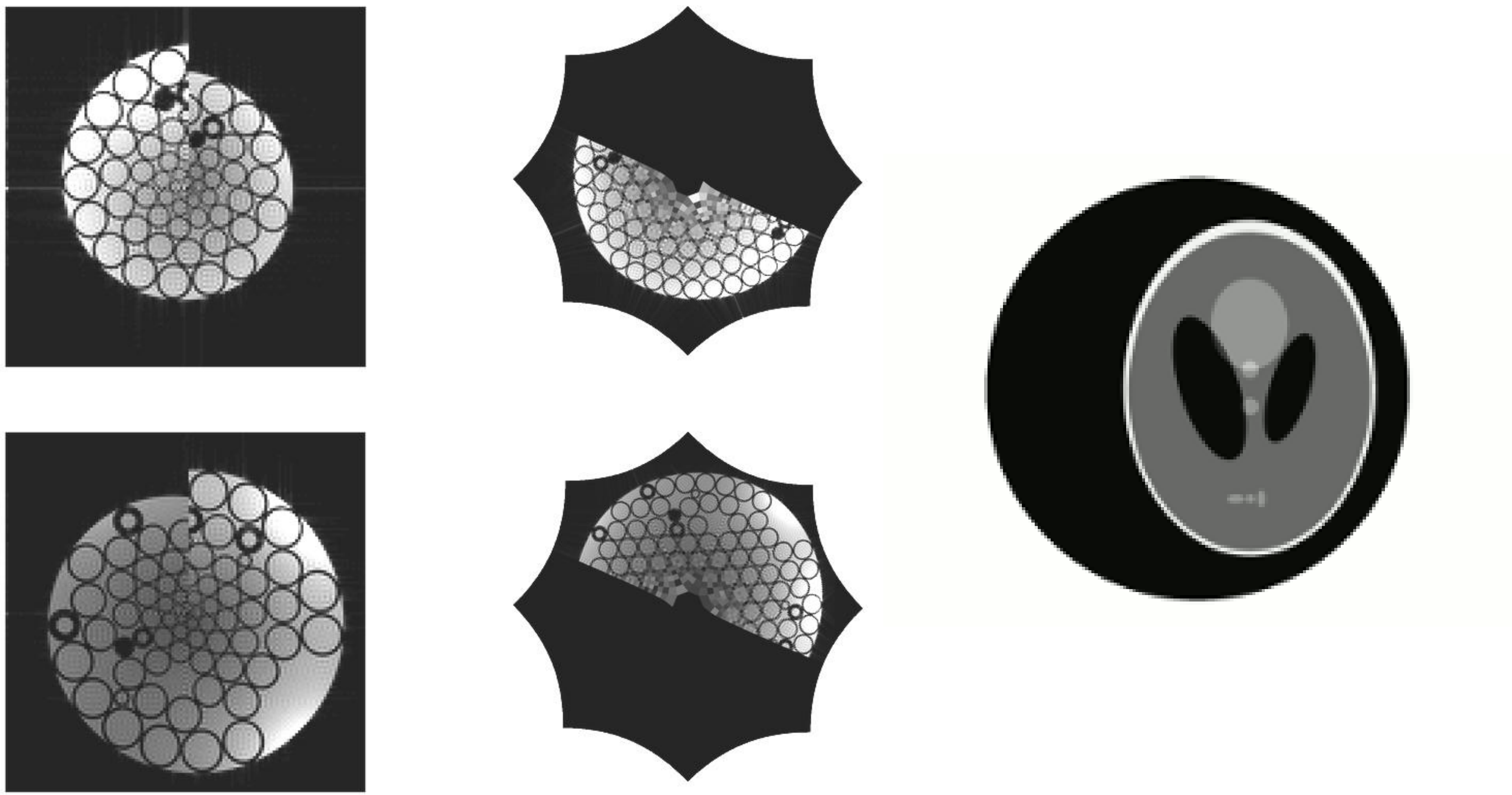
Understanding the aliasing



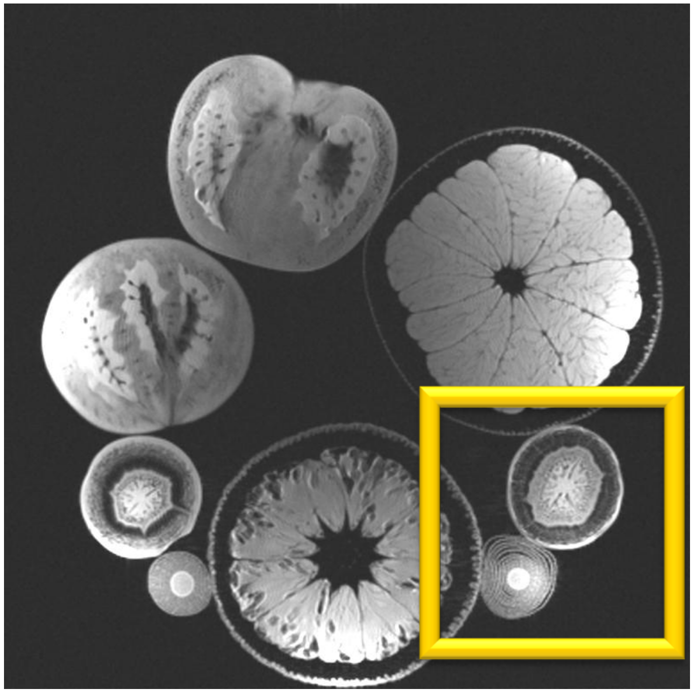




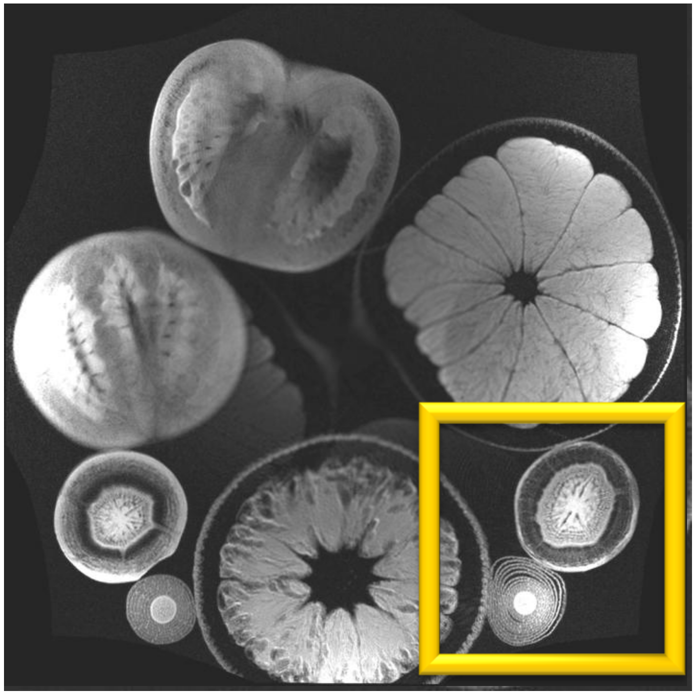
Understanding the aliasing



Seeing the benefit

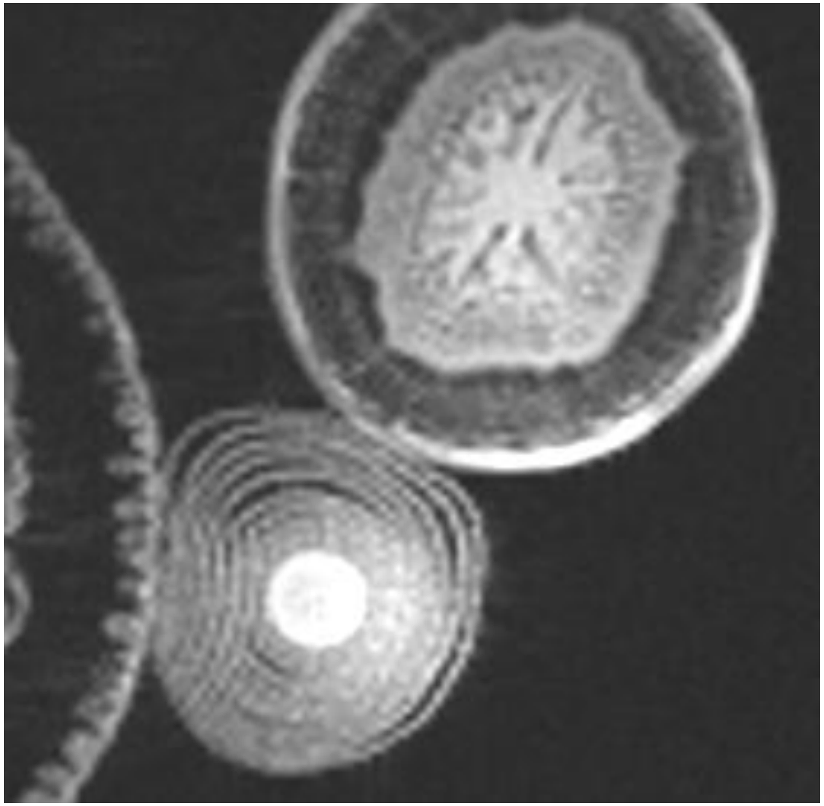


Linear gradients

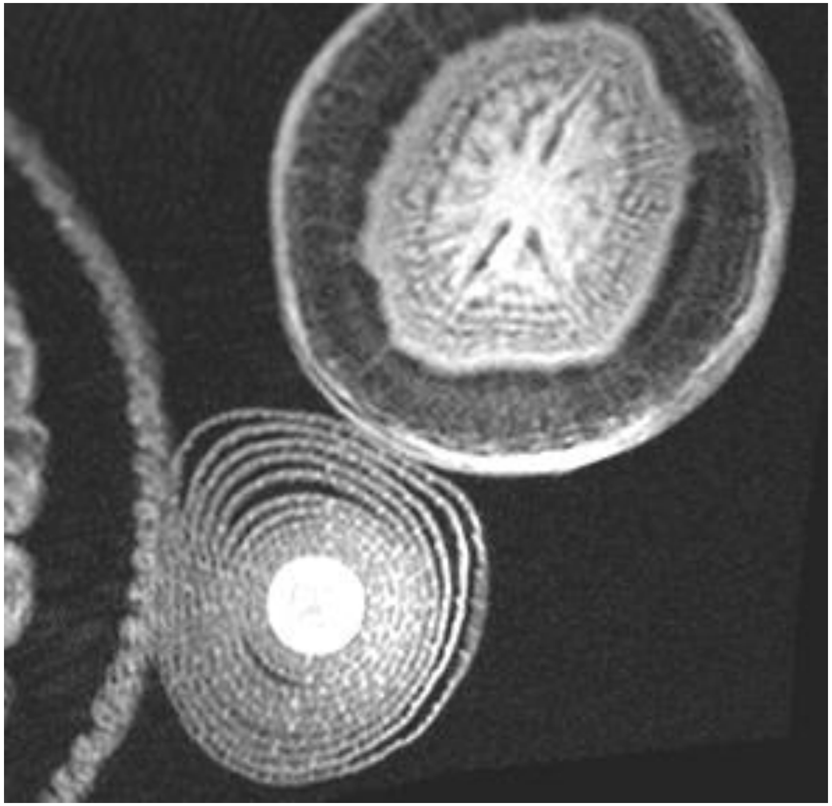


Quadratic gradients

Seeing the benefit

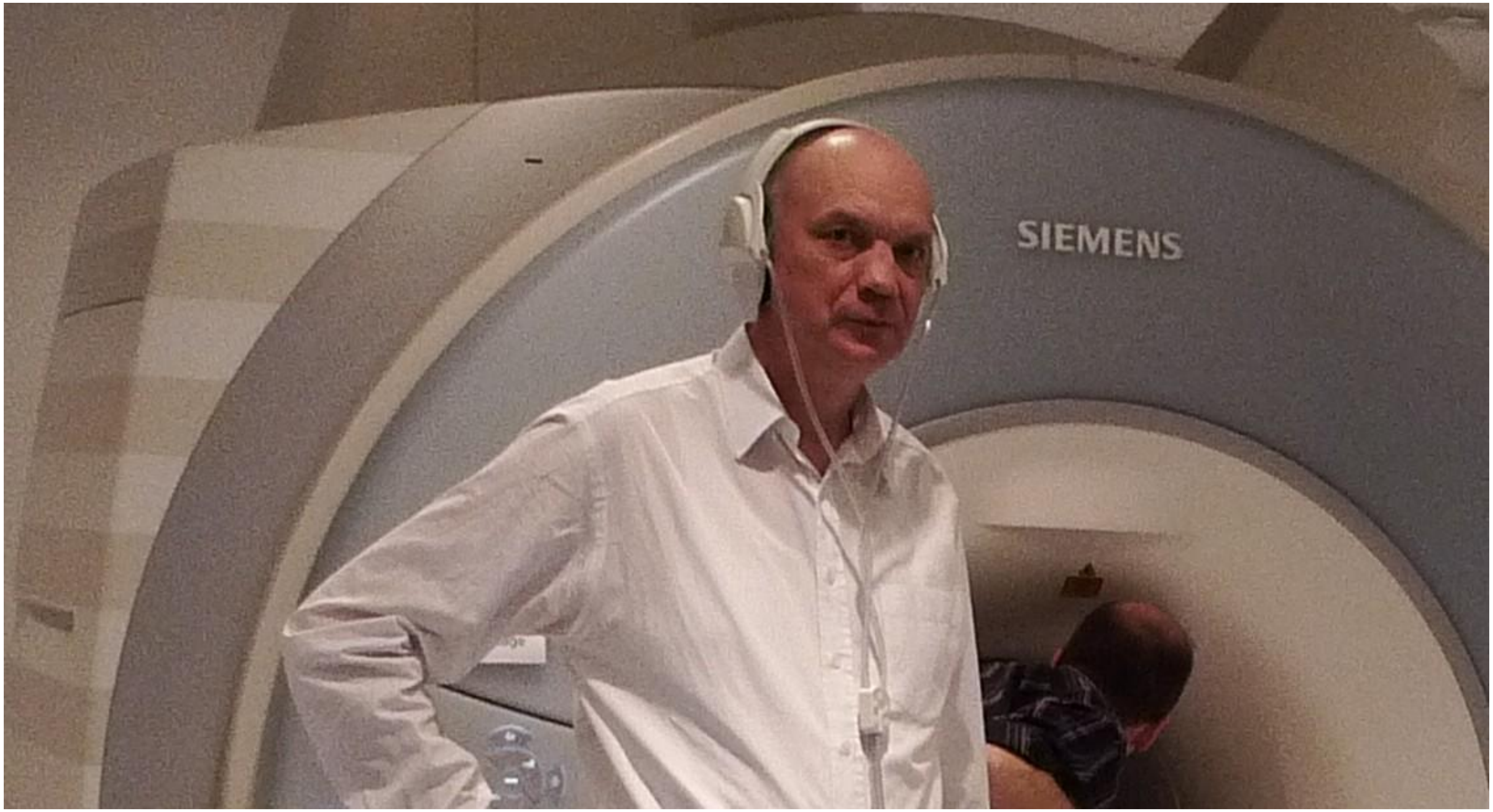


Linear gradients

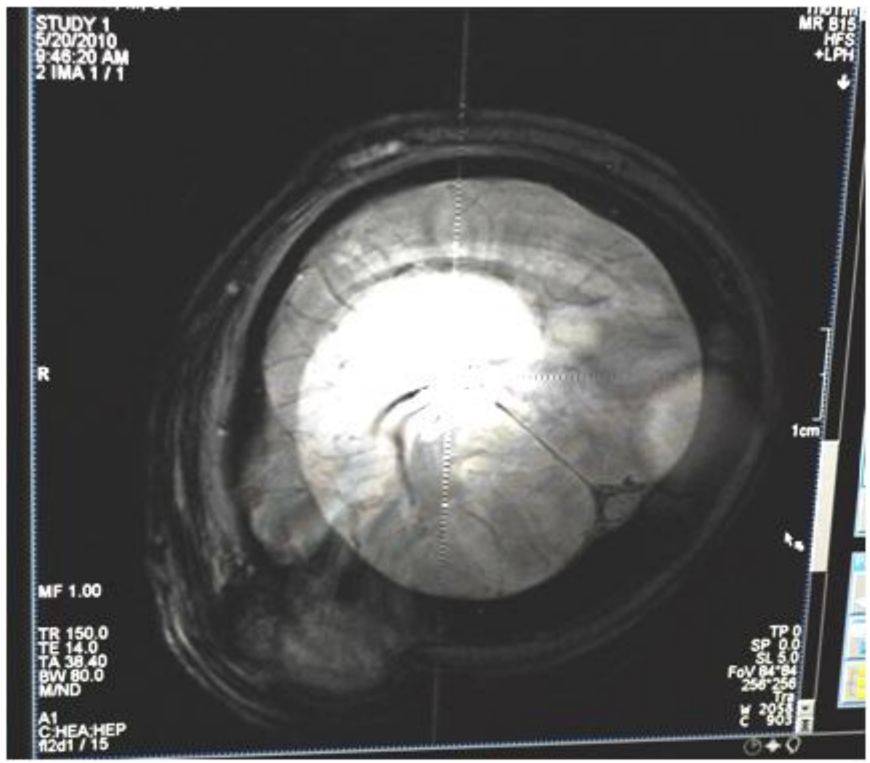


Quadratic gradients

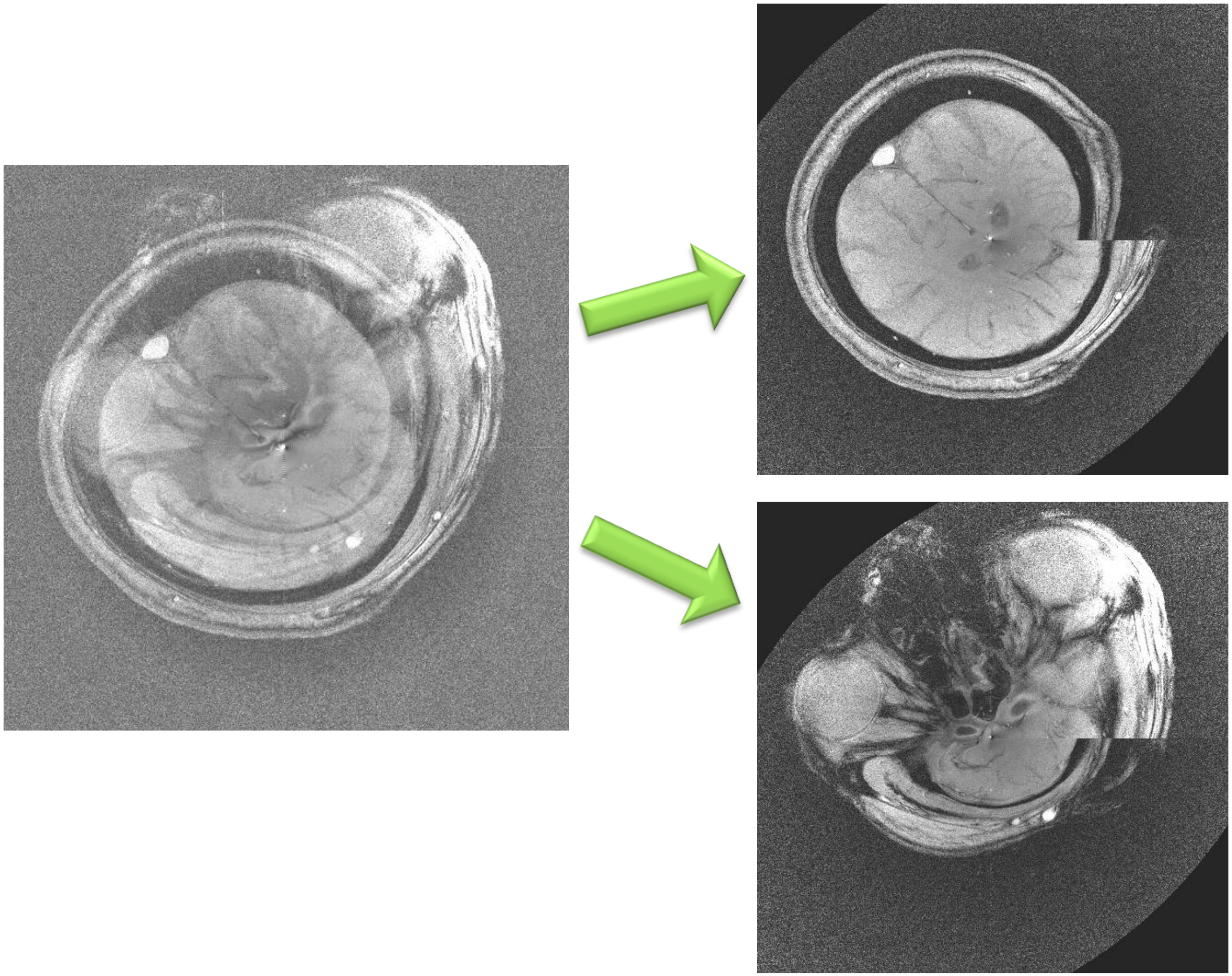
And now… the first volunteer…



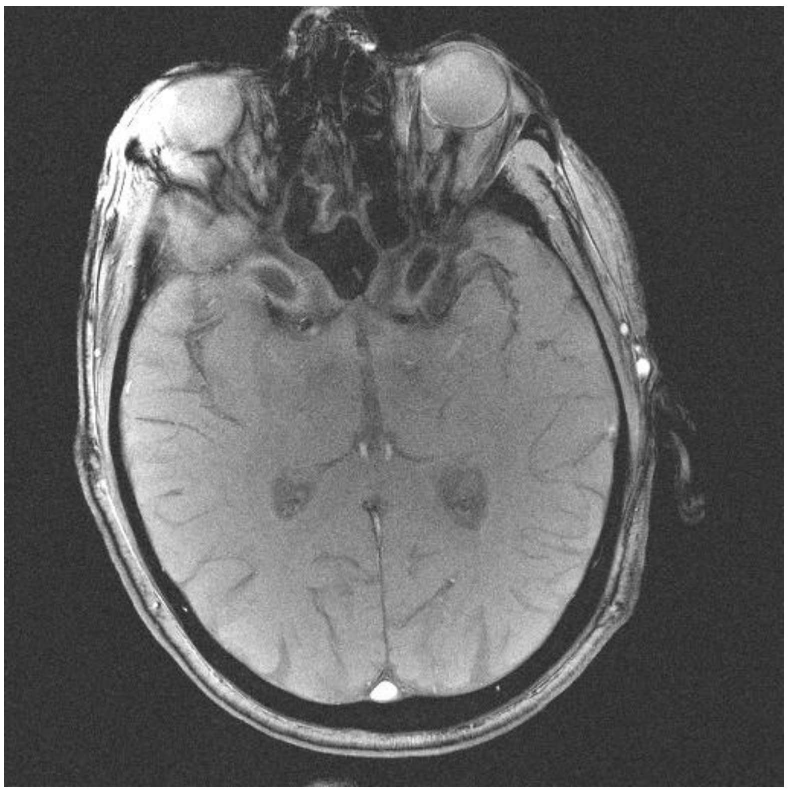
And the first image…



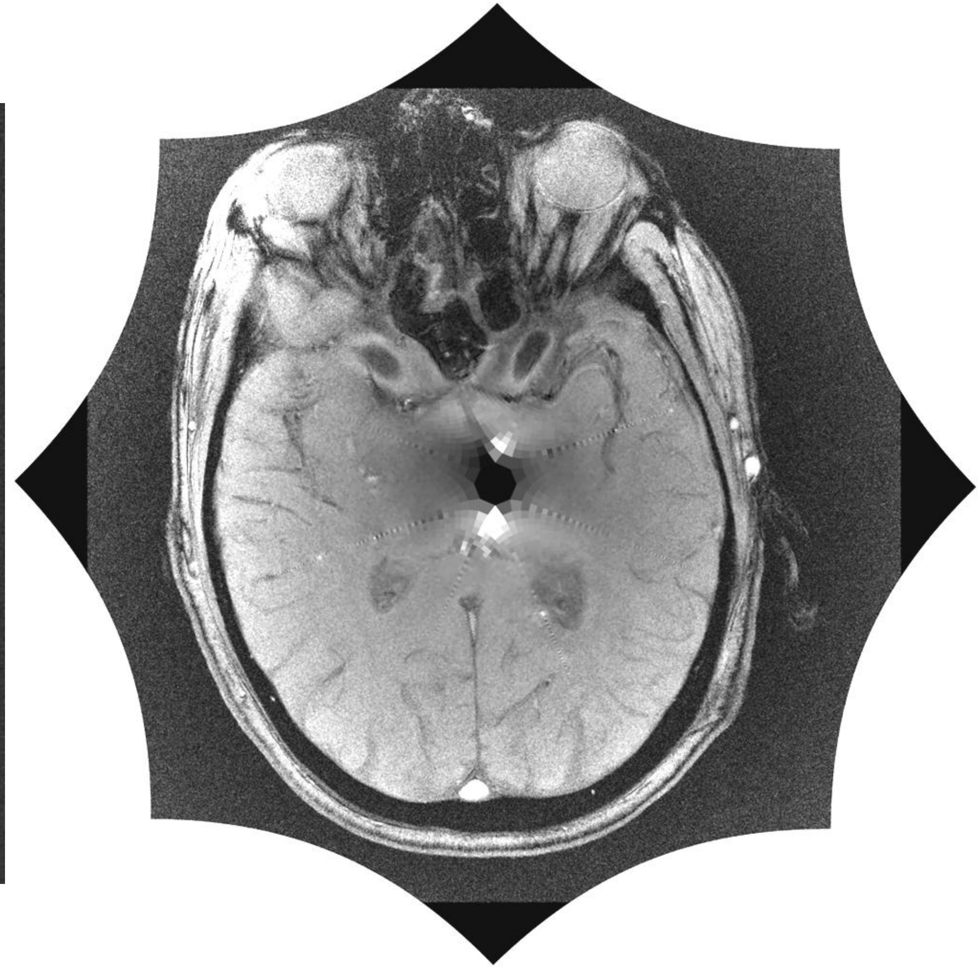
And after some processing…



And after some processing…

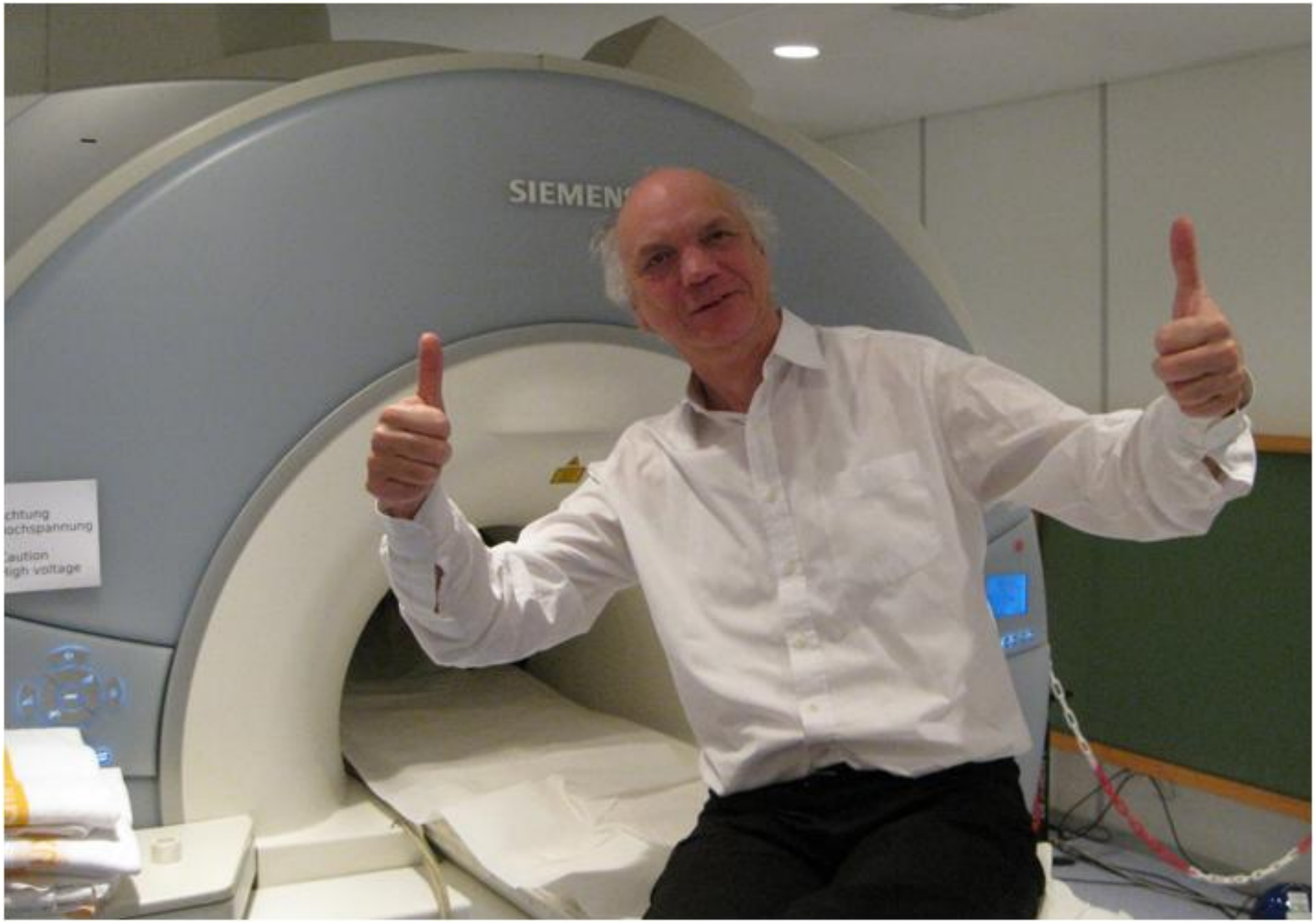


Linear encoding

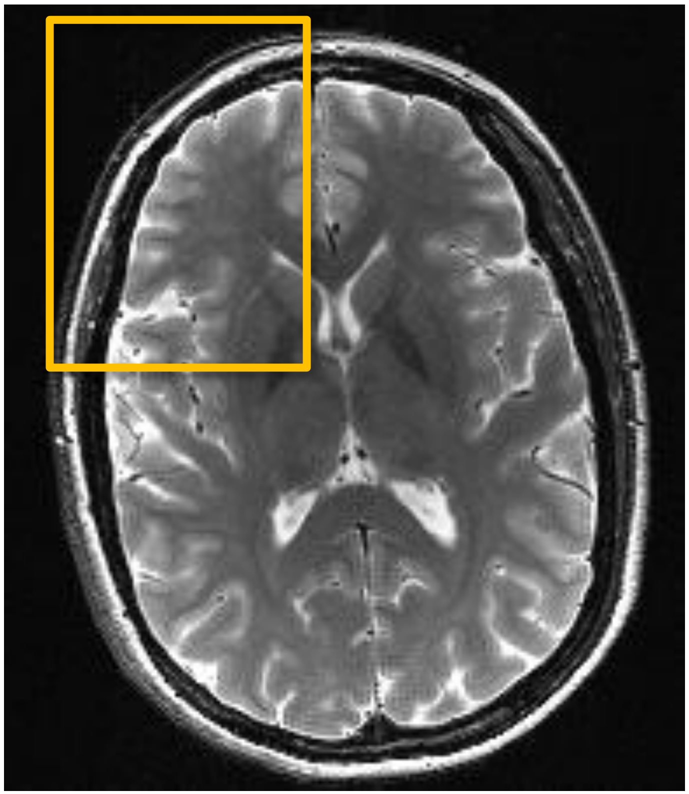


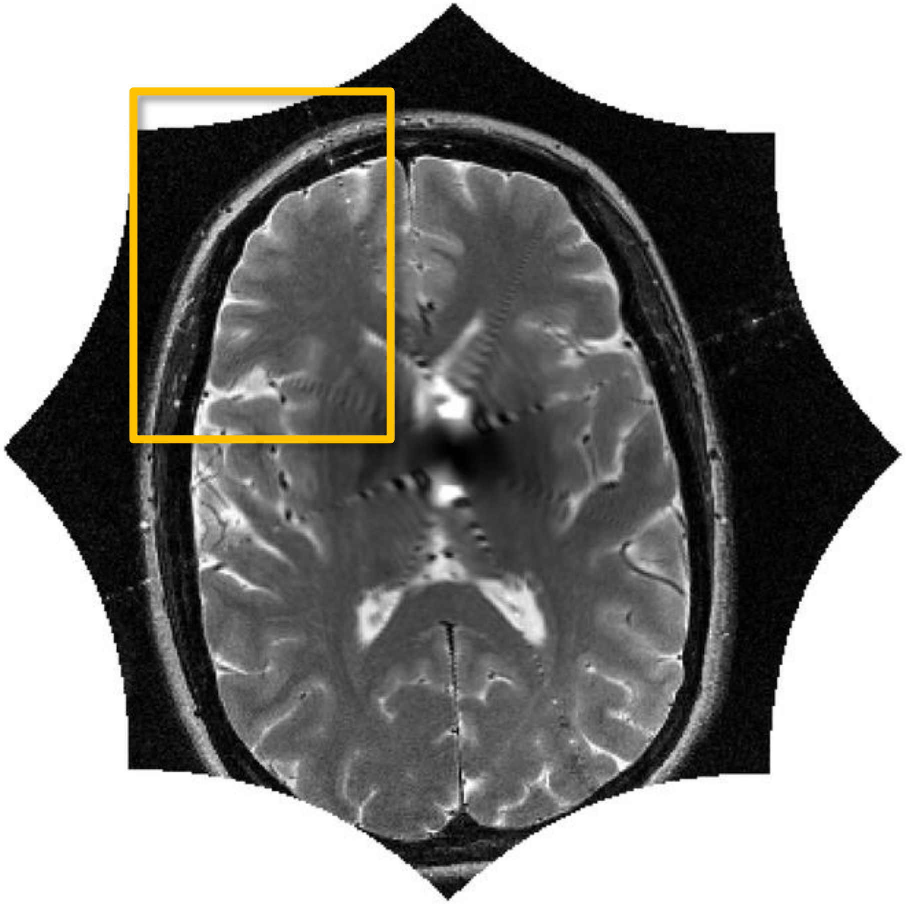
Quadratic encoding

Subject approval



And different contrast…



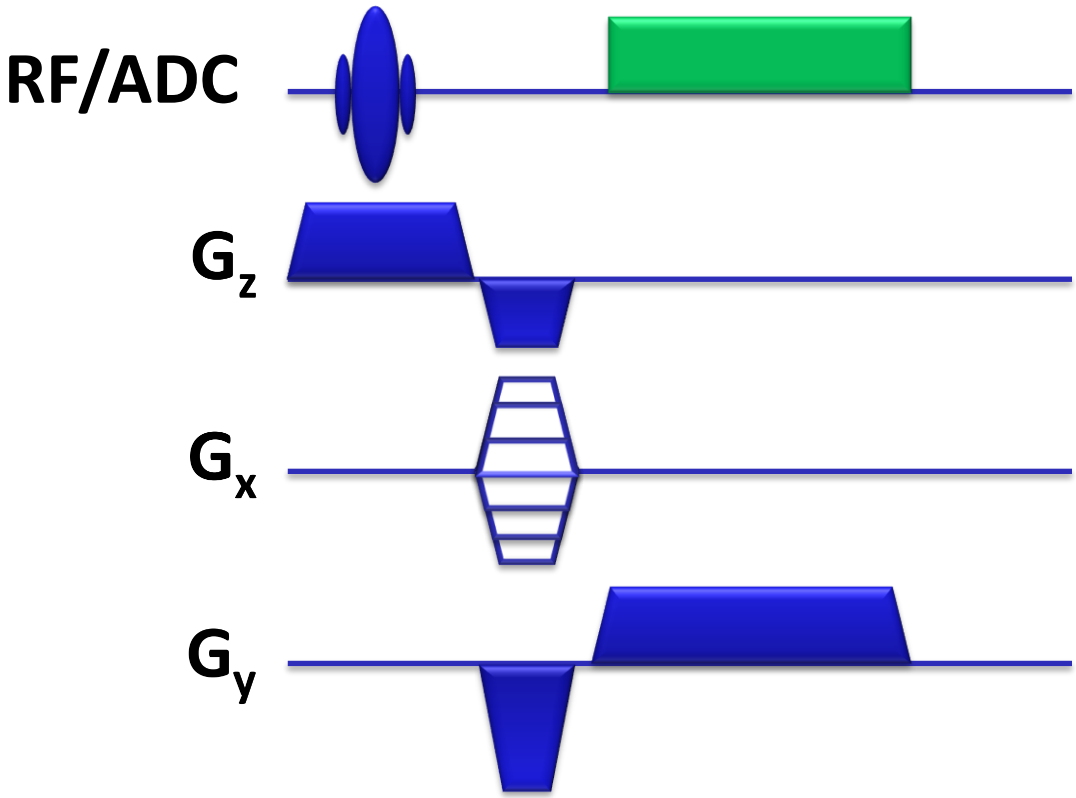


And different contrast…

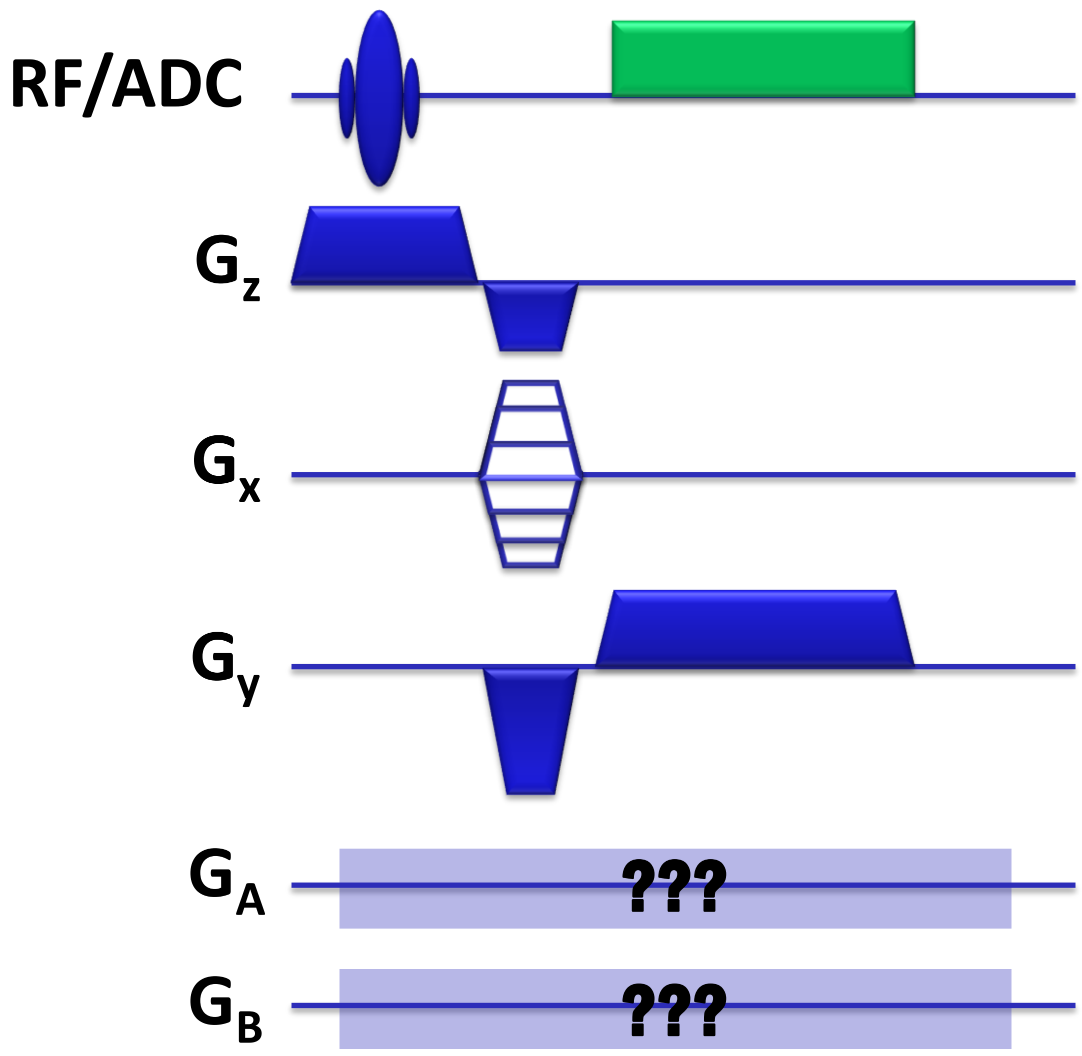
Taking things further…

Linear gradients and quadratic gradients, simultaneously

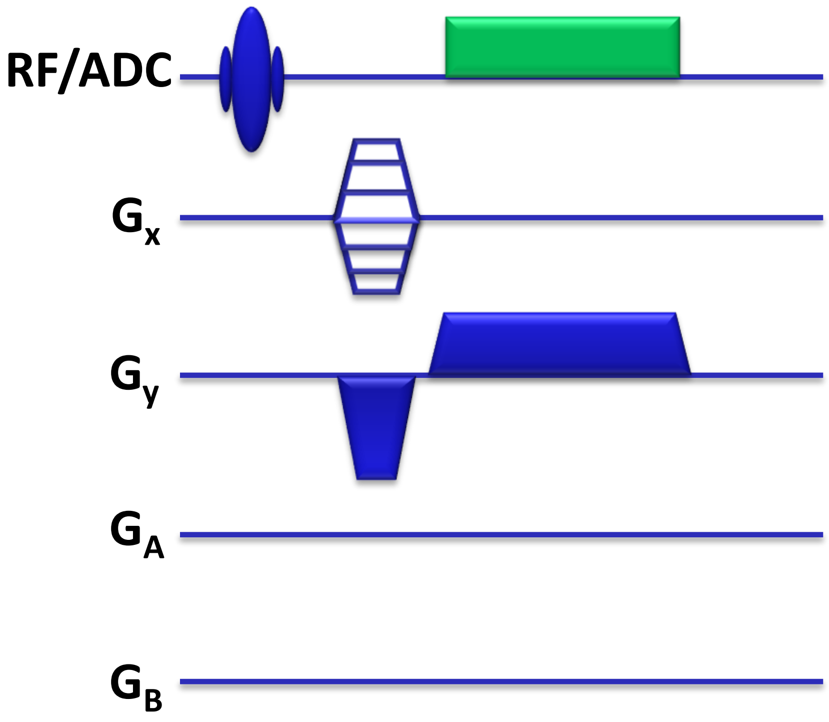
A standard pulse sequence

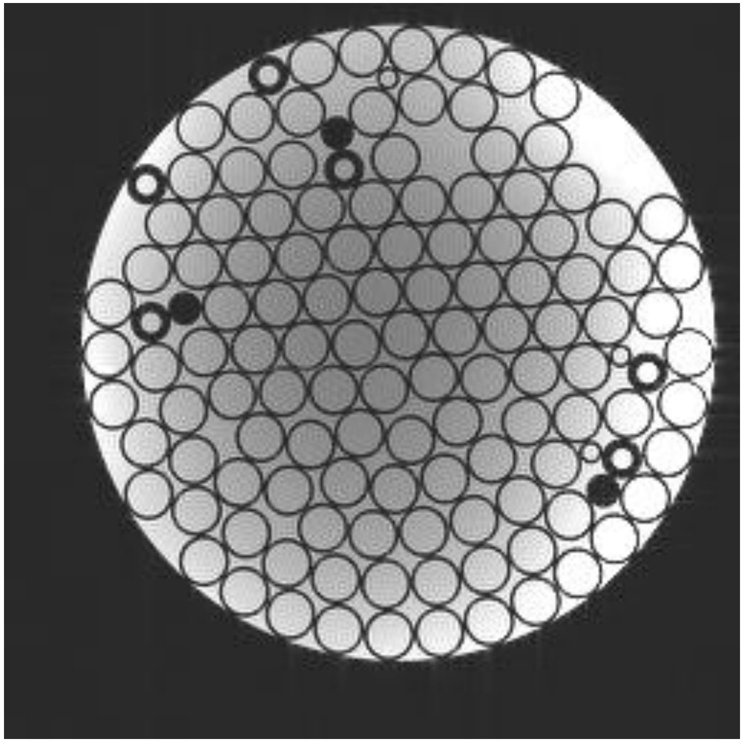


5 independent spatial encoding channels!

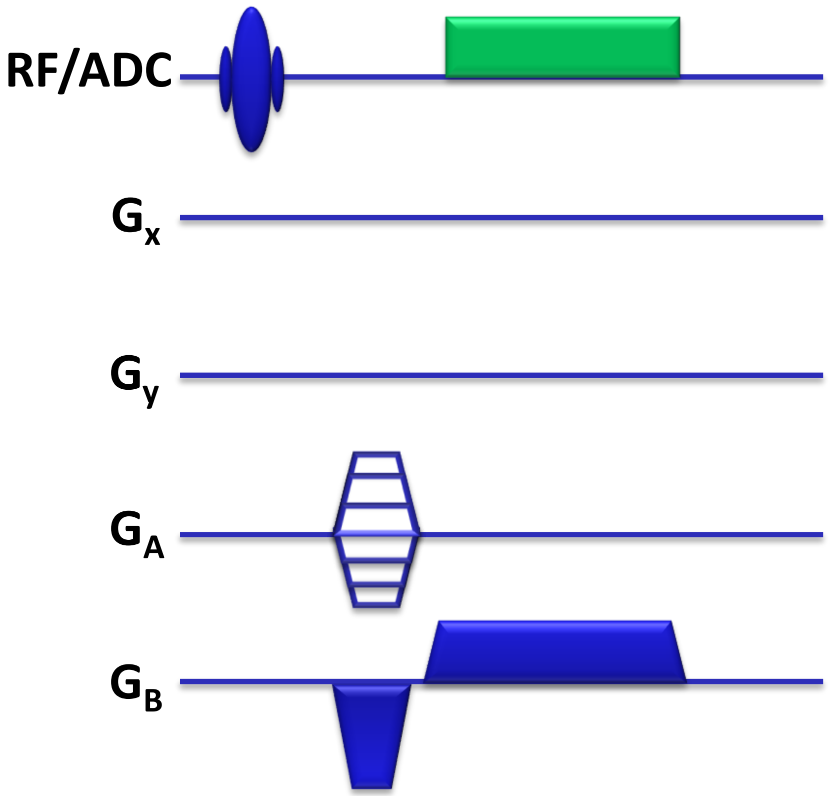


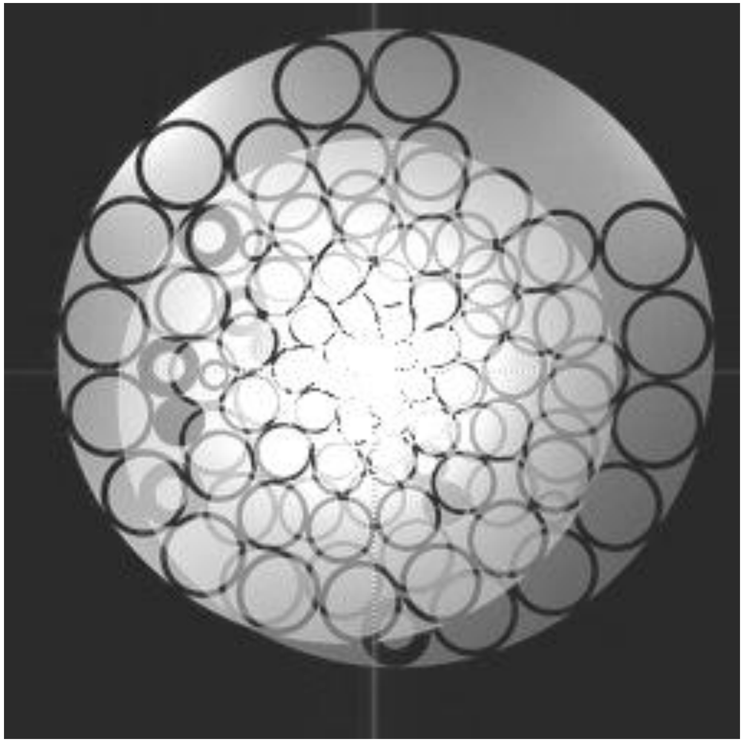
The familiar method of encoding



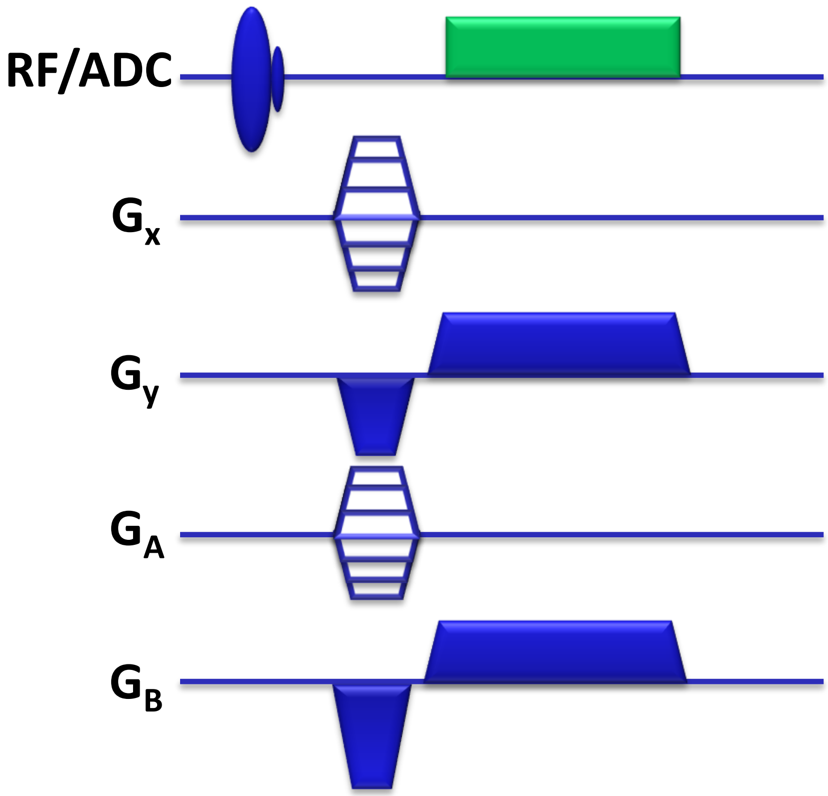


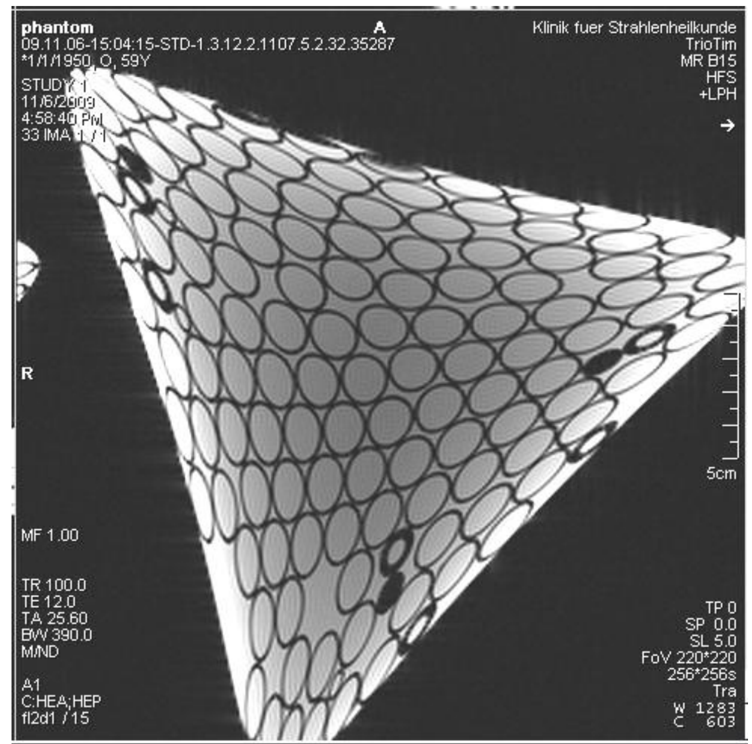
The new-but-reasonably-understood way



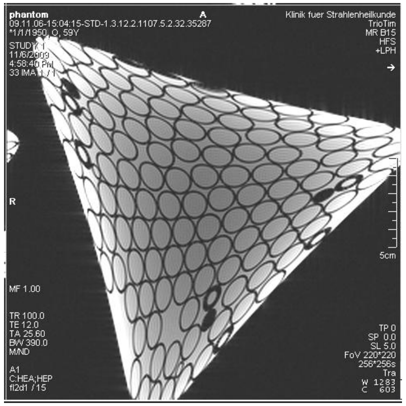


Uncharted territory…





Uncharted territory…

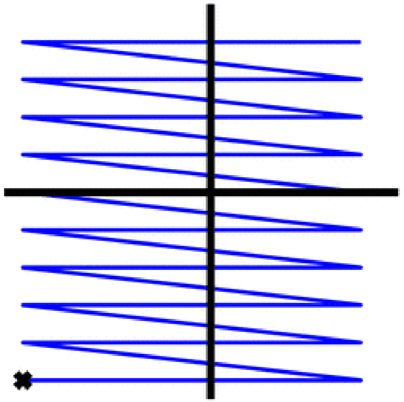


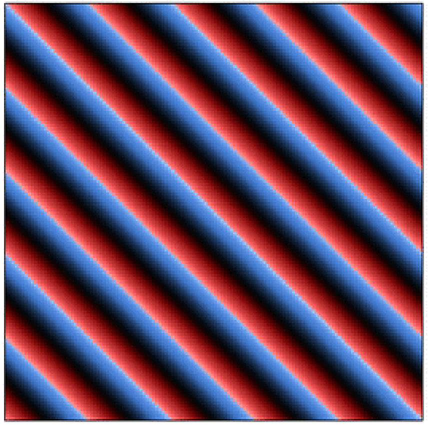
This is a weird image!

- How can we explain where this shape comes from?
- How can we predict things more generally?
- Can we use this to remove the PatLoc ‘hole’?

What patterns can we make?

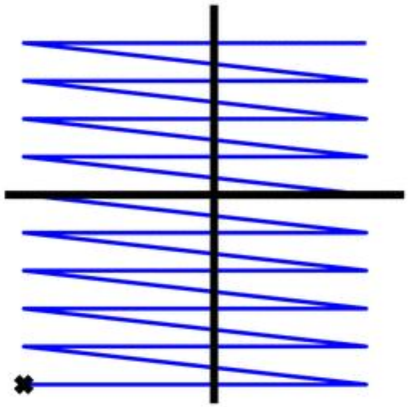
Just linear gradients

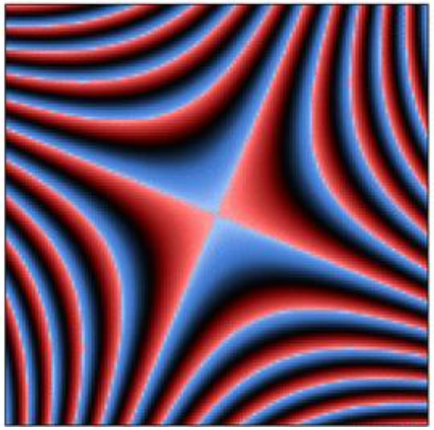




What patterns can we make?

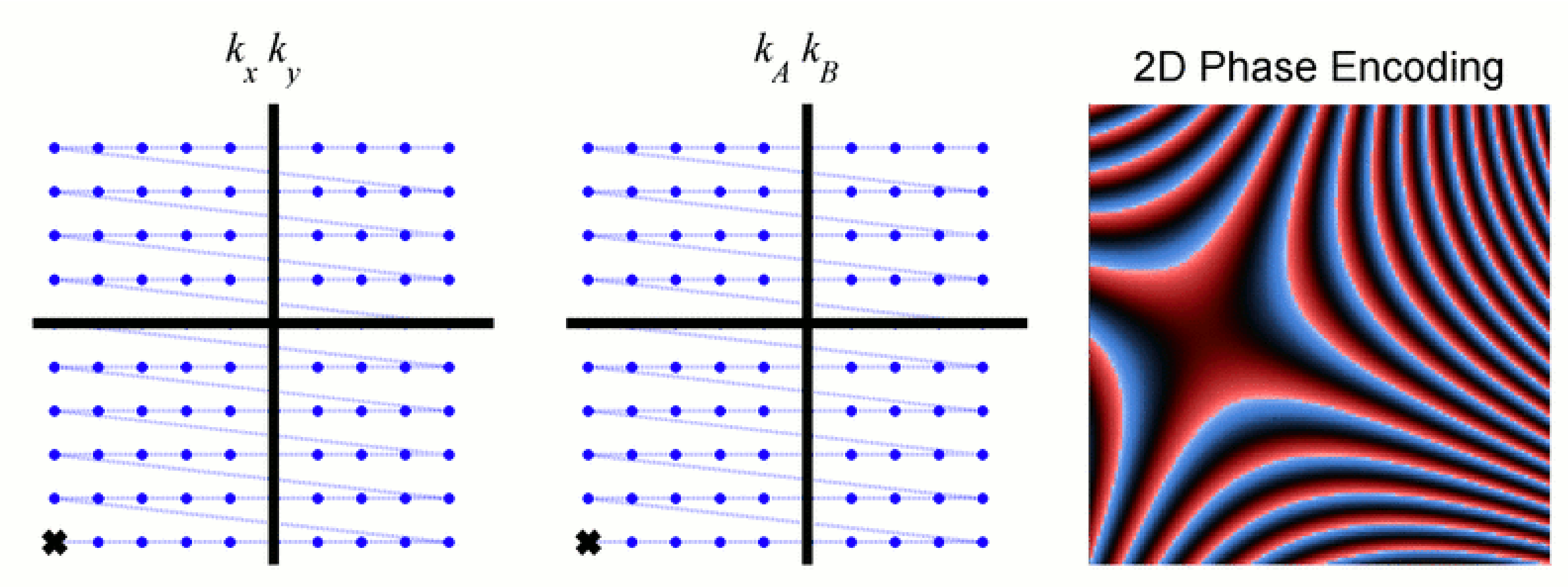
Just quadratic gradients





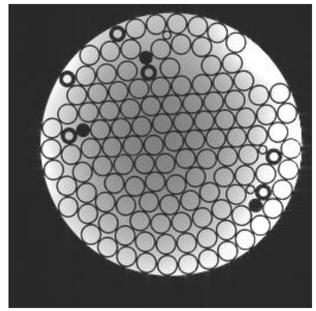
What patterns can we make?

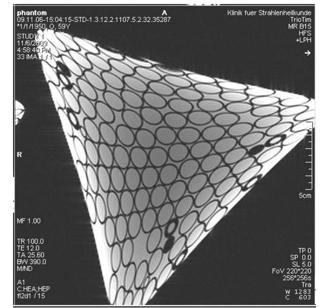
Linear gradients ***and*** PatLoc gradients



But how does that explain the weird image?

Measured data:



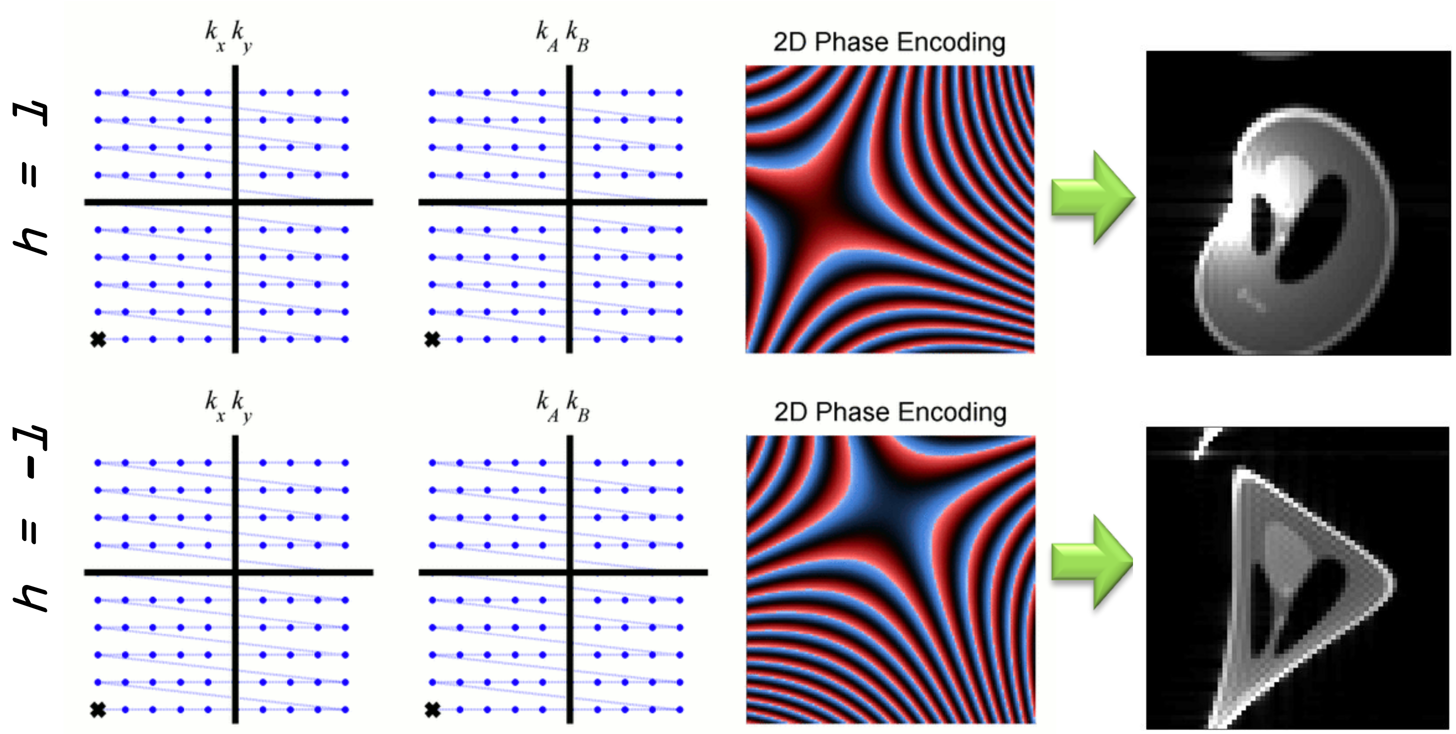


They don’t match!

Simulation:

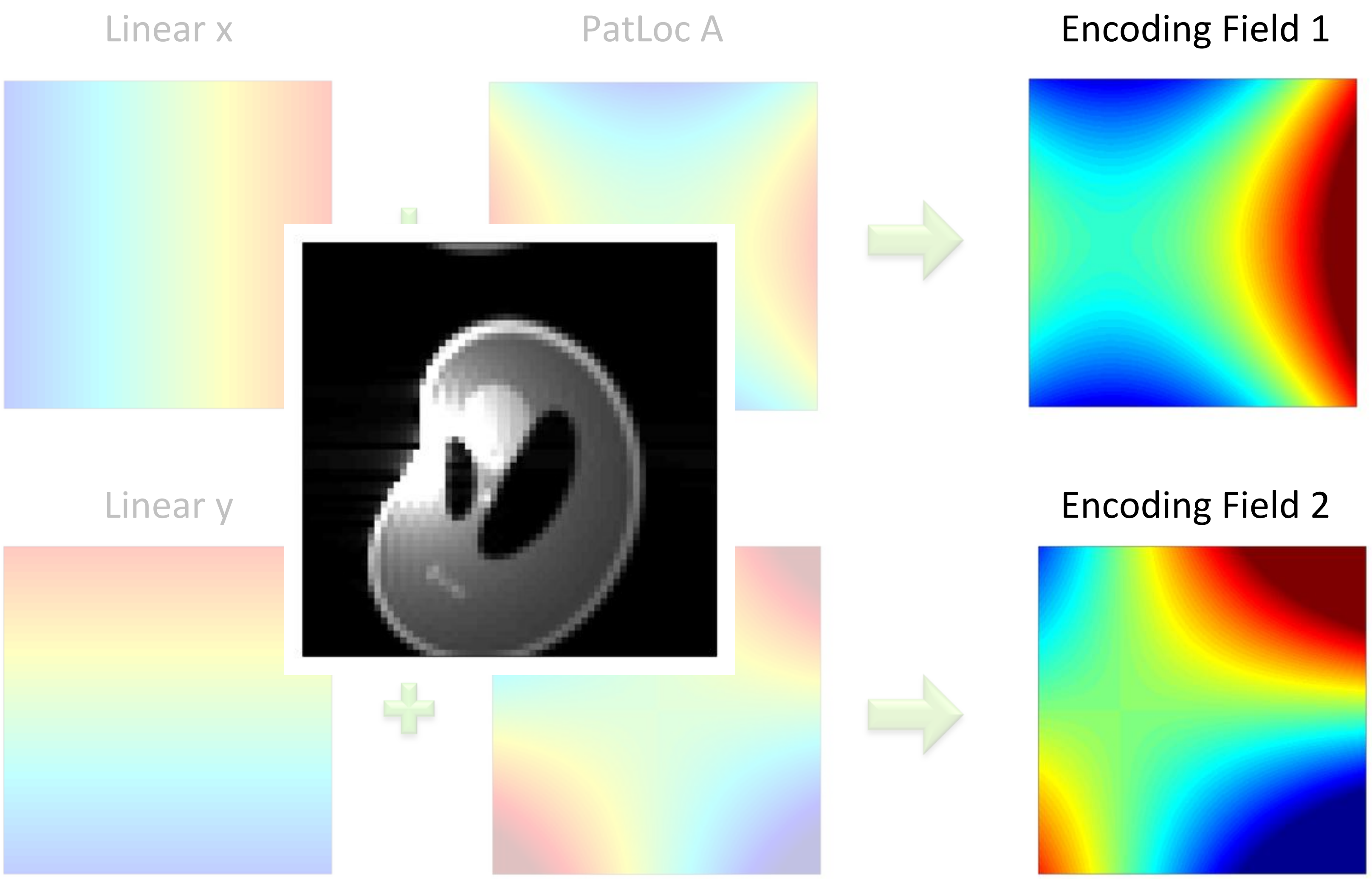
But how does that explain the weird image?

It turns out that 'handedness' of PatLoc fields is important:

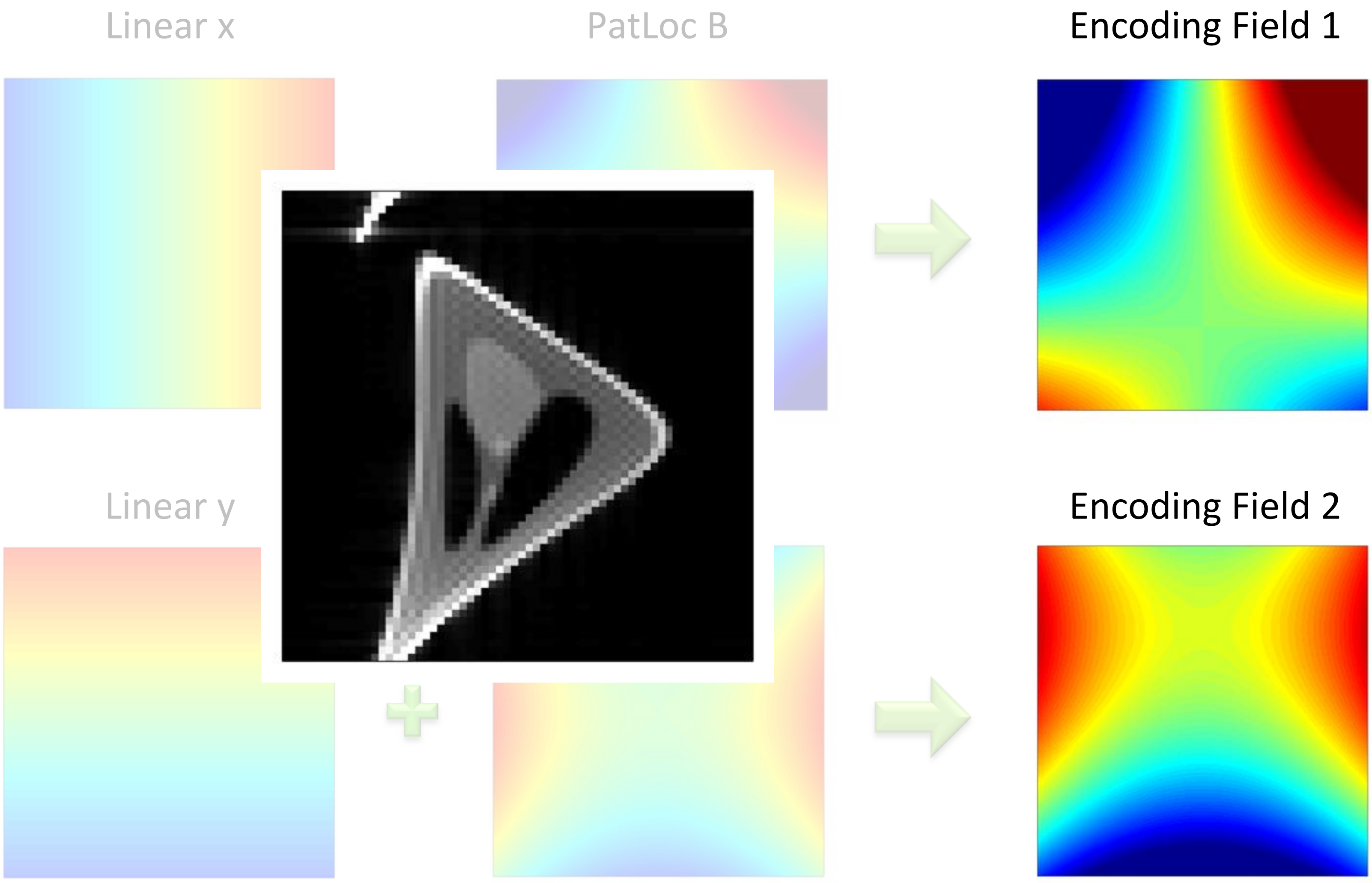


So clearly just looking at this 'dual *k*-space' is not enough to quickly tell the whole story

But how does that explain the weird image?



But how does that explain the weird image?



But how does that explain the weird image?

Pure linear

Pure quadratic

$h = 1$

$h = -1$

But how does that explain the weird image?

Pure linear

Pure quadratic

$h = 1$

$h = -1$

Getting rid of the hole…

- New encoding fields need not remain proportional to the linear gradients
- Usually have two parameters (k_x,k_y) to encode 2D image
  - Now have four parameters (k_x,k_y,k_A,k_B) to encode 2D image
- Image reconstruction more complicated…

Generalized Reconstruction

$$\mathbf{s} = \mathbf{Em}$$

Generalized Reconstruction

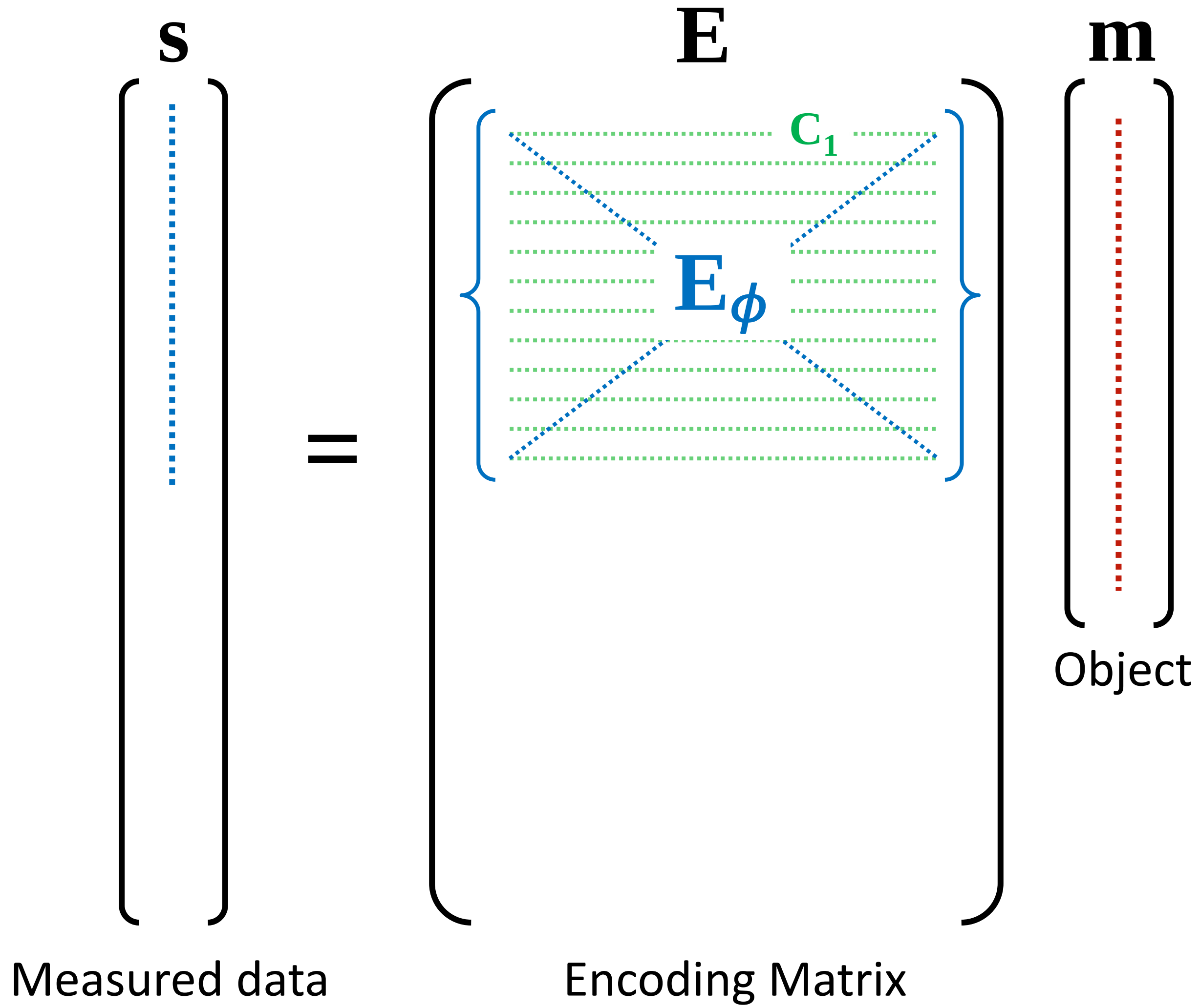
$$\mathbf{s} = \mathbf{E}\,\mathbf{m}$$

Object

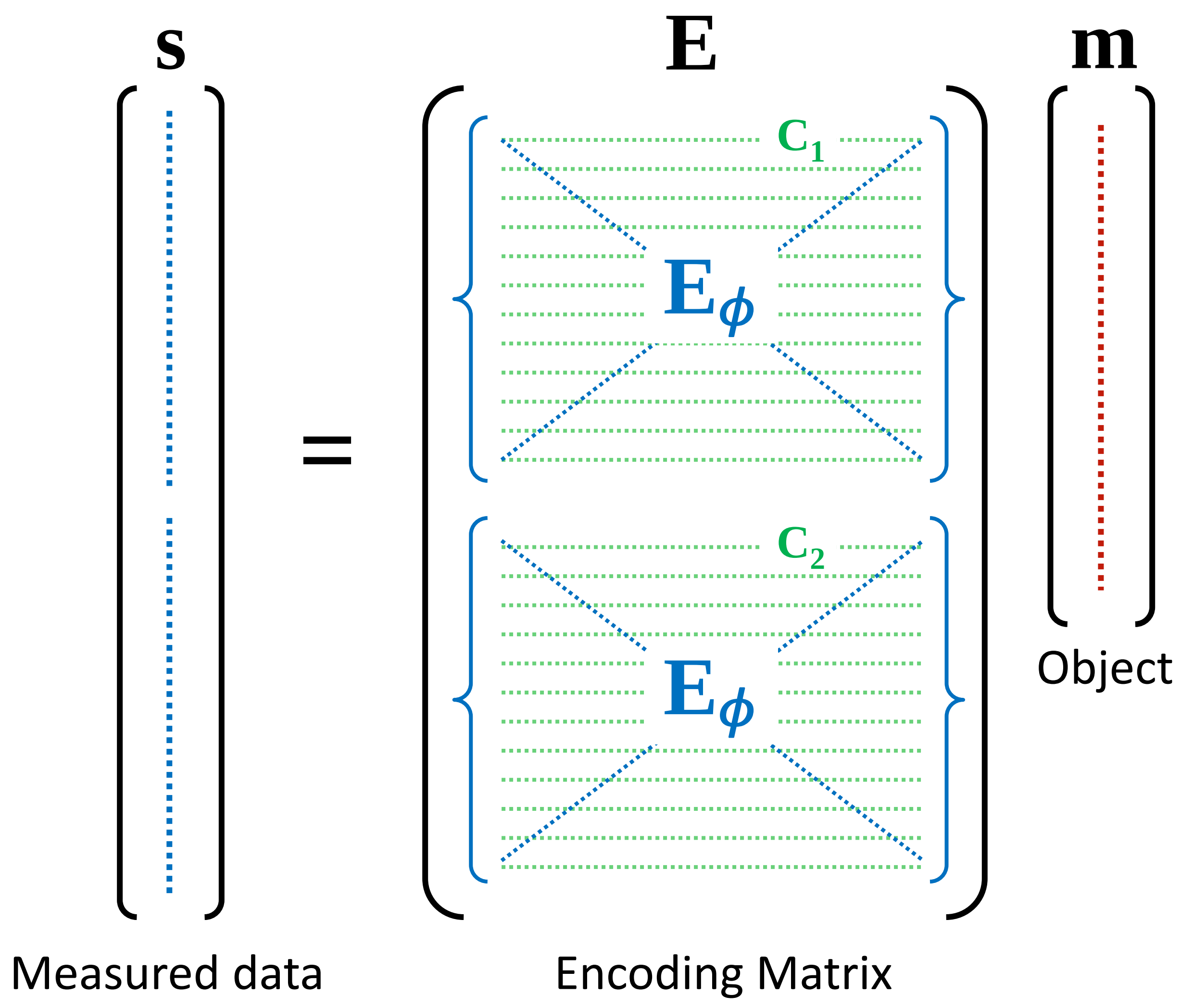
Measured data

Encoding Matrix

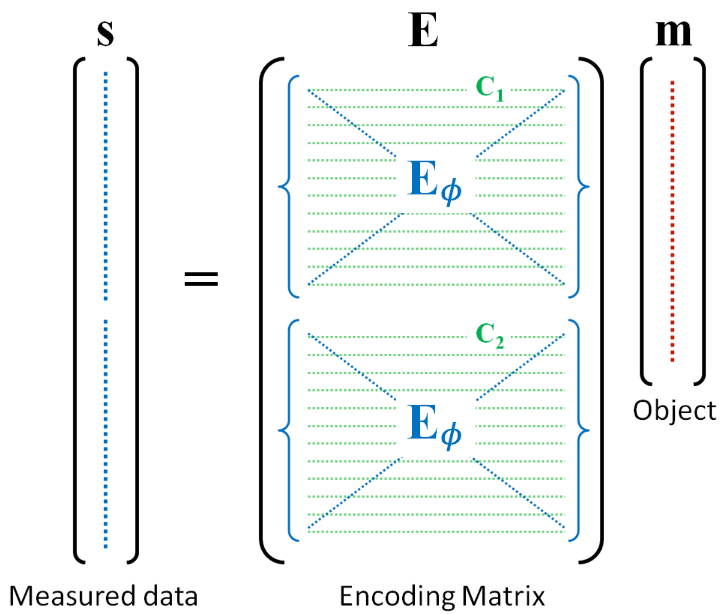
Generalized Reconstruction



Generalized Reconstruction

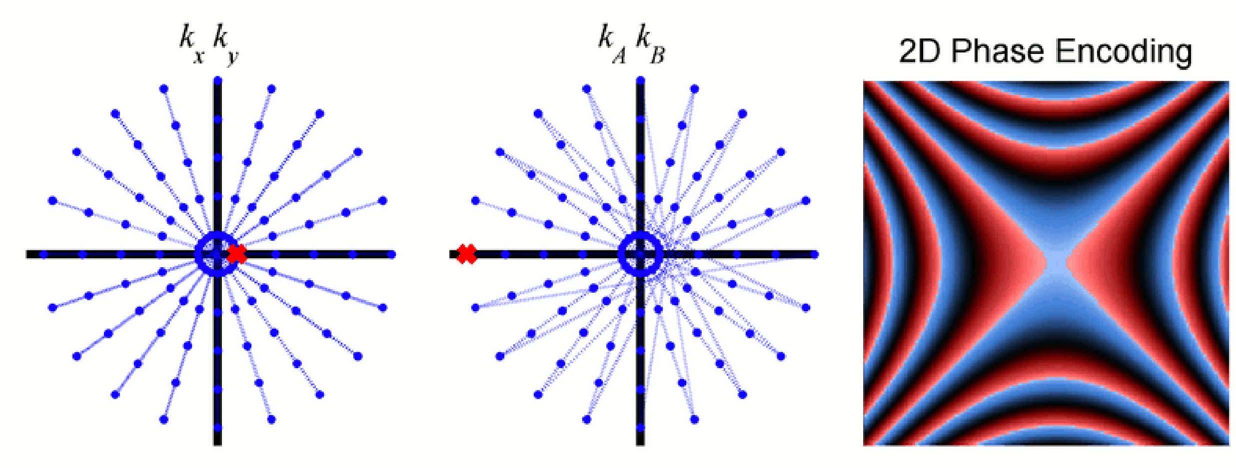


Generalized Reconstruction



- Reconstruction then performed with an iterative method, such as conjugate gradients

4D Radial-based trajectory (4D-RIO)

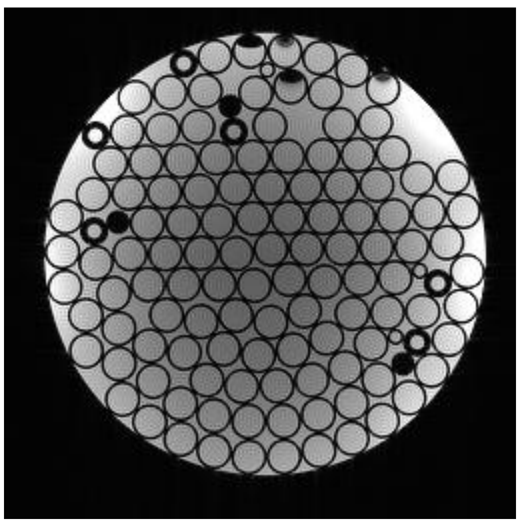


Gallichan et al, MRM 2011

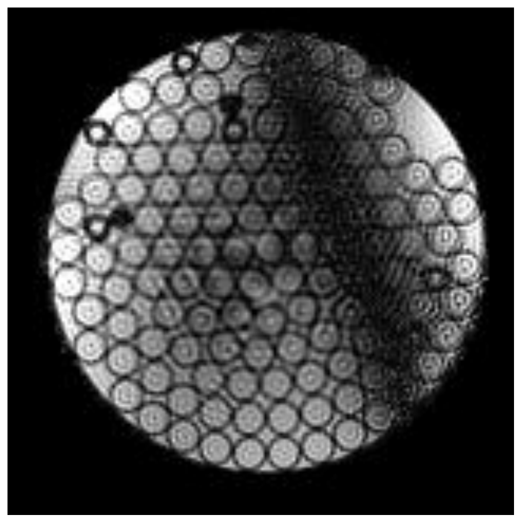
Experimental verification

- 128 samples x 128 spokes, 8 RF coils
- Reconstructed to 160x160 Cartesian grid

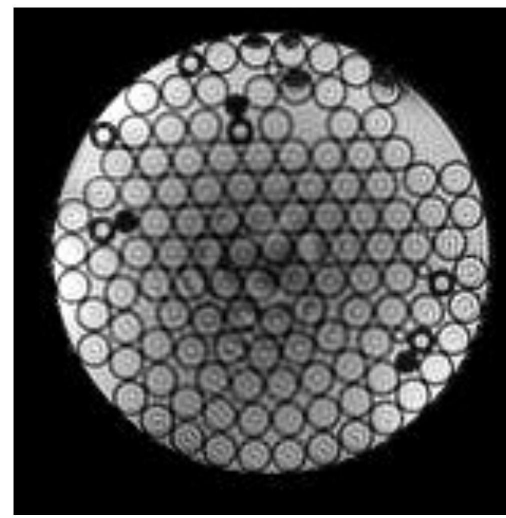
  Encoding matrix 27 Gb, recon originally took ~10 hours on Desktop PC, now ~3 minutes in a more optimised parallel accelerated version



Phantom



4D-RIO



4D-RIO
After calibration

Experimental verification – in vivo

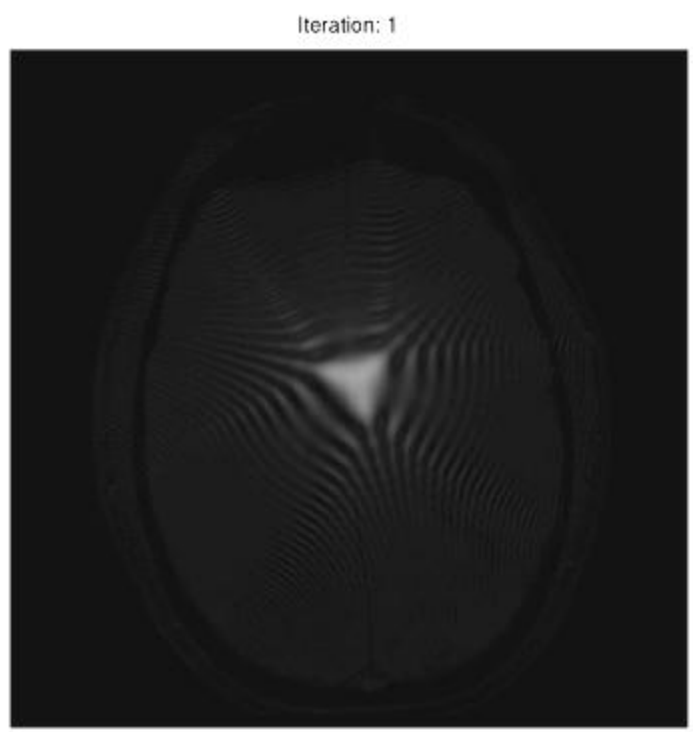
- 256 samples x 256 spokes, 8 RF coils
- Reconstructed to 320x320 Cartesian grid
  Encoding matrix 430 Gb – 'fast' code takes ~30 mins per iteration
  New Matlab-based GPU implementation ~ 10 sec per iteration

Experimental verification – in vivo

- 256 samples x 256 spokes, 8 RF coils
- Reconstructed to 320x320 Cartesian grid

  Encoding matrix 430 Gb – 'fast' code takes ~30 mins per iteration

  New Matlab-based GPU implementation ~ 10 sec per iteration



Conclusions

- PatLoc offers exciting new opportunities for spatial encoding in MRI
- Nonlinear encoding can still be performed in the 'traditional' way
  - Phase/Frequency encoding
  - SENSE-like reconstruction to resolve ambiguities
- More generally, encoding can be almost arbitrary – but reconstruction is slower
  - Is there an 'optimal' encoding pattern for a given scan time?

The making of…

Acknowledgements

Freiburg PatLoc Team


Jürgen Hennig


Chris Cocosco


Sebastian Littin


Gerrit Schultz


Anna Welz


Hans Weber


Maxim Zaitsev

Collaborators


Walter Witschey

Penn
University of Pennsylvania

SIEMENS

BRUKER

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