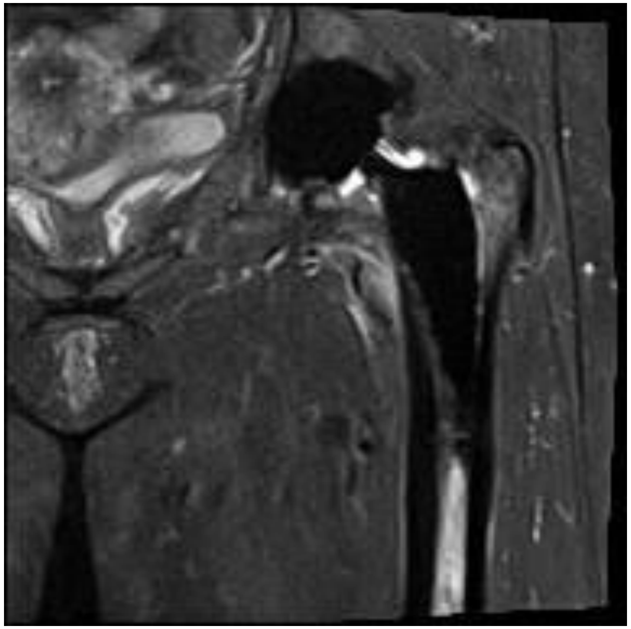
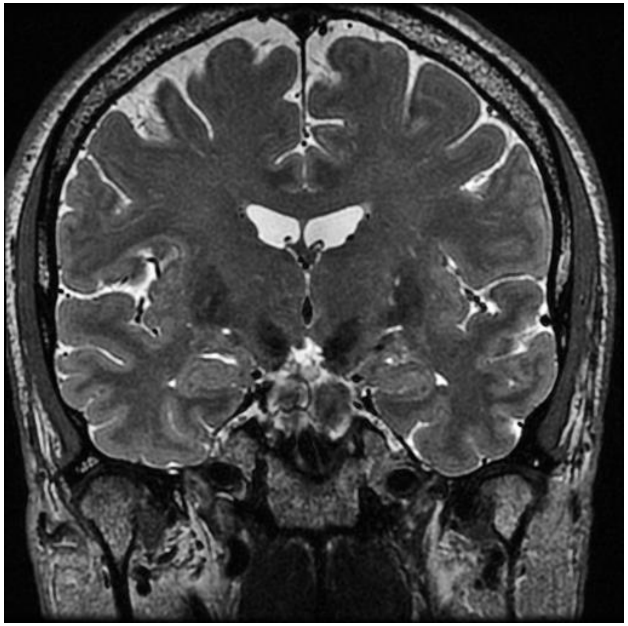
NHS
Hull University
Teaching Hospitals
NHS Trust

Magnetic Resonance Imaging

F.R.C.R. Physics Lectures





Lawrence Kenning PhD

Remarkable people.
Extraordinary place.

Hull University Teaching Hospitals NHS Trust

7.7 Acceleration techniques, their impact on image quality and potential artefacts

- Zero-filling (interpolation)
- Half-Fourier
- Parallel imaging
- Simultaneous multislice (multiband)
- Compressed sensing
- Temporal sharing (TWIST/TRICKS)
- *Deep Learning Reconstruction*

Zero-filling

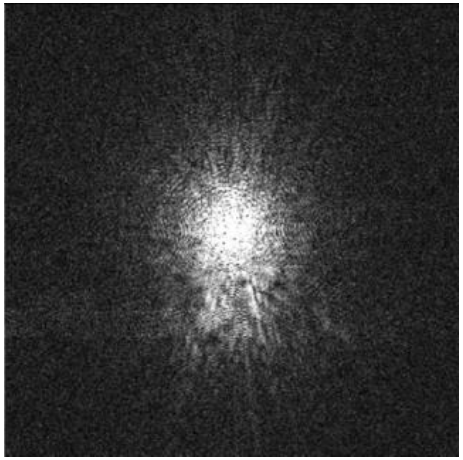
- Scan Time = Number Phase Encodings x Repetition Time x #averages
- Once the data acquisition is complete and k-space has been filled, a inverse Fast Fourier Transform (FFT) algorithm is performed generate an MR image
- By reducing the number of phase encodings (and resolution), scan time can be decreased / sequence accelerated
- However, the computational requirements generally require the dimensions k-space to be a power of 2 such as 128x128, 256x256, 512x512, 1024x1024 etc.
- So what happens if the matrix is 256 x 192?

Zero-filling

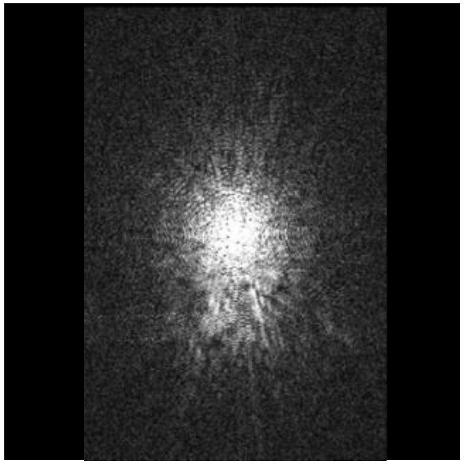
- When lines of k-space are missing or omitted, the missing data is filled with zeroes, a technique called zero padding, zero filling, or zero-interpolation filling (ZIP)

- The downside of this technique is a loss of spatial resolution in the phase encoding direction

256x256 Acquisition
256x256 Reconstruction



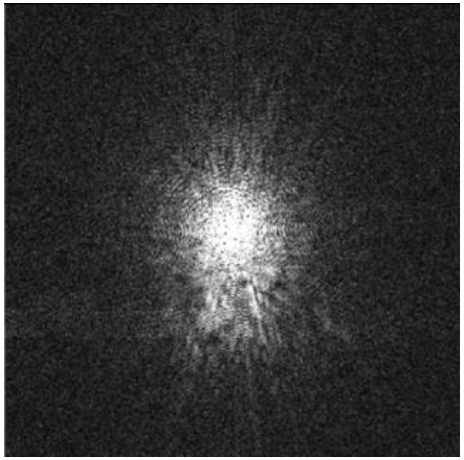
256x192 Acquisition
256x256 Reconstruction



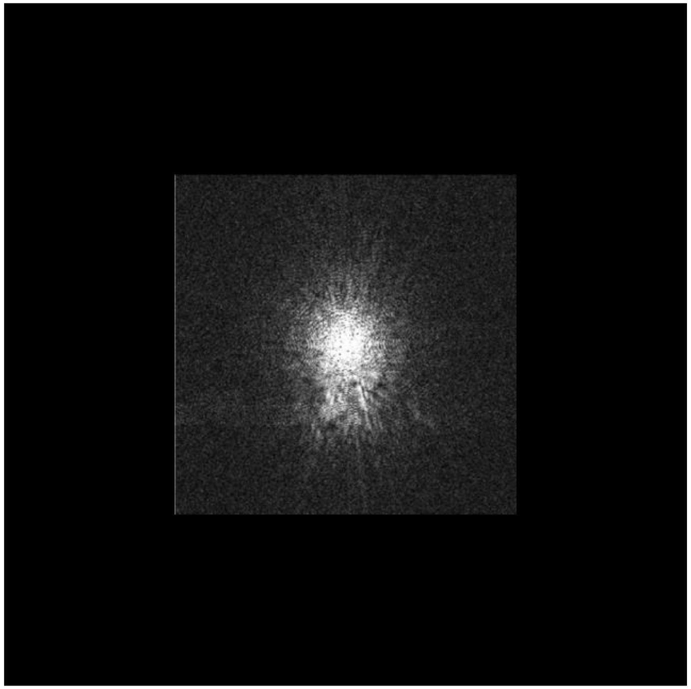
Acquisition Matrix	256 x 256	256 x 192
Reconstruction Matrix	256 x 256	256 x 256
TR (ms)	500	500
FOV (mm)	240	240
Scan Time (s)	**128**	**96**
Acquired Resolution (mm)	**0.94 x 0.94**	**0.94 x 1.25**
Reconstructed Resolution (mm)	0.94 x 0.94	0.94 x 0.94

In-plane interpolation

- It is also possible for the user to decide to add extra zeroes to improve the apparent resolution of the final image.
- ZIP512/ZIP1024 better to visualize the available in-plane resolution
- Enhance resolution without an increase in scan time if you keep the pixel size (phase matrix and FOV) the same



256x256 Acquisition
256x256 Reconstruction

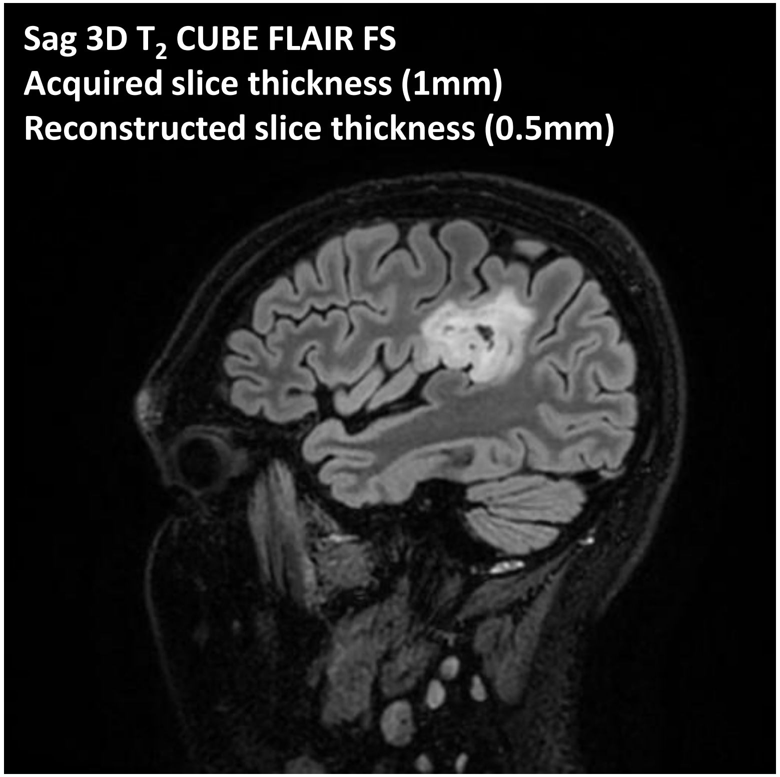


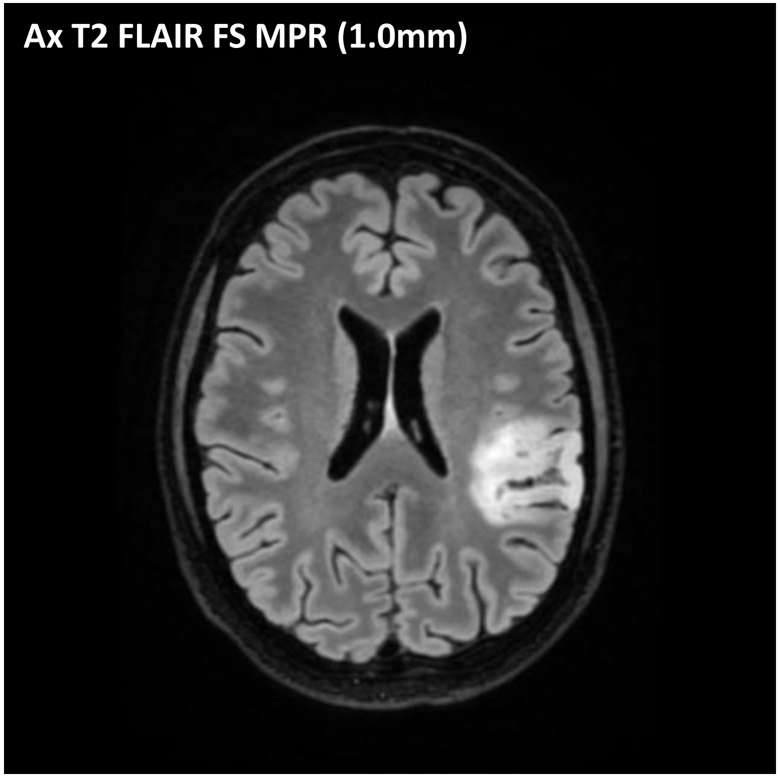
256x256 Acquisition
512x512 Reconstruction

Through-plane interpolation

NHS
Hull University
Teaching Hospitals
NHS Trust

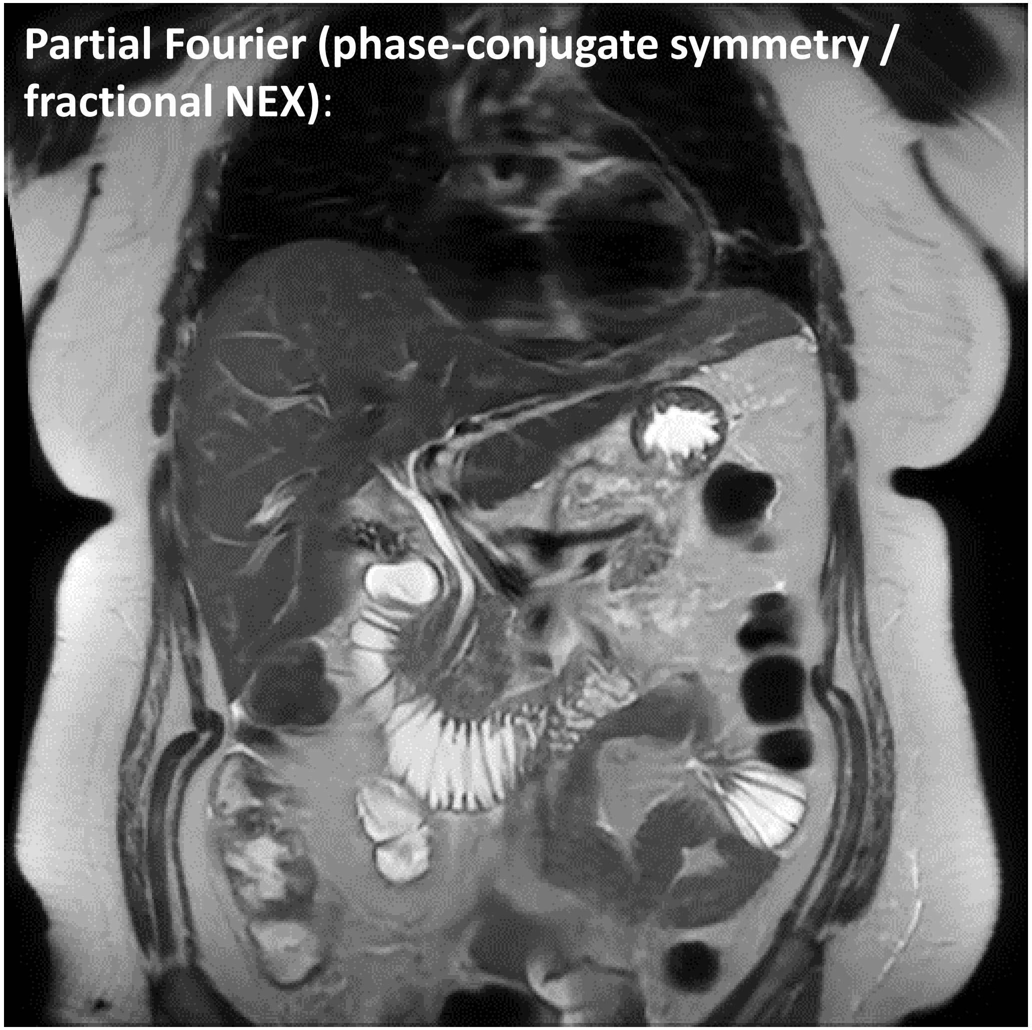
- 3D sequences can also be interpolated through-plane to reduce scan time at the expense of through-plane spatial resolution





Partial k-space (Single shot)

- HASTE (Half Fourier Acquisition Single Shot Turbo Spin Echo) / SS-FSE (Single-shot fast spin echo)
- Often make use of partial Fourier to reduce breath-hold time
- Short acquisition time makes sequence motion insensitive
- Image contrast is determined by the effective echo time TE_{eff}, that is, the echo time in the raw-data centre.



Partial k-space (Single shot)

- Echo Train technique to fill entire Fourier plane with a single 90° pulse (so TR is infinite)
- Requires successive application of as many 180° pulses as there are k-space lines to fill
- Fill-in missing lines of k-space using ***conjugate symmetry***

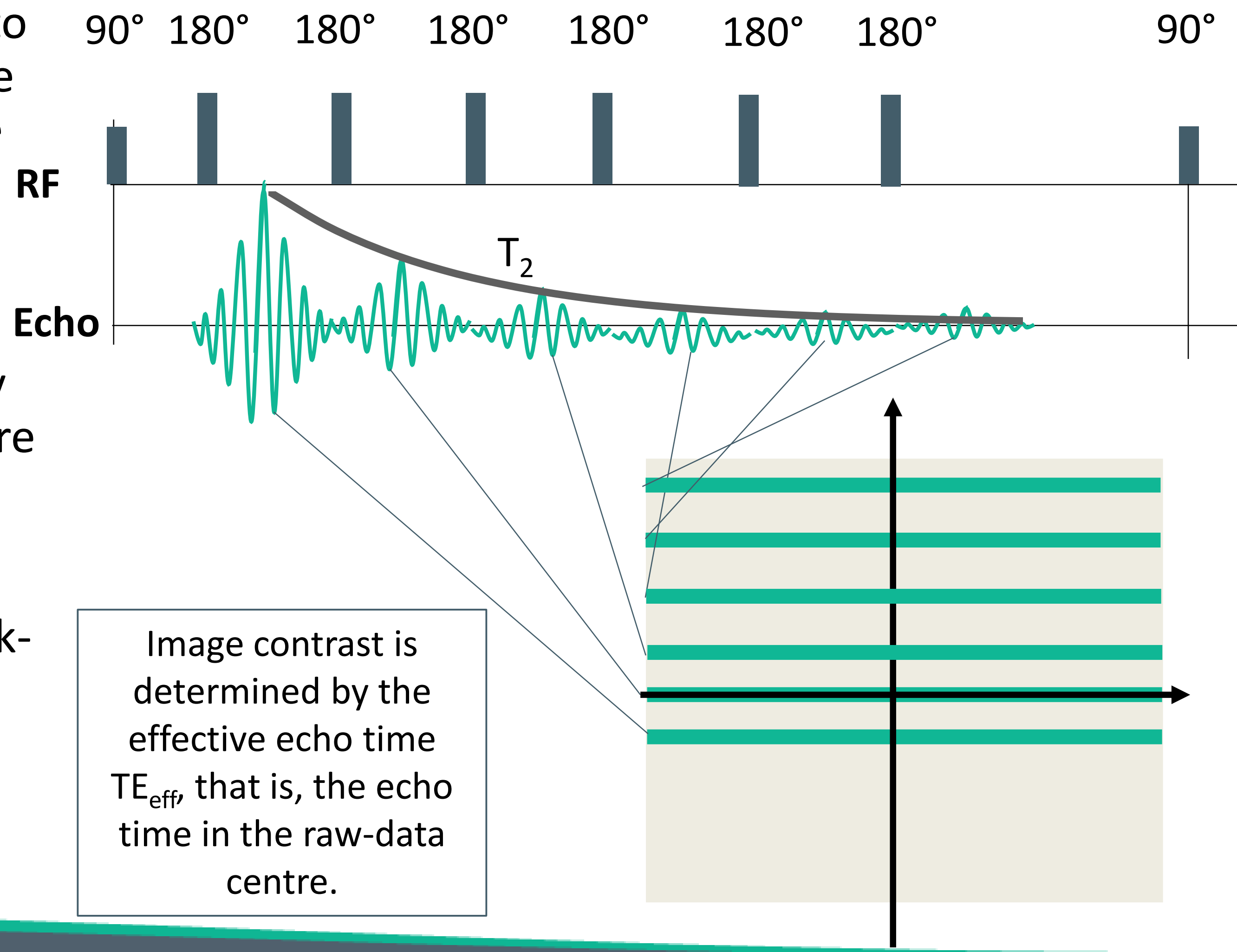


Image contrast is determined by the effective echo time TE_{eff}, that is, the echo time in the raw-data centre.

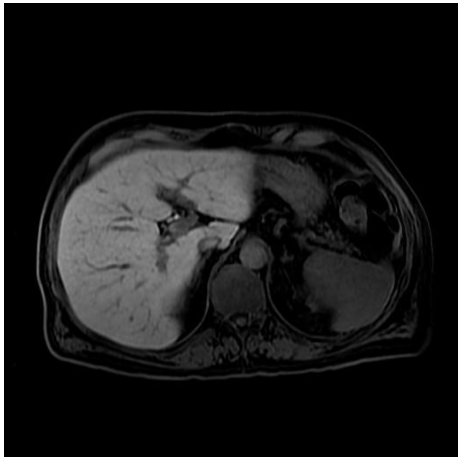
Partial k-space (Single shot)

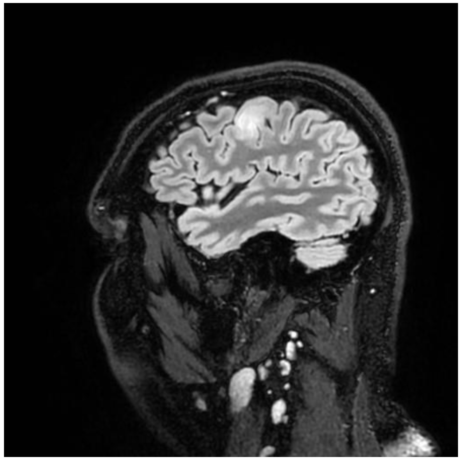
- This produces a time saving of approximately 50%, does not significantly affect spatial resolution but loses about 30% in signal-to-noise ratio (SNR).

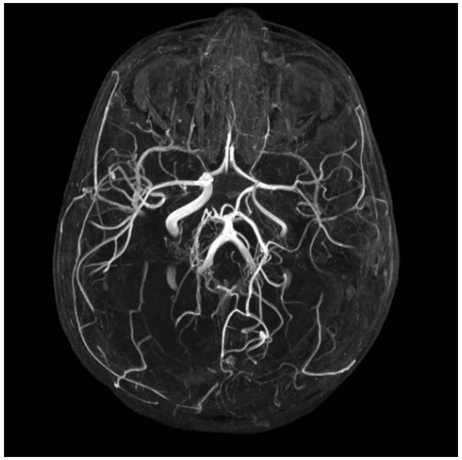
- Reduced SNR. Square root % of data acquired. E.g. ½ data has 70% SNR compared to full k-space.

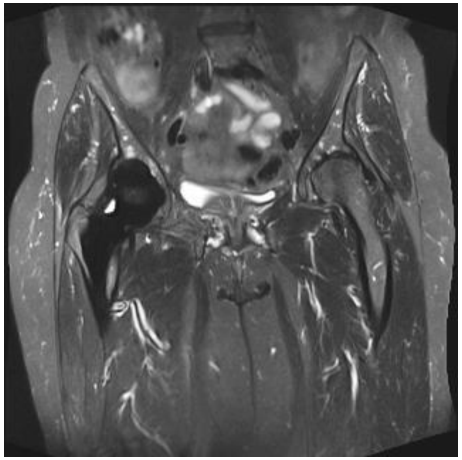
k-space trajectory	Advantages	Disadvantages
Cartesian	Simple to acquire. Minimal distortion artefacts. Works with parallel imaging	Prone to ghosting in PE direction. Requires complete filling of k-space. Image contrast generated ½ way through acquisition.
Partial Fourier (phase-conjugate symmetry)	Reduced acquisition time Preservation of spatial resolution	Reduced SNR. Square root % of data acquired. E.g. ½ data has 70% SNR compared to full k-space.

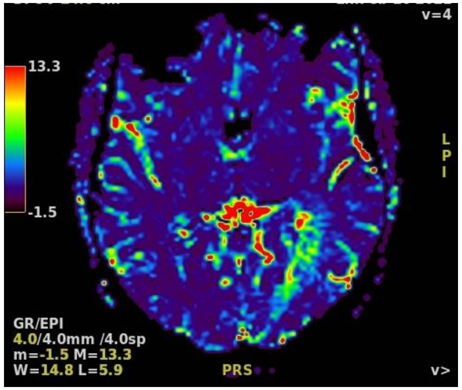
Parallel Imaging (PI)







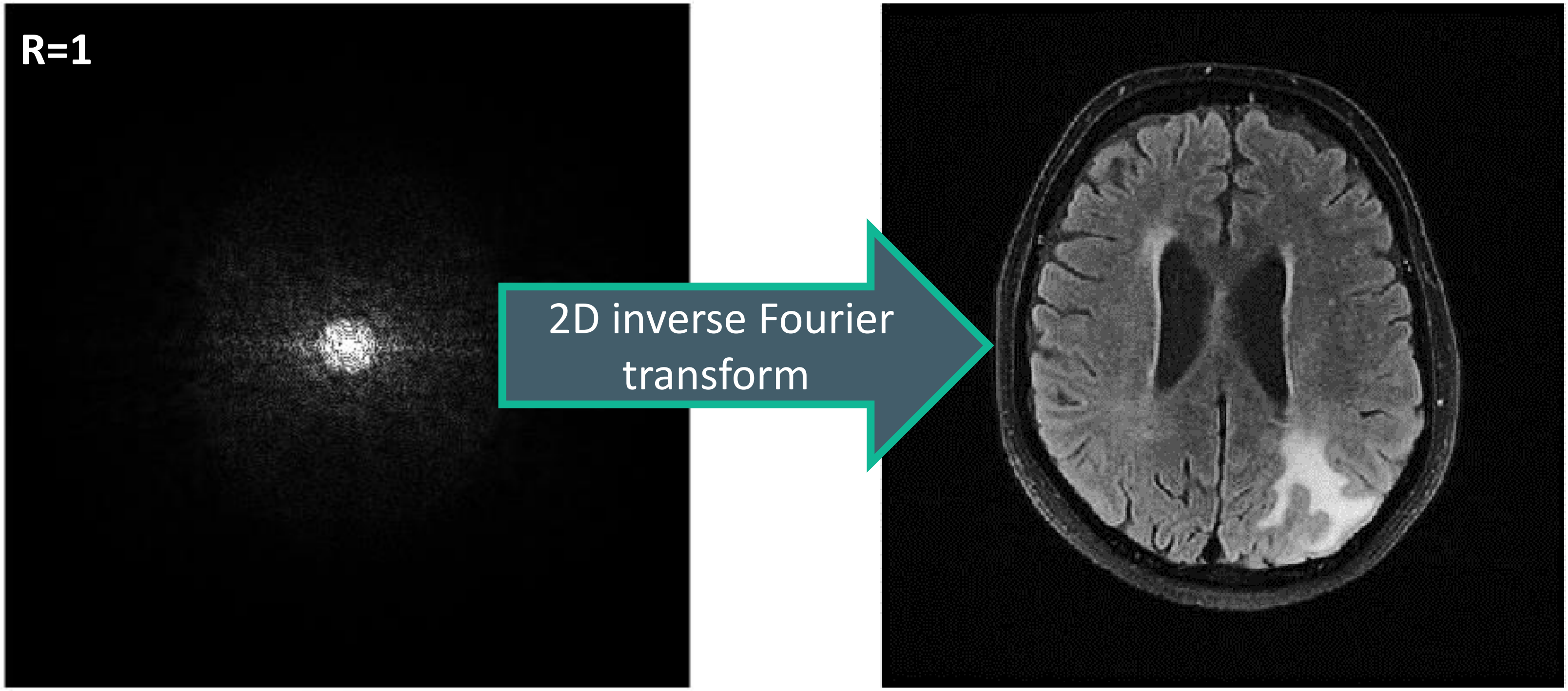




Parallel Imaging (PI)

- Scan Time = Number Phase Encodings x Repetition Time x #averages

- PI can be used on most MR sequences but particularly helpful for accelerating dynamic, breath-hold and volumetric imaging studies



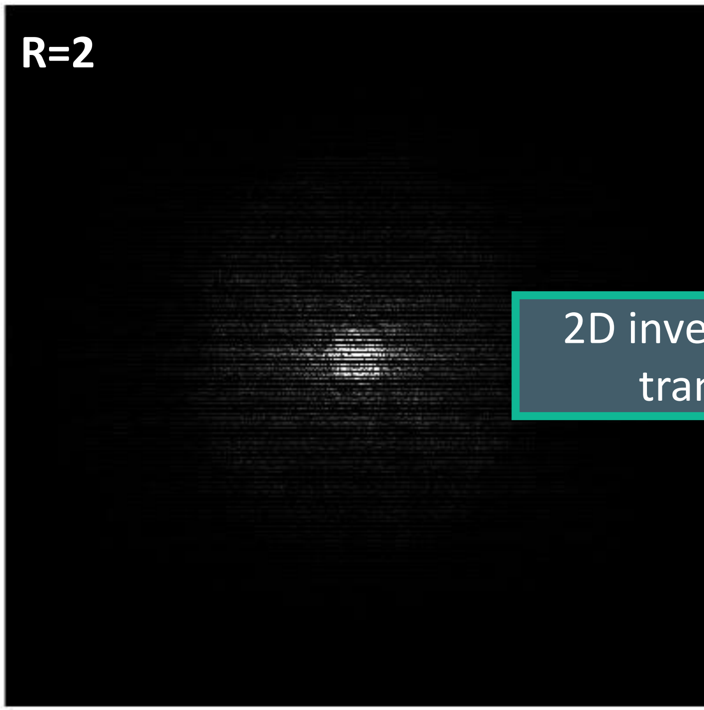
Parallel imaging

- Parallel Imaging
  - Image Space Calibration/ Reconstruction
    - SENSE
    - Simultaneous Multislice (SMS)
  - K-space Calibration/ Reconstruction
    - GRAPPA
    - CAIPIRINHA
      - Wave CAIPIRINHA
    - Compressed Sense (CS)

Parallel Imaging

- How do we make the scan quicker?

- Skip lines of k-space. The ratio of the reduced PE steps is known as the acceleration factor (R). R=2 means half the scan time, R=3 1/3 scan time…

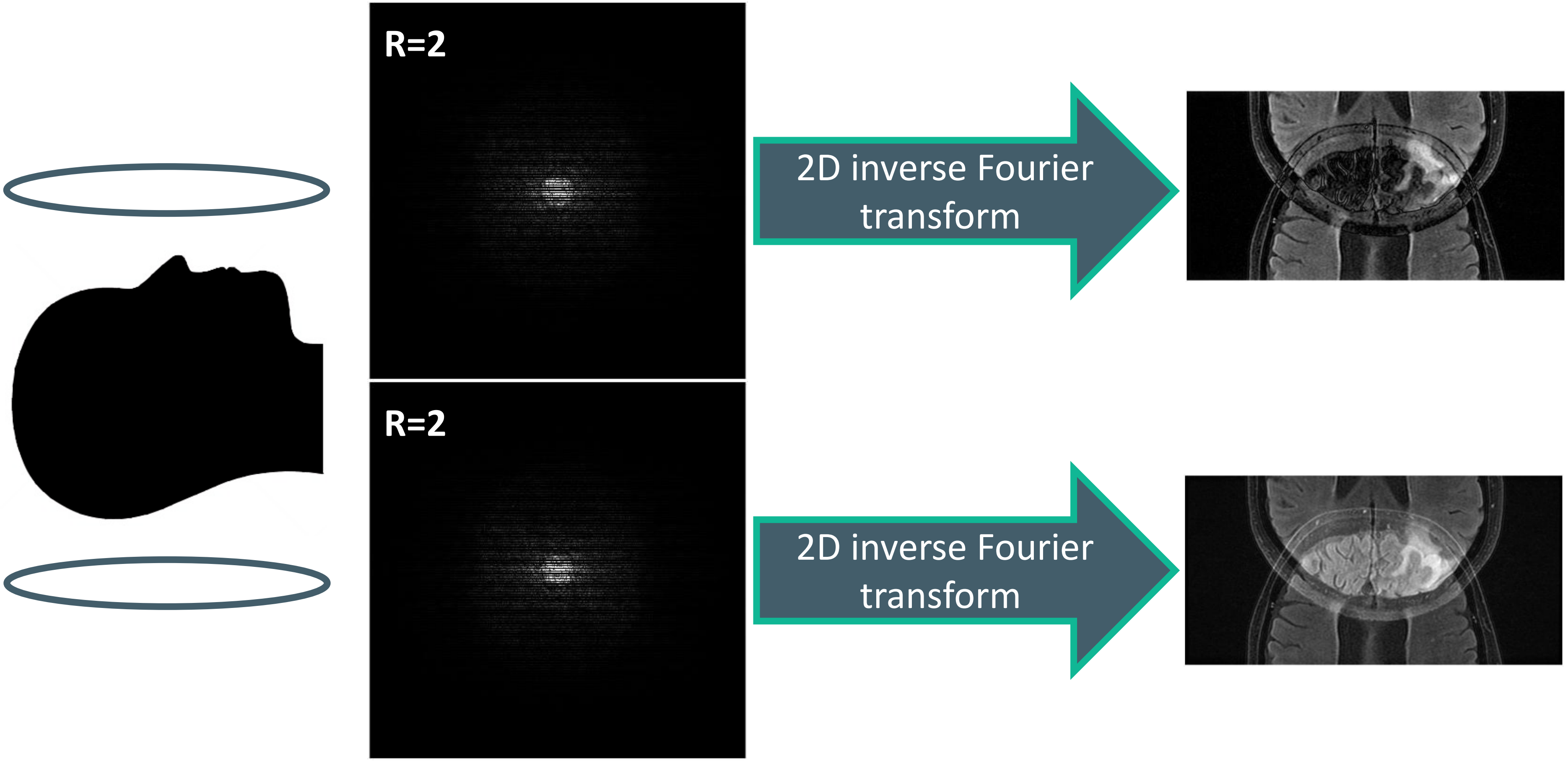


The concept of parallel imaging is to combine the spatial localisation of individual coils in a phased-array to unwrap/unallias the data collected

NHS Hull University Teaching Hospitals NHS Trust

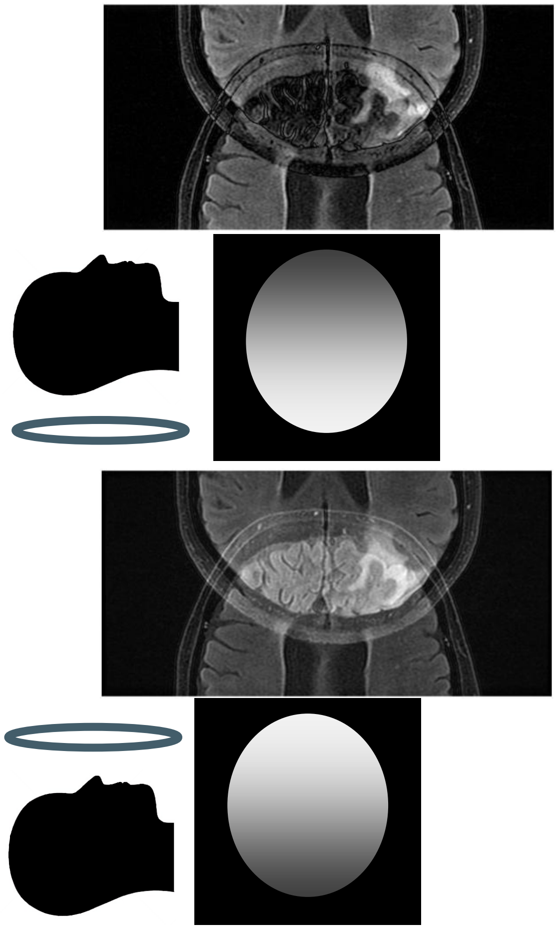
Parallel Imaging

- With parallel imaging, a separate set of k-space is partially filled for each receiver coil within the phased-array



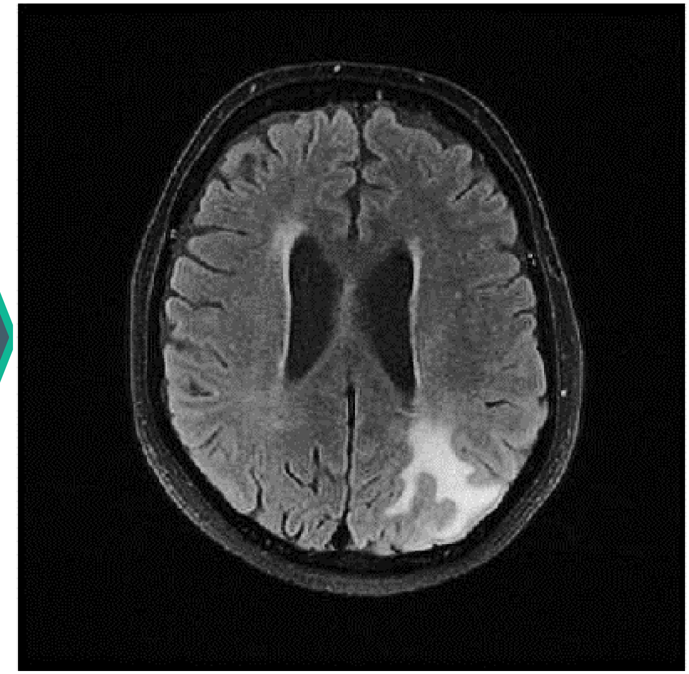
SENSE/ASSET

- Techniques that reconstruct the final image after FT, are known as SENSE (**SENS**itivity **E**ncoding) or mSENSE and rely on calibration data



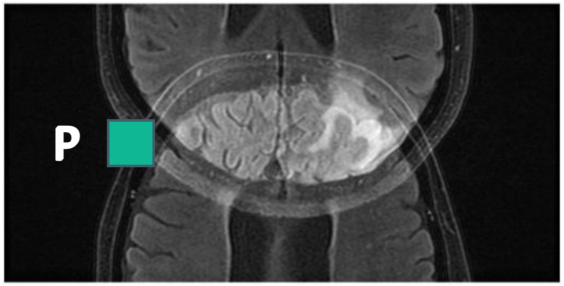
Generate coil sensitivity maps (low res image)

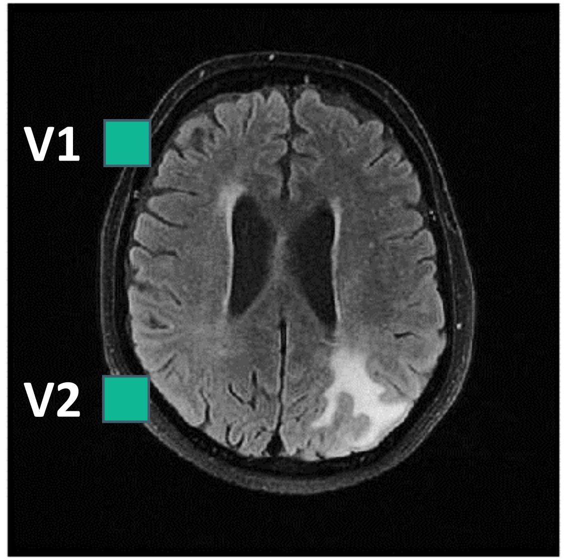
Unfold/Combine partial FOV images by matrix inversion

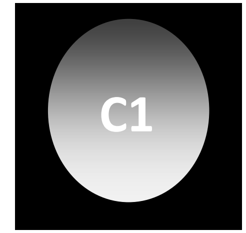


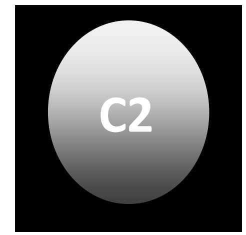
The sensitivity map determines the position of the signal based on its amplitude, where signal near the coil has a higher amplitude than farthest away. As a result, the image can be unwrapped and combined with the unwrapped images from each of the other coils.

SENSE









- This point (P) actually represents two voxels in real space, V_1 and V_2 that are superimposed. The coil sensitivities are C_1 and C_2. Therefore:

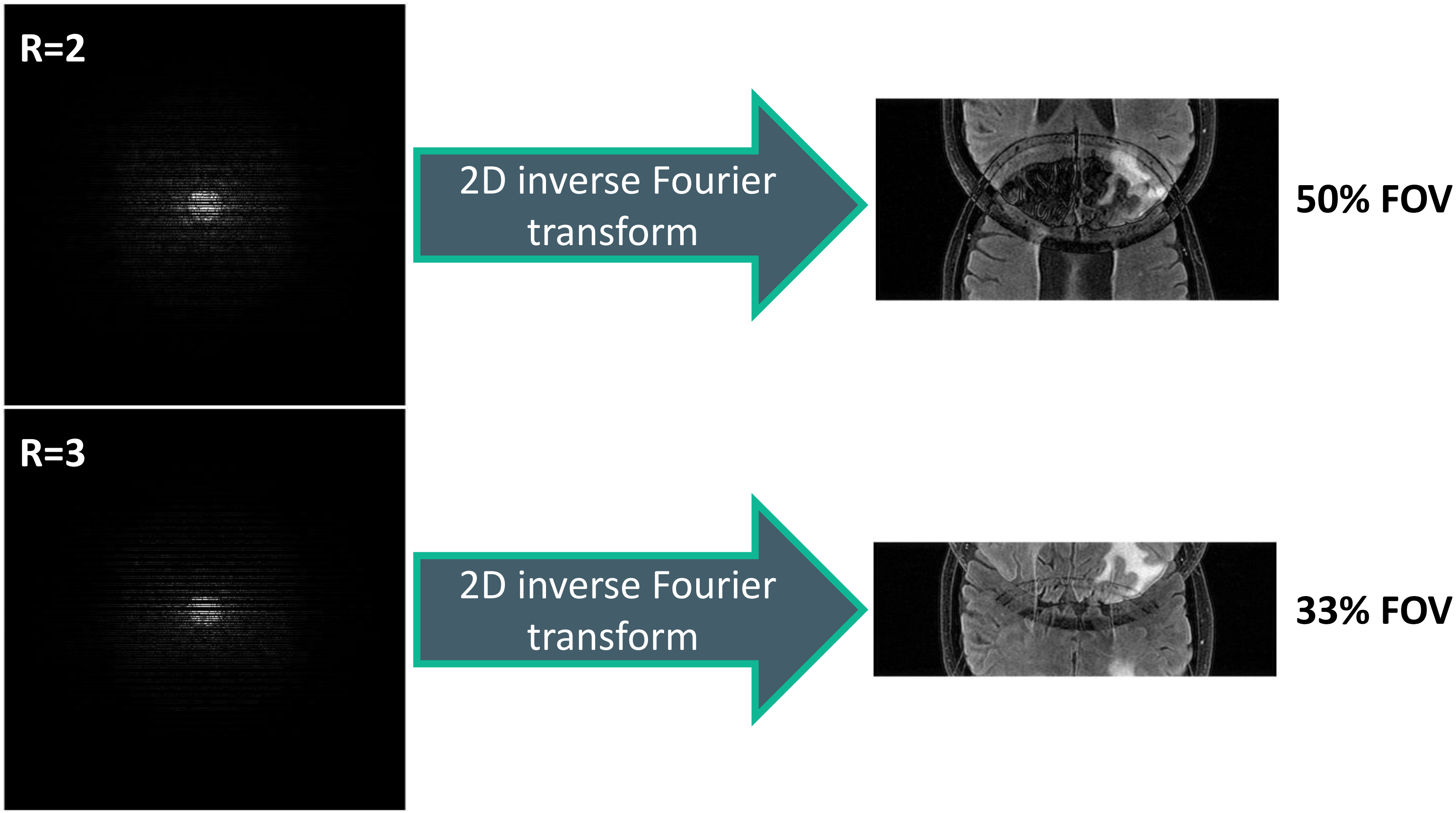
$$Signal_{1,P} = C_{1,V1} * Signal_{V1} + C_{1,V2} * Signal_{V2}$$
$$Signal_{2,P} = C_{2,V1} * Signal_{V1} + C_{2,V2} * Signal_{V2}$$

- The 2 signals can be calculated using simultaneous algebra. This works the same for any number of coils and acceleration factor, as long as $R \leq$ coils.

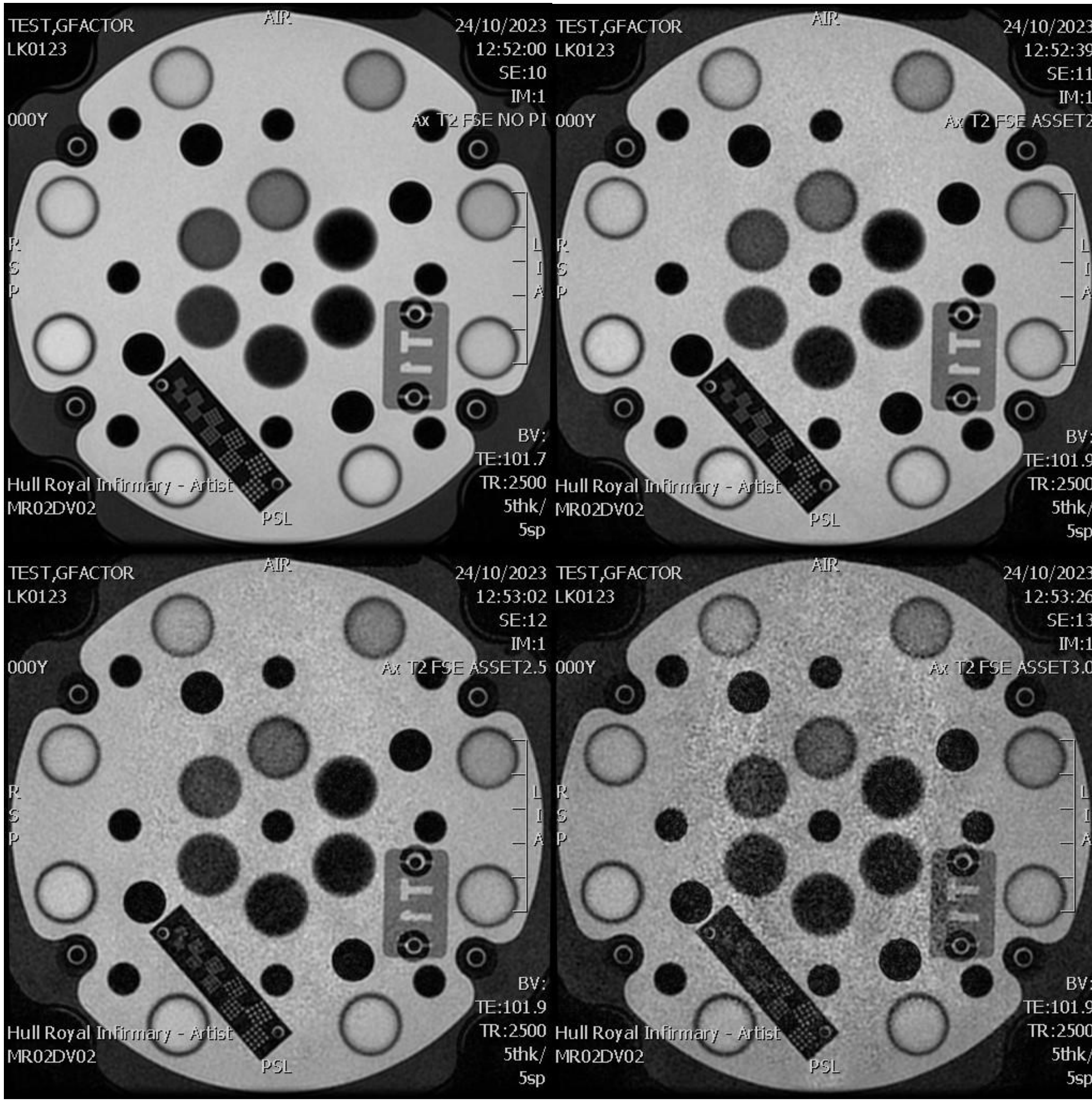
Hull University Teaching Hospitals NHS Trust

SENSE

Higher parallel imaging factors (R) are more likely to result in loss of SNR and increased image reconstruction artefacts.



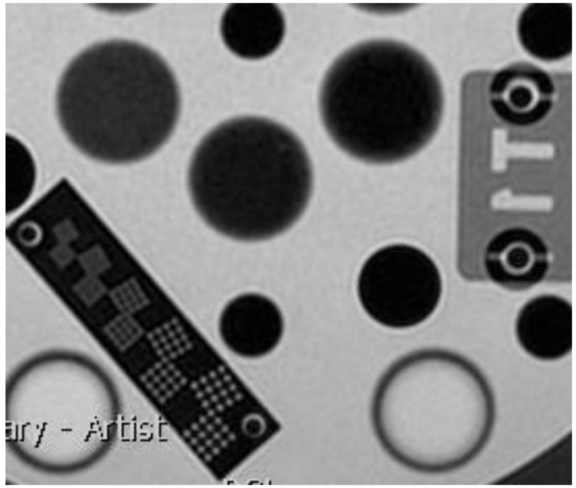
Parallel imaging

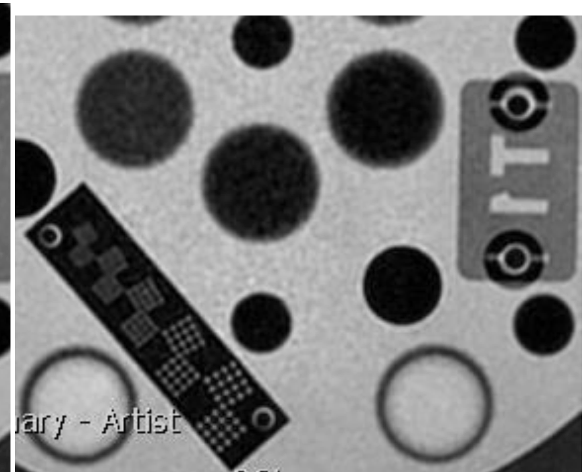


Parallel Imaging – SENSE/ASSET

ASSET/SENSE

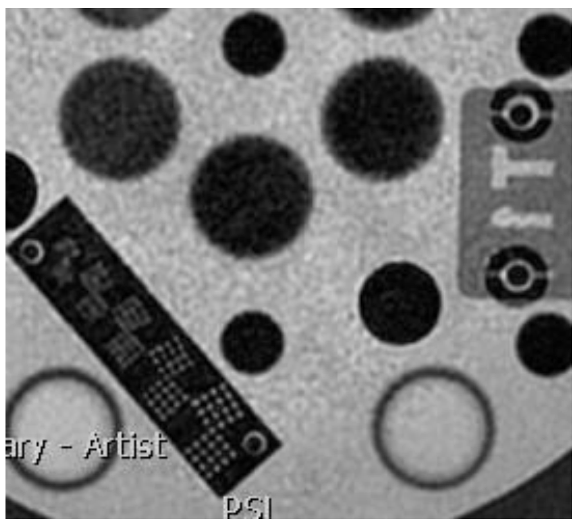
No parallel imaging acceleration

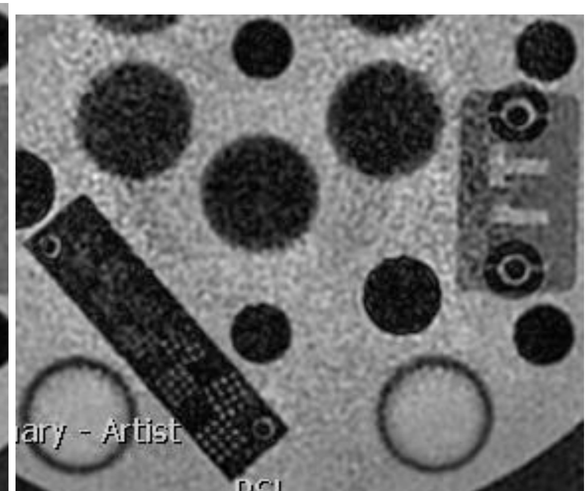




SENSE Parallel imaging factor = 2.0

SENSE Parallel imaging factor = 2.5





SENSE Parallel imaging factor = 3.0

GRAPPA/ARC

In SENSE/ASSET, coil sensitivities are used to unalias the data in the image domain after Fourier transformation.

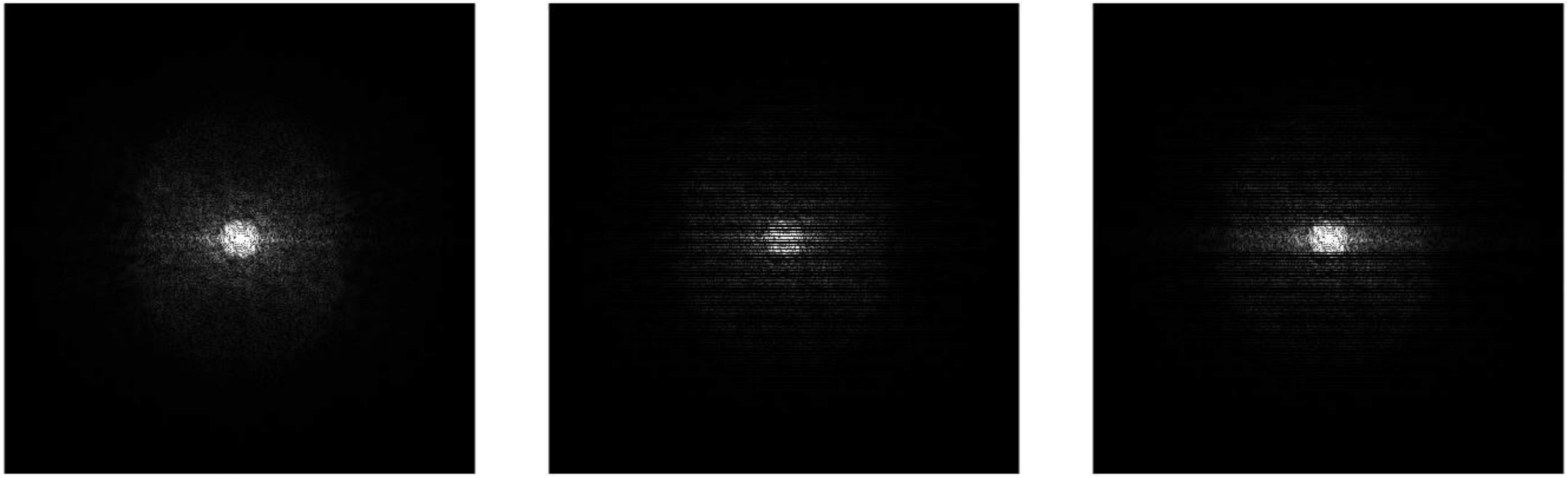
Main disadvantage to this approach is that if the patient moves (or breathes) between the low resolution calibration image and the high resolution data, reconstruction artefacts can manifest and obscure the anatomy of interest.

One solution is to acquire **both** the low resolution, full field of view scan *and* the high-resolution, reduced field of view (aliased) scan at the same time. This can actually be done by oversampling the centre of k-space during the accelerated scan.

In GRAPPA/ARC the correction is made in k-space prior to Fourier transformation

GRAPPA (**G**ene**R**alized **A**utocalibrating **P**artial **P**arallel **A**cquisition)
ARC (**A**utocalibrating **R**econstruction for **C**artesian imaging)

Integrated Calibration Scans



R=1 **R=2** **R=2 + Reference Lines**

By acquiring the central lines of k-space, the coil sensitivities can be mapped

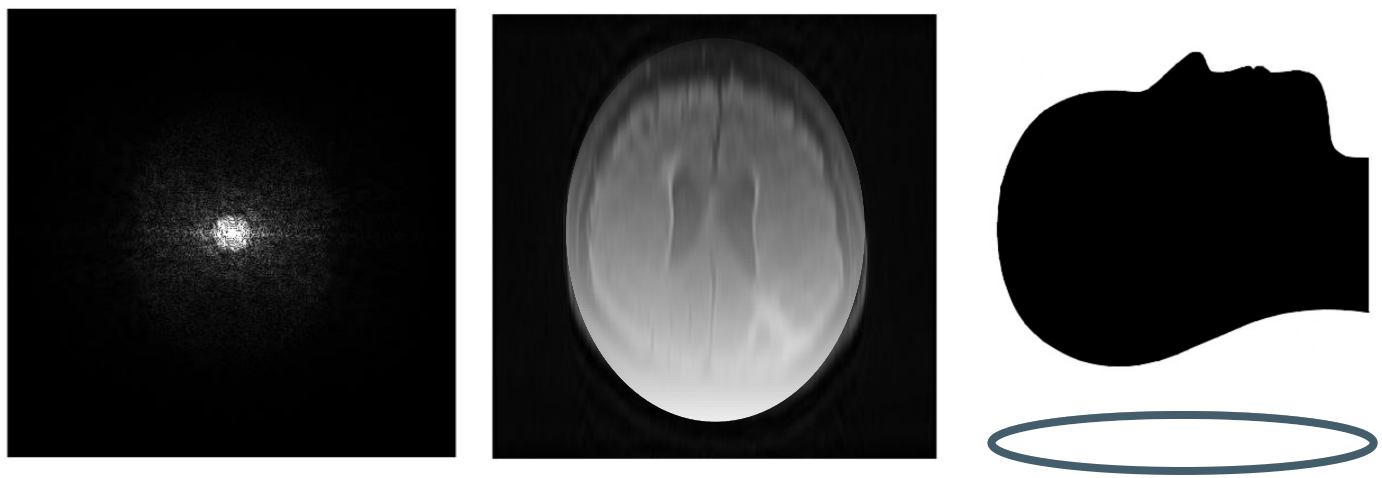
The outside lines of k-space will be skipped/spaced according to by R.

This is how ARC and GRAPPA work.

https://mriquestions.com/grappaarc.html

GRAPPA/ARC

Estimation of Missing Lines - Known data from the auto calibration signal (ACS) are used to calculate weighting factors for each coil. These weighting factors reflect how each coil distorts, smears, and displaces spatial frequencies within the full FOV k-space data.

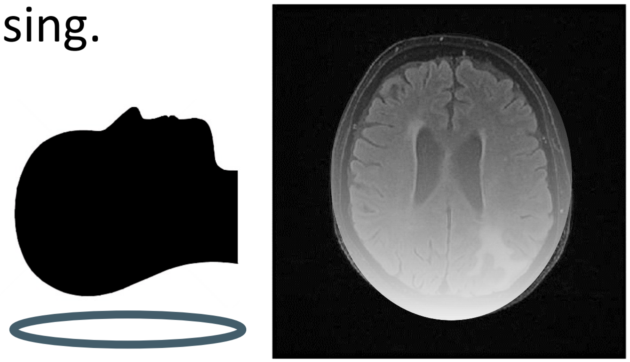


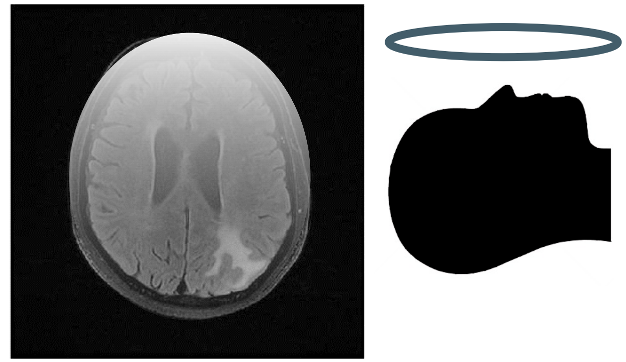
Missing k-space points are estimated in an iterative fashion using these global weighting factors combined with local known data for each small region (known a block or kernel). It should be noted that weighting factors and known data from all coils are used to estimate missing data for each coil.

Hull University Teaching Hospitals
NHS Trust

GRAPPA/ARC

Generate Individual Coil Images - With the missing lines of k-space now filled, Fourier transformation is performed to create individual images from each coil. Unlike the coil images in SENSE/ASSET, these GRAPPA/ARC images are free from aliasing.

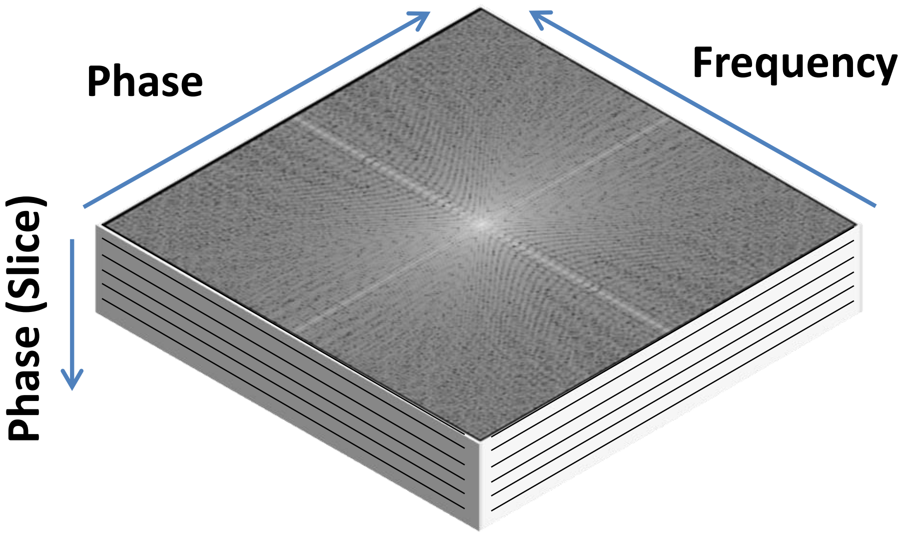


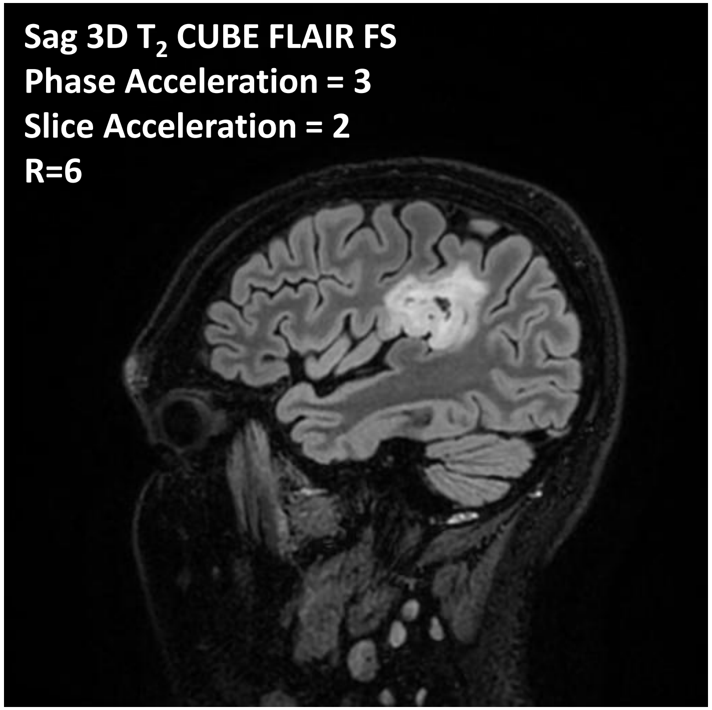


Coil Combine - The individual coil images are at last combined using a sum of squares method into the final magnitude image.

Parallel imaging

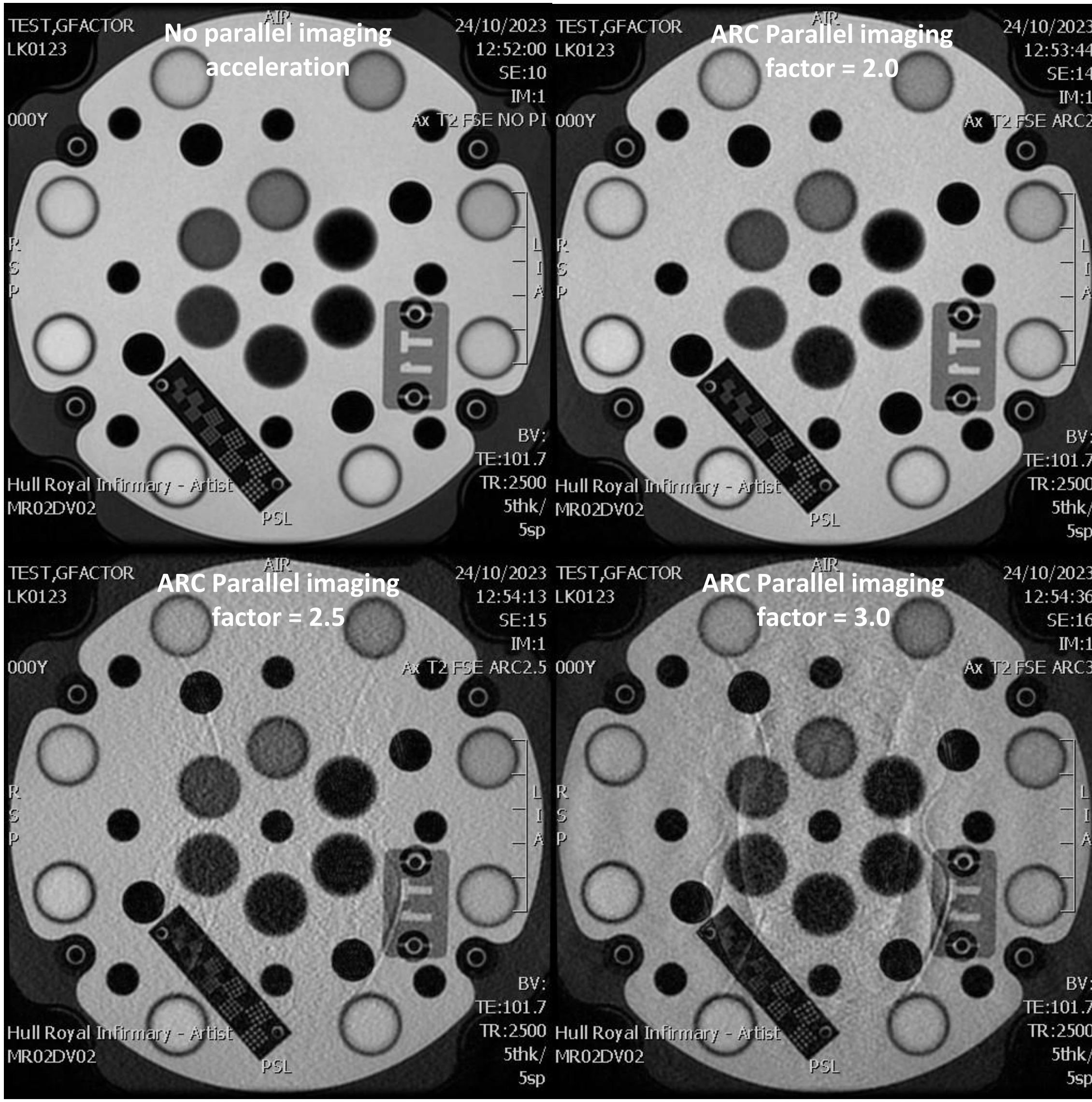
3D





- Since 3D sequences have 2 phase encoding directions, parallel imaging (ARC/GRAPPA) can also be applied in two directions depending on the number of slices, sequence and SNR

Parallel imaging

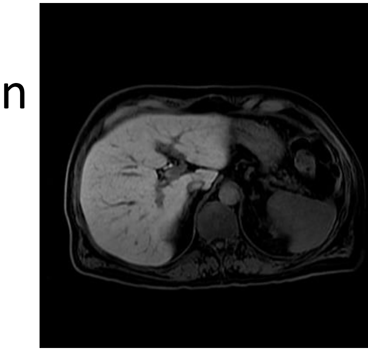


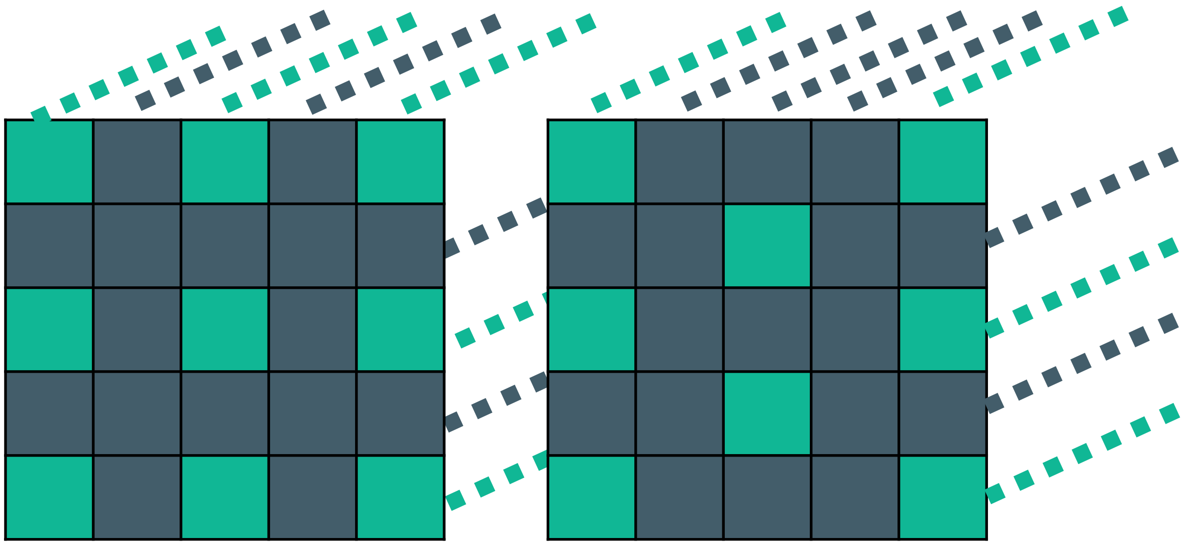
Parallel Imaging – GRAPPA/ARC

CAIPIRINHA

CAIPIRINHA is a parallel imaging technique offered by Siemens and used for 3D imaging (VIBE and SPACE). Different sampling scheme improves the accuracy of reconstruction while reducing noise and aliasing.

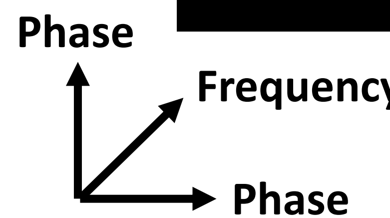
Controlled **A**liasing **i**n **P**arallel **I**maging **R**esults **i**n **H**igher **A**cceleration





Acceleration in two directions (R = 2 x 2 = 4)

CAIPIRINHA pattern with acceleration in two directions plus phase shift of alternate rows



AXIAL T1 VIBE DIXON TECHNIQUE caipi_W

https://mriquestions.com/caipirinha.html

NHS
Hull University
Teaching Hospitals
NHS Trust

Simultaneous Multislice (SMS) / Hyberband / Multiband

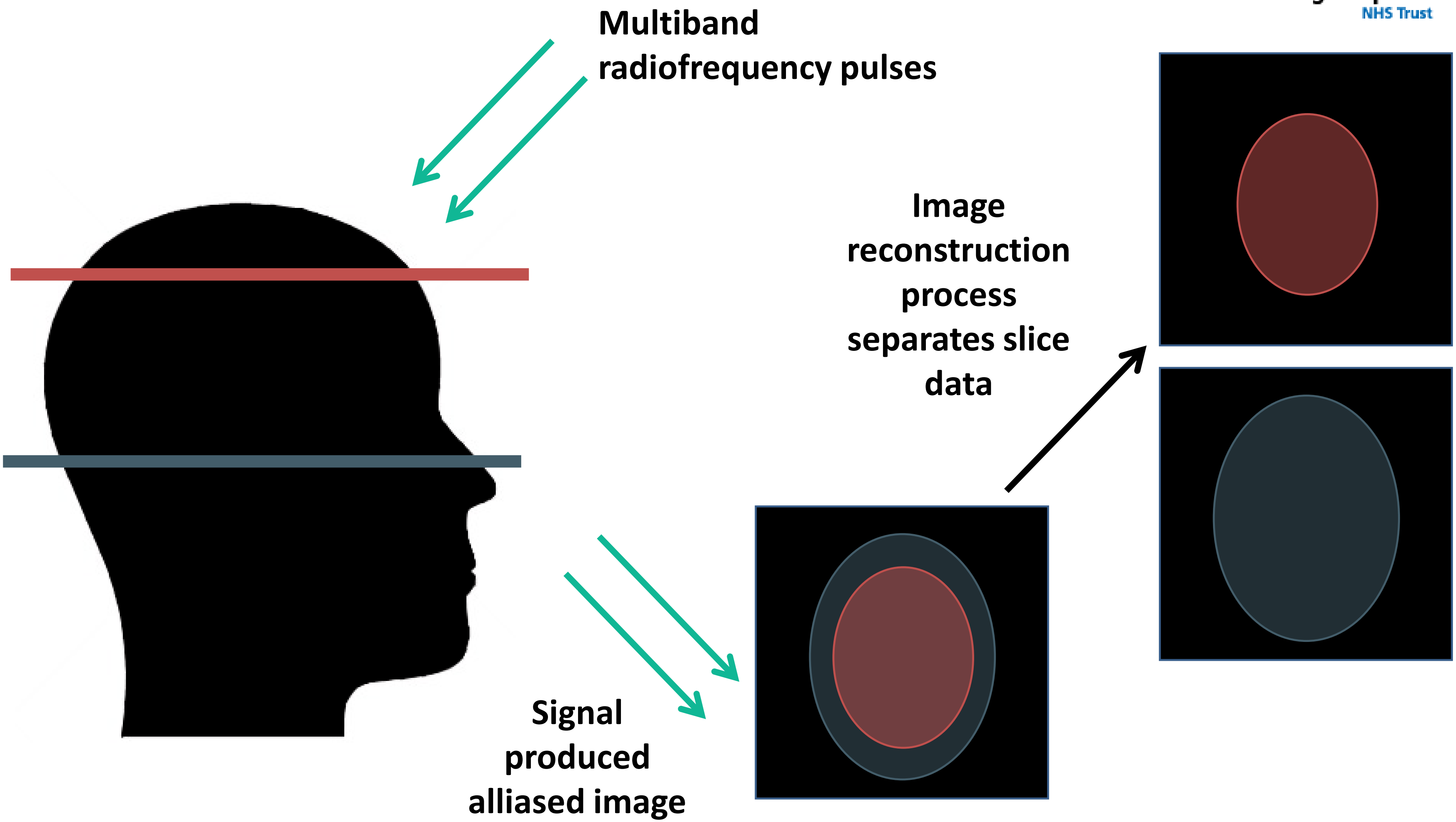
- SMS techniques exploit differences in coil sensitivity in the slice-encoding direction but are still reply on the same imaging principles as in-plane parallel imaging to unalias the data
- SMS techniques excite several slices concurrently using multiband radiofrequency pulses
- Analogous to the acceleration factor (R), the number of slices acquired simultaneously is called the multiband factor (MB)
- Multiband pulses consist of a sum of RF waveforms that are each centred on a different frequency band
- The composite pulse is applied along with a slice-select gradient to excite spins across multiple frequency bands and hence multiple slices

Hull University Teaching Hospitals NHS Trust

Simultaneous Multislice (SMS) / Hyberband / Multiband

- The main advantage of SMS techniques is scan time reduction which is especially important for lengthy acquisitions like diffusion tensor imaging (generally a reduction in TR)
- Depending on the vendor/platform, SMS is clinically available for 2D DWI/DTI/GRE-EPI and/or TSE/FSE
- The commercially available implementations use combine SMS with GRAPPA/ARC to produce a minimum of 4x acceleration (2x inplane & 2x through plane)
- If the multiband factor (MB) is too great for the coil and/or the number of slices is too low or the through-plane coverage is too small, through-plane aliasing artefacts will occur

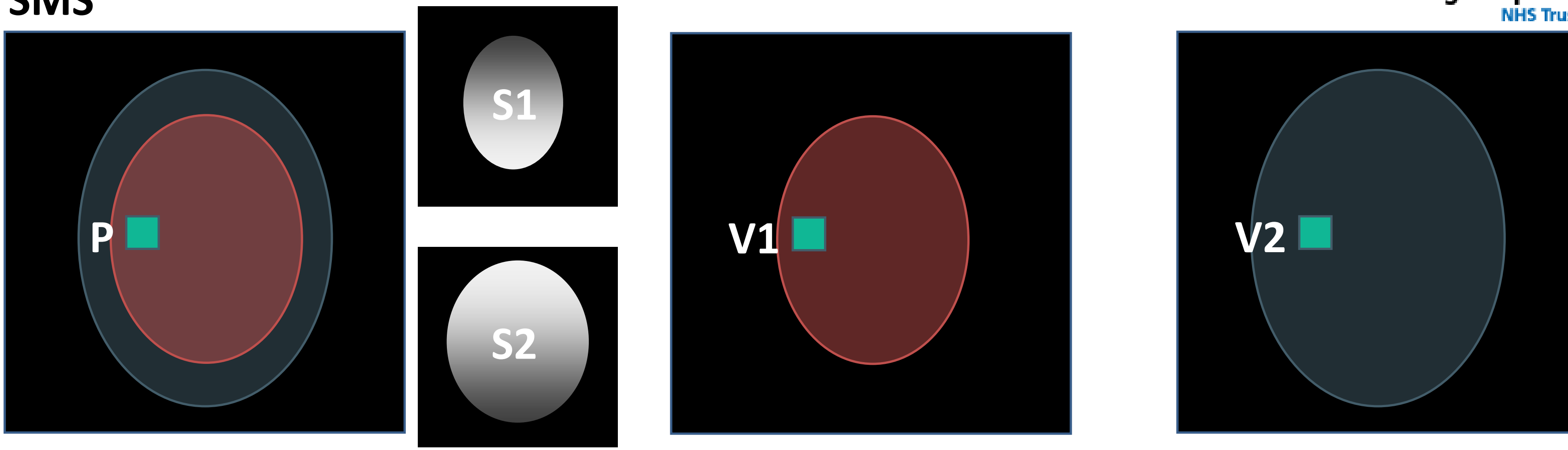
Simultaneous multislice (multiband)



*Simplified version without phase offset

Simultaneous multislice (multiband)

SMS



- This point (P) actually represents two voxels in real space, V_1 and V_2 that are superimposed. The coil sensitivities for different slices are S_1 and S_2. Therefore:

$$Signal_{1,\,P} = S_{1,\,V1} * Signal_{V1} + S_{1,\,V2} * Signal_{V2}$$
$$Signal_{2,\,P} = S_{2,\,V1} * Signal_{V1} + S_{2,\,V2} * Signal_{V2}$$

- The 2 signals/slices can be separated using simultaneous algebra but only if the coil has a high geometry factor, *g* and suitable through-plane coverage.

*Simplified version without phase offset

Simultaneous multislice (multiband)

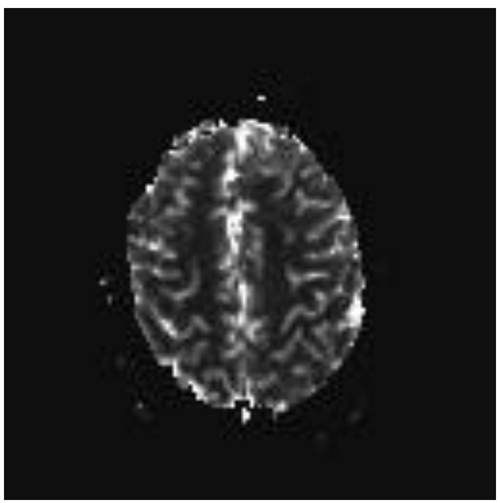
Hull University Teaching Hospitals NHS Trust

Simultaneous Multislice Acceleration (SMS) / Hyperband (HB)

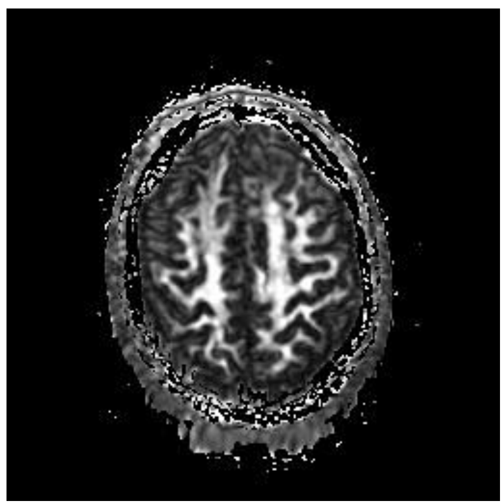
The available implementations of SMS depends on the vendor.

t2_tse_tra_416 sms_p2

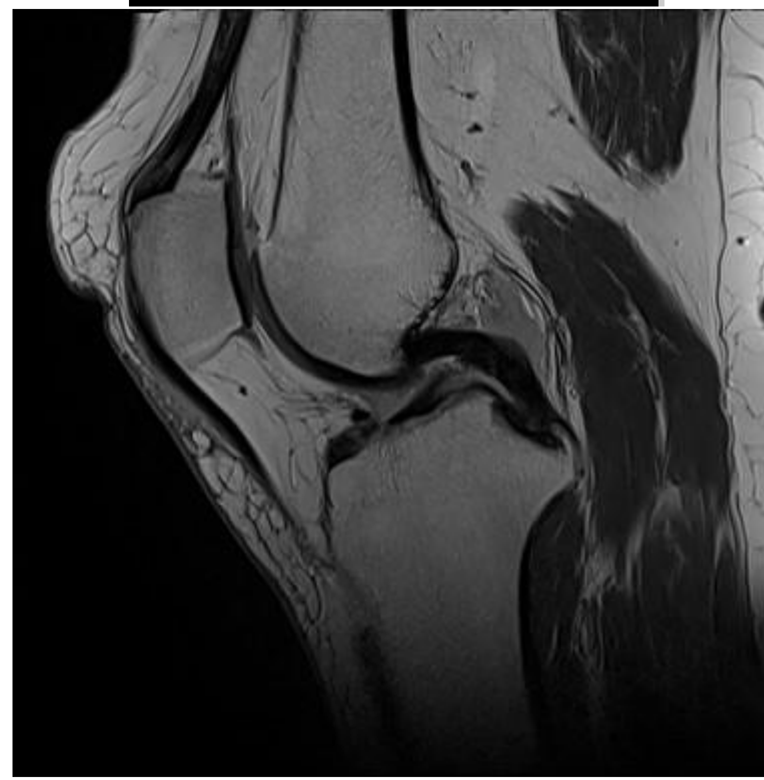
Ax EPI-GRE DSC HB2



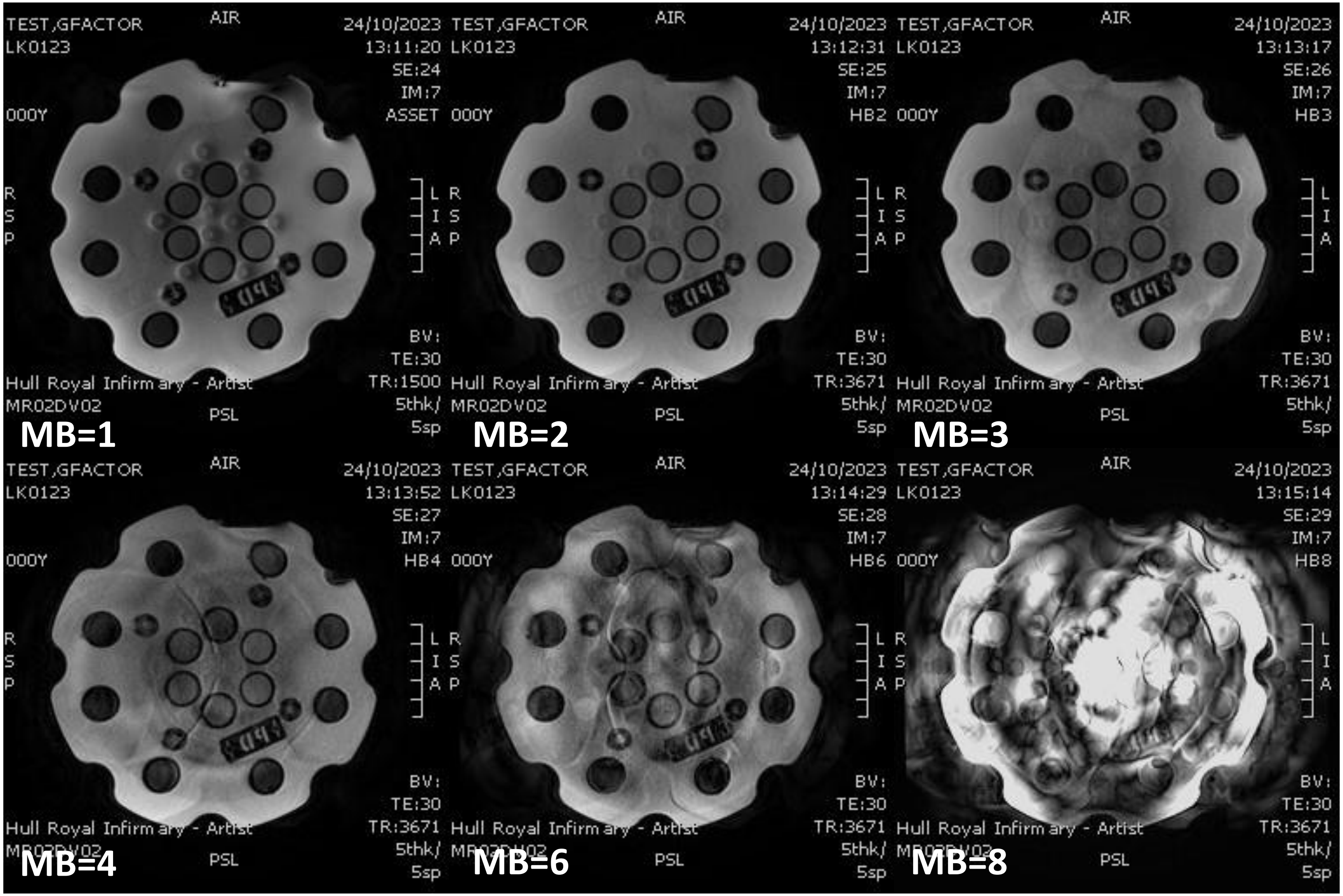
Ax DTI HB2



pd_tse_sag SMS



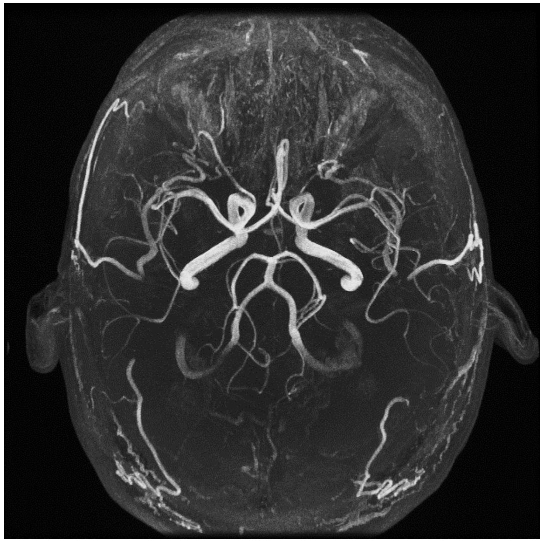
Simultaneous multislice (multiband)



Hull University Teaching Hospitals NHS Trust

Compressed Sensing (CS)

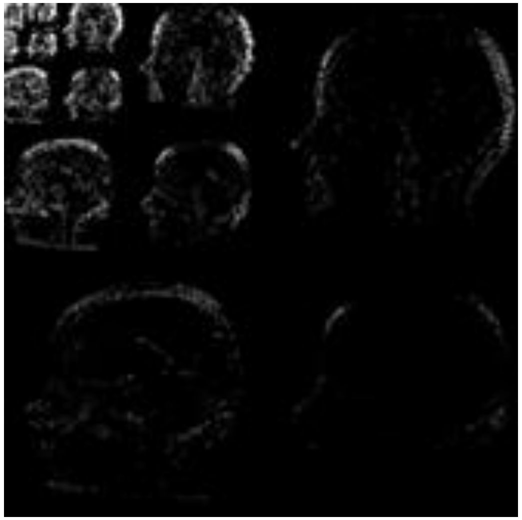
- CS is a signal processing technique based on the fact that signals contain redundant information and can be 'compressed'
- This concept has existed in digital photography for sometime. i.e. to ability to shrink large files (.raw) using image compression techniques such as .jpeg
- If image compression without loss of detail is possible in photography, can the same concept be applied to MR? If so, can it be reserve engineered so to create an image without all of k-space?
- If less data is required, the acquisition can be sped up and/or higher matrix sizes acquired



Sparse data in image domain

Compressed SENSE Speed done right. Every time.
Liesbeth Geerts-Ossevoort, et al.

- In general, compressed sensing can be exploited in clinical practice under the following four conditions:
  - The under-sampling pattern of k-space needs to promote **noise-like incoherent artefacts**
  - The data needs to be **sparse** either directly or in a transform domain
  - **Combination with current parallel imaging** technology to leverage further acceleration on phased array coils
  - An **iterative reconstruction** implementation that balances data consistency and sparsity needs to be present

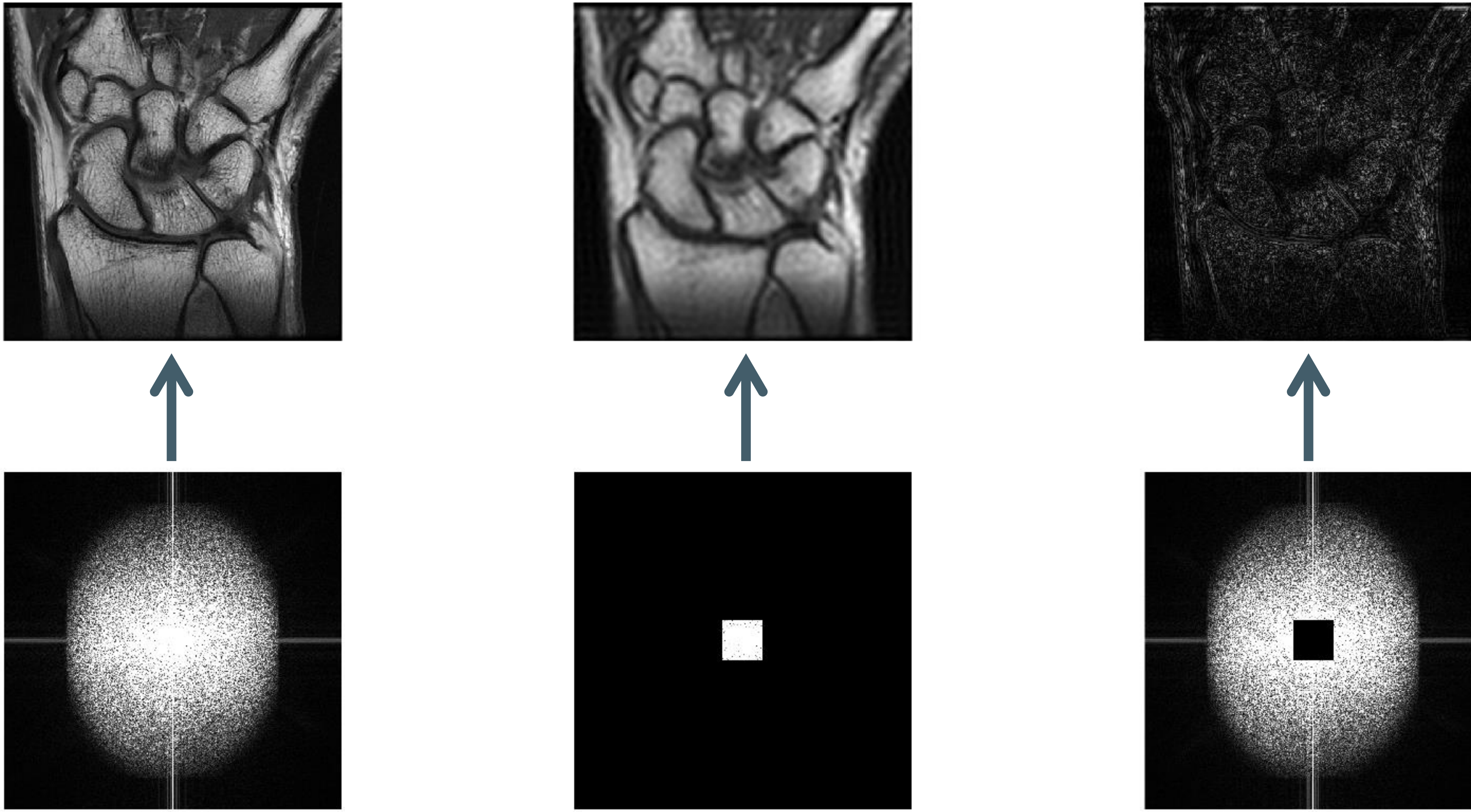


Sparse data in transform (wavelet) domain

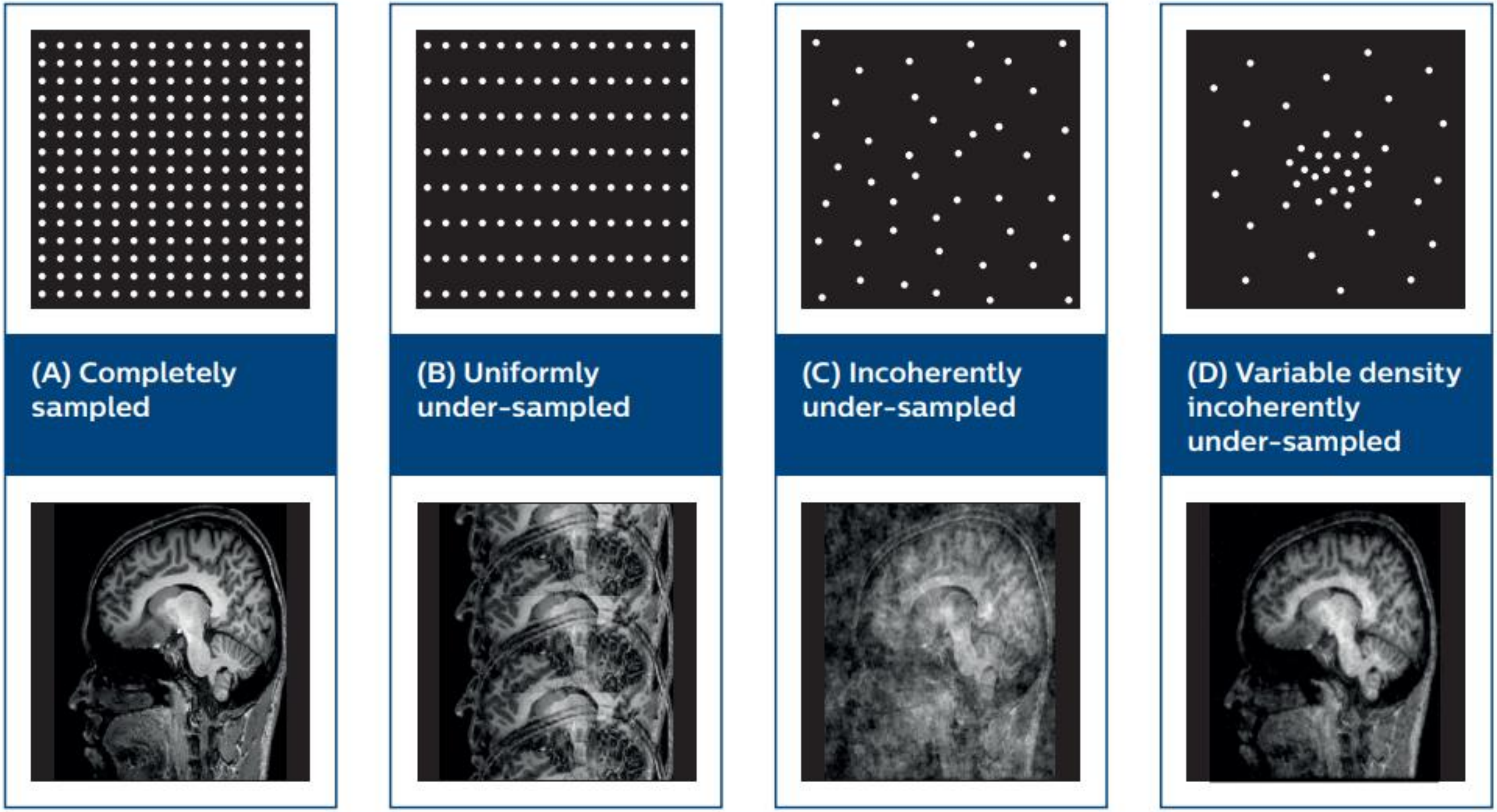
Compressed Sensing

Hull University Teaching Hospitals NHS Trust

k-space



Compressed Sensing

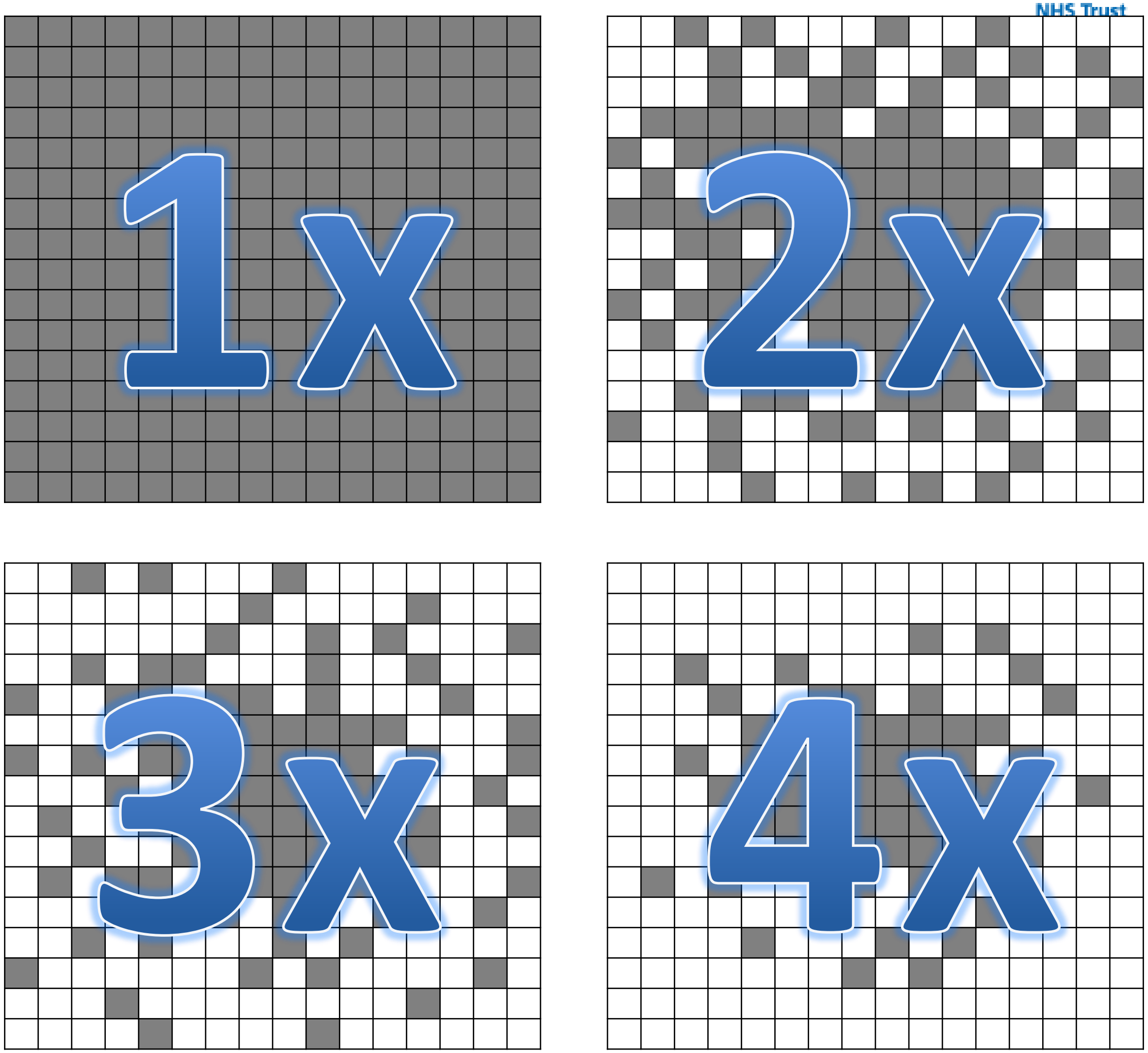


Compressed SENSE Speed done right. Every time.
Liesbeth Geerts-Ossevoort, et al.

Compressed Sensing

NHS
Hull University
Teaching Hospitals
NHS Trust

- Pseudo-random undersampling for compressed sensing in MR
- Offline iterative reconstruction methods to fill in k-space
- Advantages:
    - improves SNR
    - reduce scan time
    - reduce energy deposited into the patient
- Aim is to reconstruct the spatial information



Hull University Teaching Hospitals NHS Trust

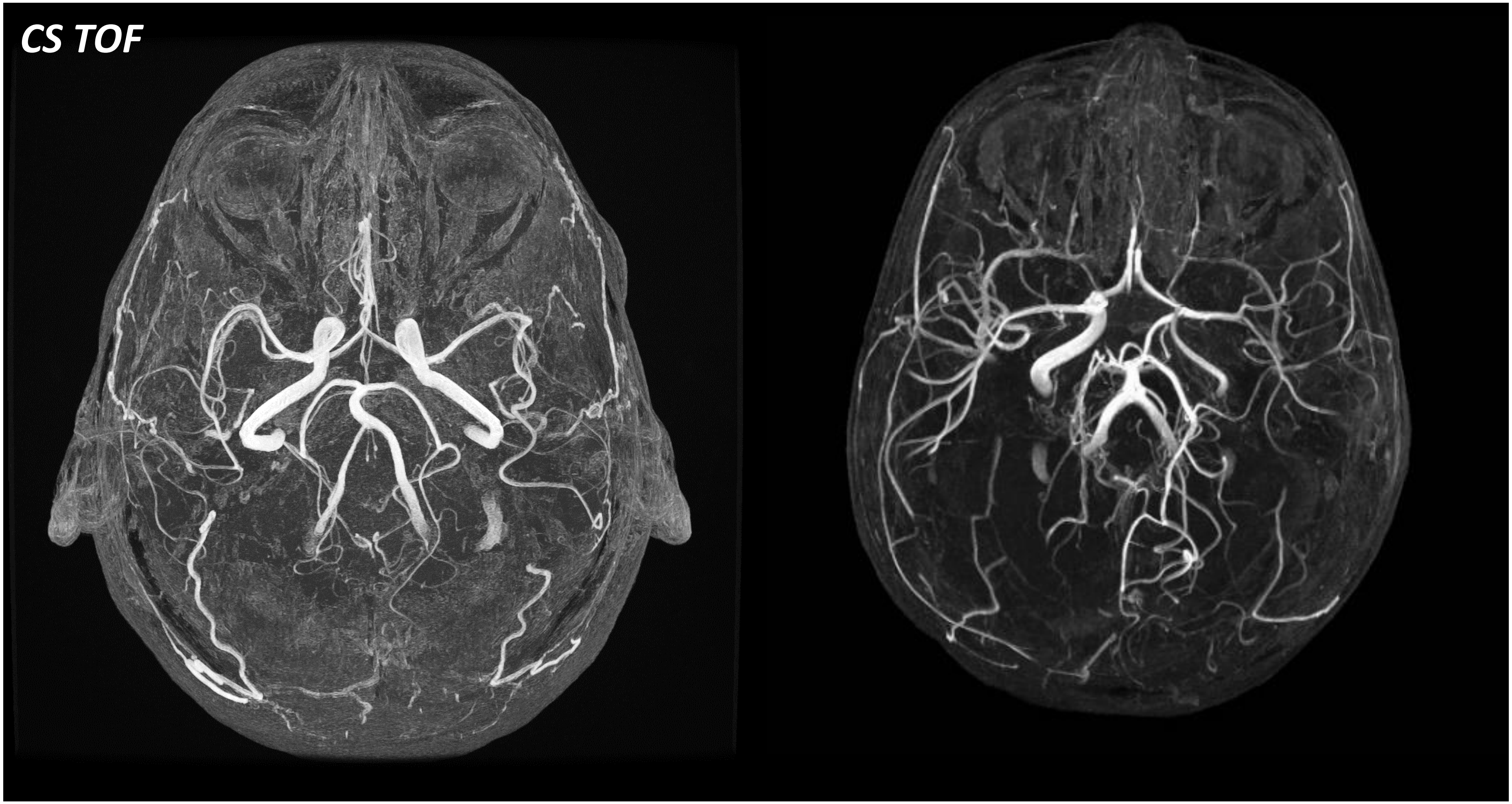
Iterative Reconstruction

CS involves multiple steps and data transformations to denoise the image:

1. **Fourier transform** of k-space to create an initial image. The initial image will be very crude, suffering from diffuse aliasing artefacts manifest as "noise".
2. Apply a **sparsifying transform (wavelet transform)** that will concentrate meaningful imaging characteristics into a smaller number of high-intensity pixels. The aliasing "noise" will now be of lower intensity and distributed over many pixels, most in the background.
3. Remove aliasing ("denoise") the sparsified data by zeroing out pixels with values below a minimum threshold, digital filtering, and/or subtraction.
4. Apply **inverse sparsifying and Fourier transforms** to reconvert this "denoised" data back into k-space format.
5. Create a k-space "difference matrix" by subtracting the original from the denoised k-space data and setting all other points to zero. By **Fourier transformation**, a "difference image" can then be created. Add the initial and difference images together to create an "updated image".
6. Compare the initial and updated images. If significant disparity is present, repeat Steps 2-6. Otherwise Stop.

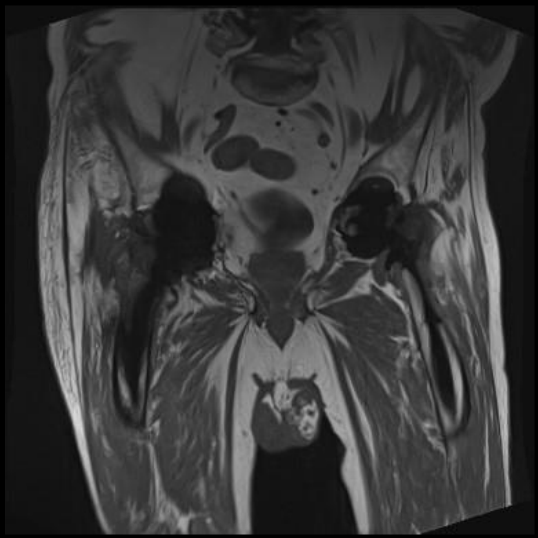
Compressed Sensing

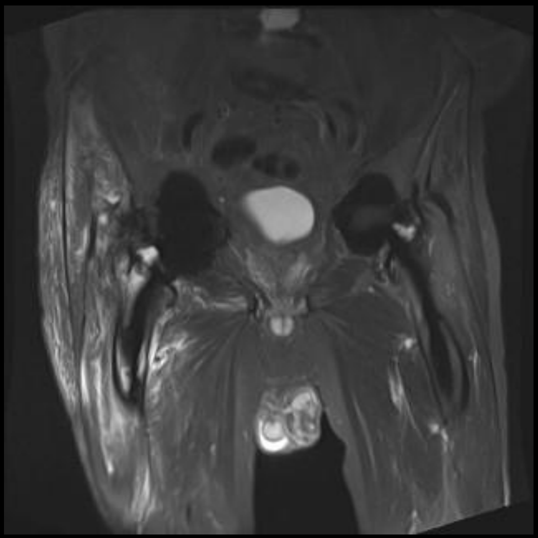
Hull University Teaching Hospitals NHS Trust

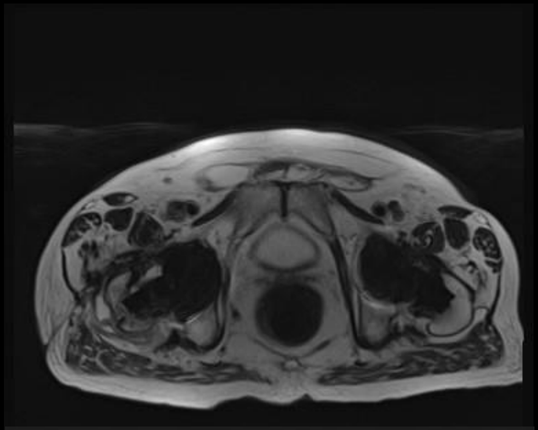


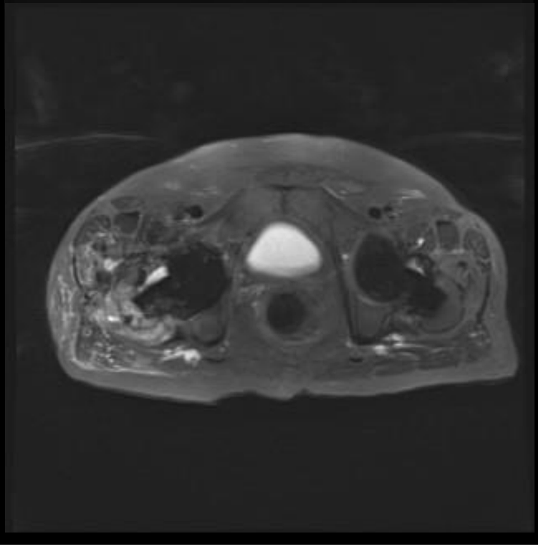
Hull University Teaching Hospitals NHS Trust

CS SEMAC







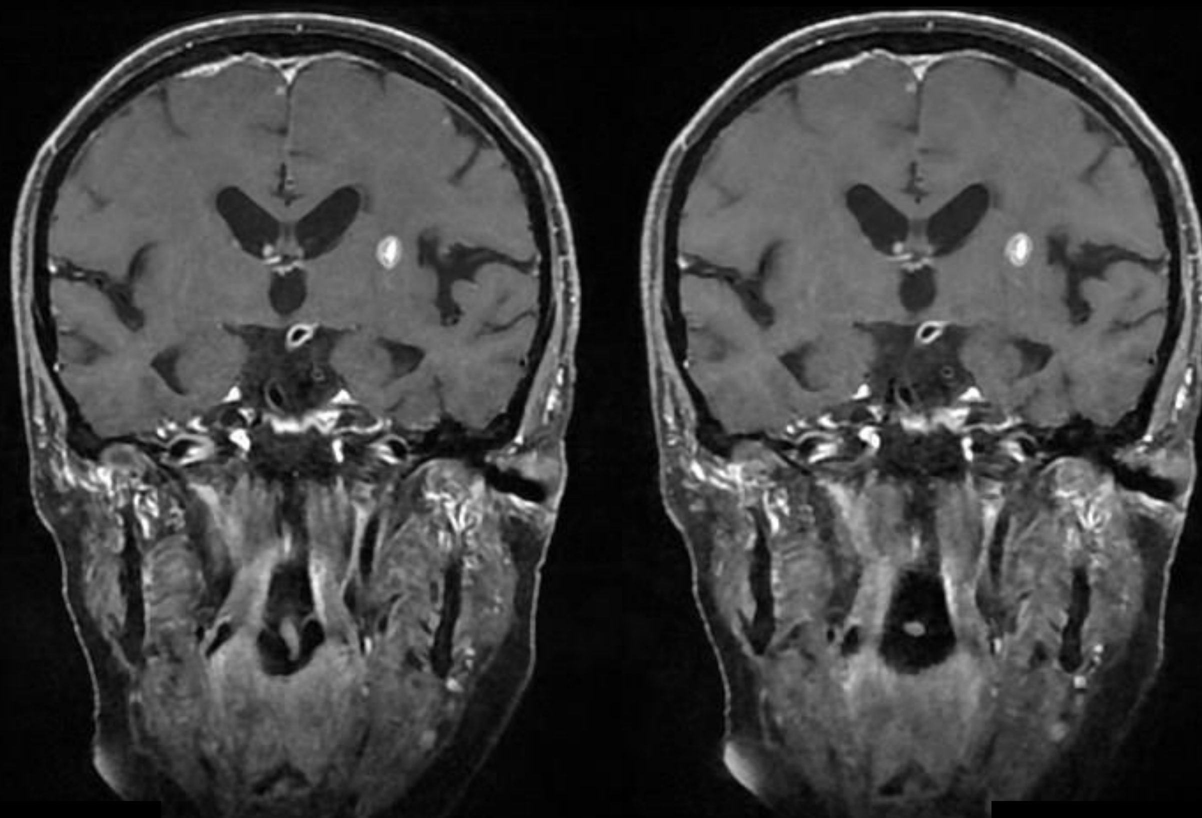


t2_tse_stir_cor_semac_cs8

3D T_1 FSE FS +C

FOV = 24cm
Matrix = 320x320
Phase FOV = 0.8
TR/TE = 602/14.4
ARC = 2 x 2
SL Thick = 0.6/0mm

Hypersense Factor = 1.6 (R = 6.4)



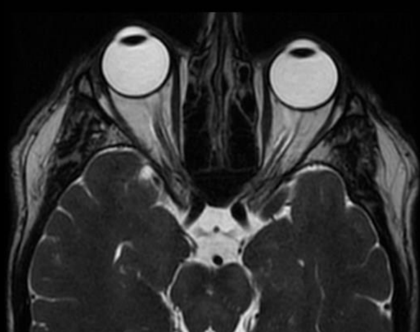
Scan Time = 3:35

Scan Time = 2:17

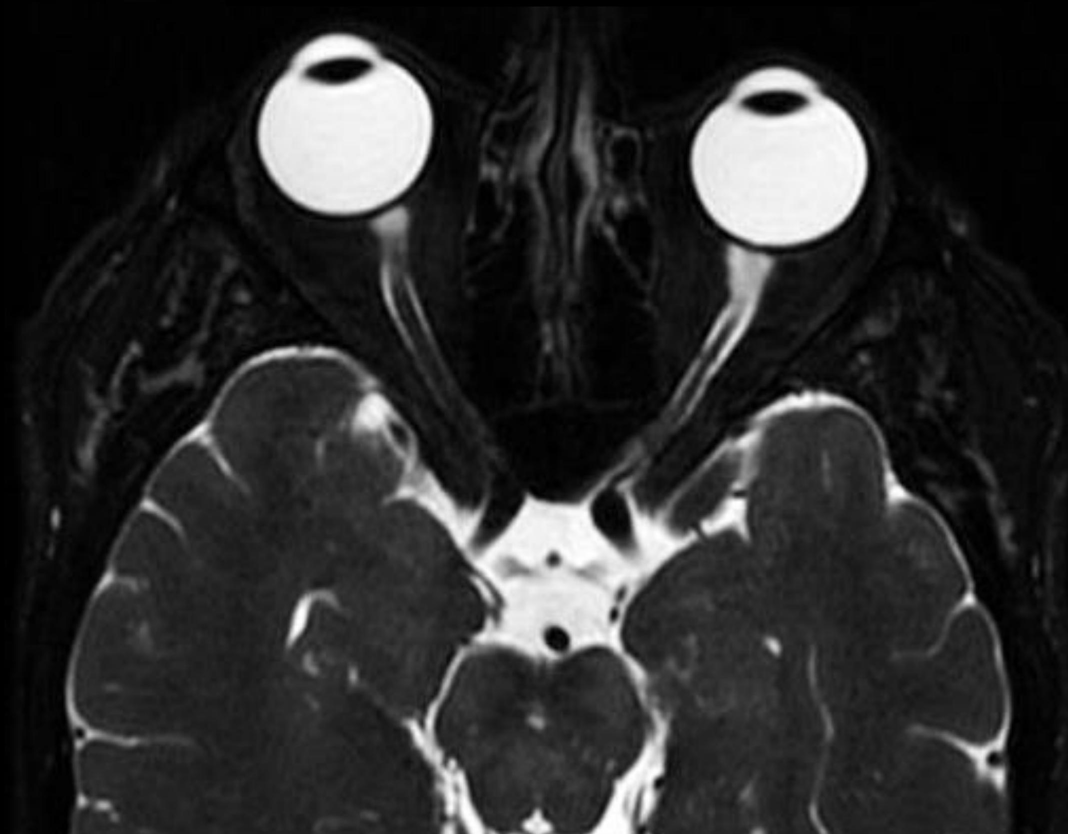
Compressed Sensing

rFOV 3D T_2 FSE DIXON

FOV = 15cm
Matrix = 240x212
Phase FOV = 0.8
TR/TE = 2502/148ms
ARC = 2, CS=1.2
SL Thick= 0.6/0mm
Scan Time = 4:44



Hypersense Factor = 1.2 (R = 2.4)

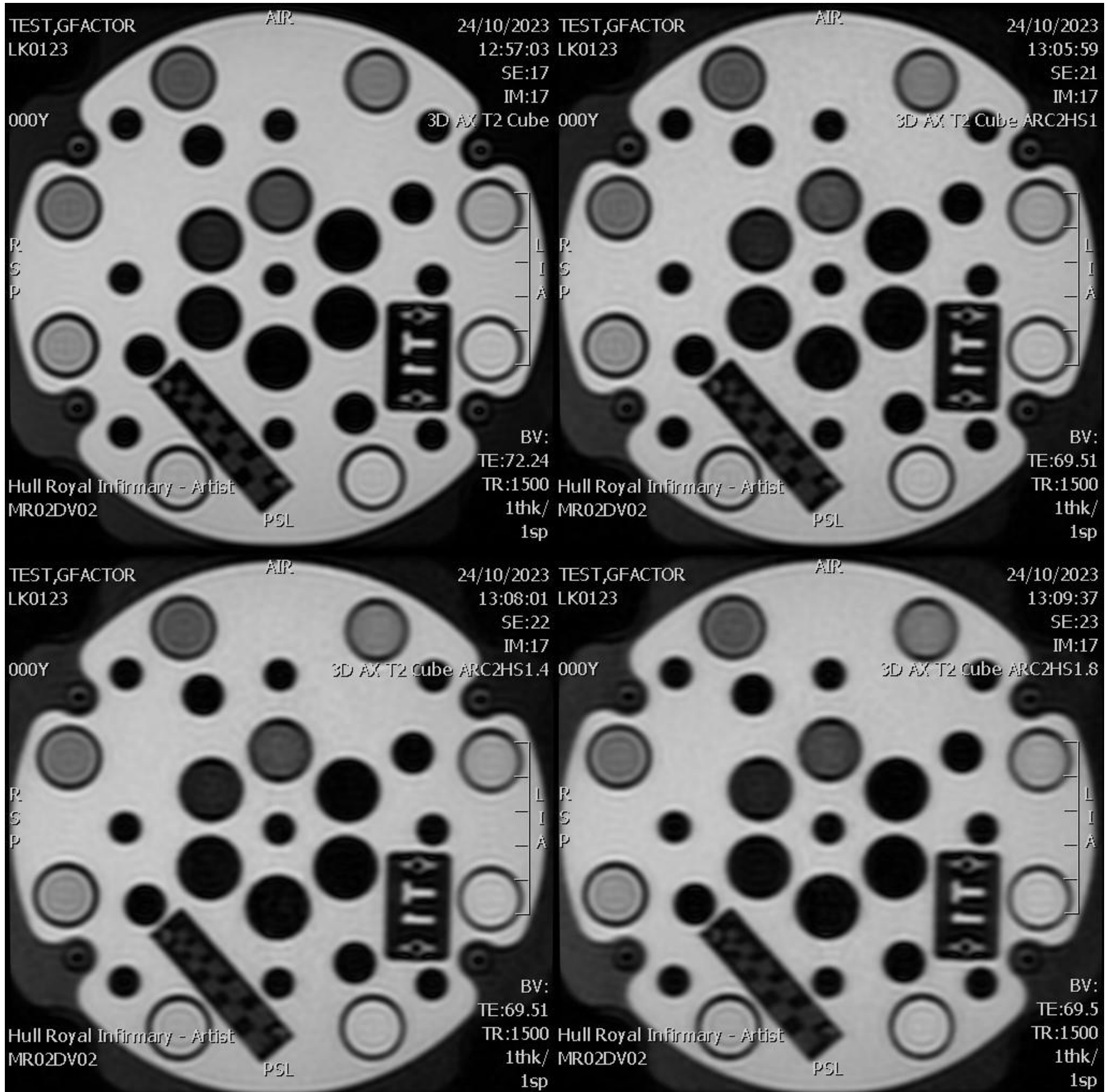


Compressed Sensing

NHS
Hull University Teaching Hospitals NHS Trust

No parallel imaging acceleration

ARC Parallel imaging factor = 2.0 Compressed Sense factor = 1.0



ARC Parallel imaging factor = 2.0 Compressed Sense factor = 1.4

ARC Parallel imaging factor = 2.0 Compressed Sense factor = 1.8

CS Summary

- Pseudo-random under-sampling of k-space
- Iterative reconstruction methods to fill in k-space
- Performs better on high contrast, high SNR, 3D acquisitions
- Advantages:
  - improves SNR (denoising)
  - reduce scan time (less phase encodings)
  - reduce energy deposited into the patient (reduced number of RF pulses)
- Aim is to reconstruct the spatial information

Contrast Enhanced (CE) MRA: Time-resolved MRA

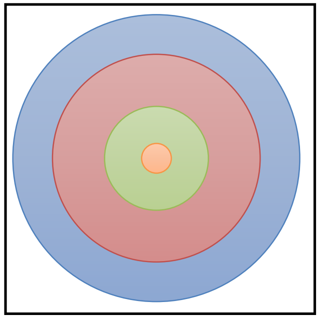
- Time-resolved MRA sequences, known under acronyms such as TRICKS and TWIST, obtain a series of images displaying passage of the contrast bolus
- Typical time-resolved MRA study temporal resolution =1-2 seconds
- An inherent trade-off exists between spatial and temporal resolution
- The centre of k-space contains information about basic image contrast, while edges and details are encoded in the k-space periphery
- Increasing spatial resolution requires that more k-space points be sampled. However, sampling more points requires additional imaging time, adversely impacts temporal resolution.

Contrast Enhanced (CE) MRA: Time-resolved MRA

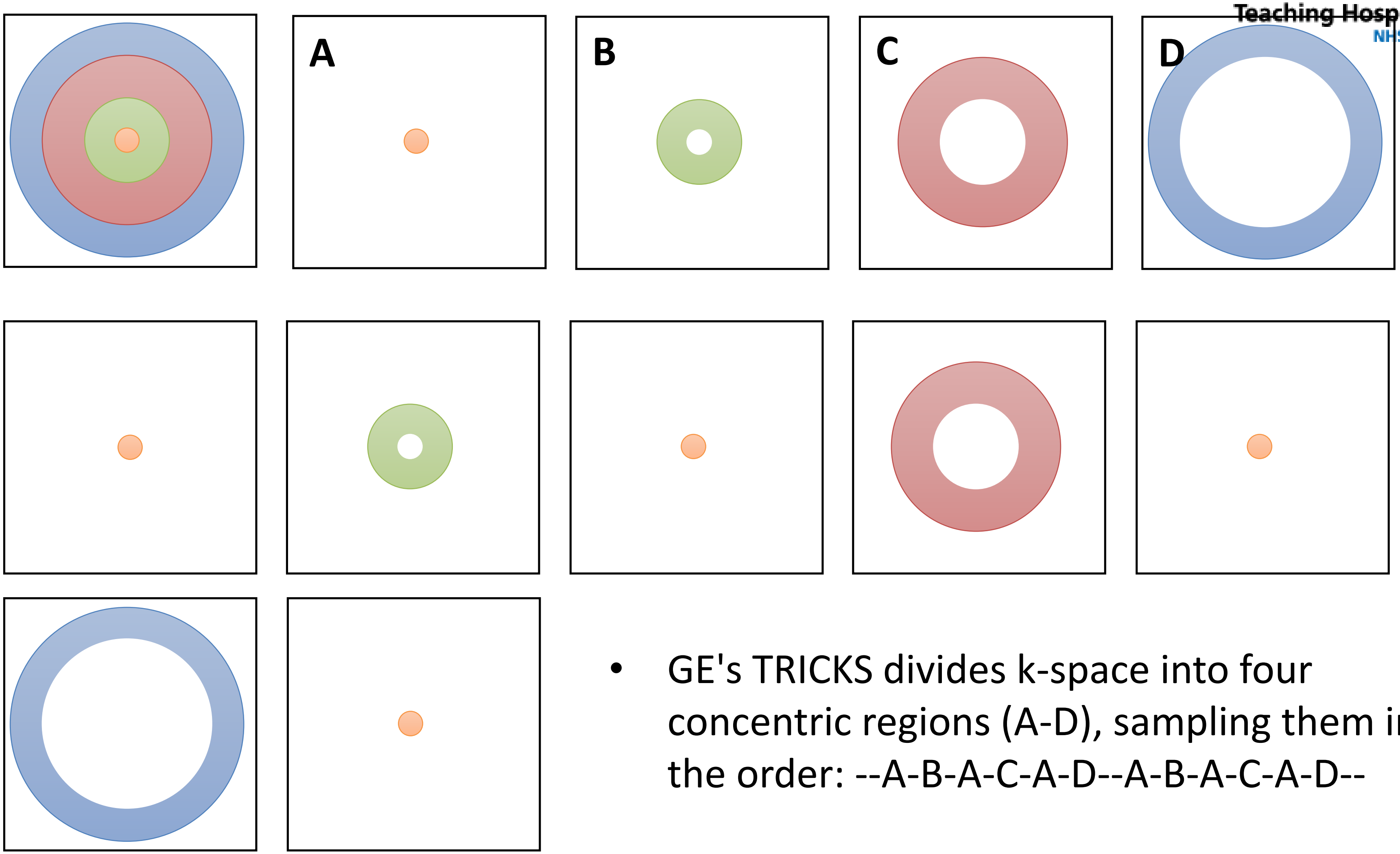
- Time-resolved MRA techniques balance these competing resolution requirements through a process known as view-sharing
- Although the details of these methods vary, all begin by acquiring a non-contrast, full-resolution image (all of k-space) of the area of interest
- During passage of the contrast bolus, the centre of k-space is sampled more frequently than the periphery, which is updated only periodically
- The data from the different partial k-space samplings are combined to create a series of time-resolved images with satisfactory spatial resolution.
- The original non-contrast image can be used as a mask for subtraction to improve vascular conspicuity.

Contrast Enhanced (CE) MRA

- Time Resolved Imaging of Contrast KineticS (TRICKS) technology provides MR Angiography imaging with excellent spatial and temporal resolution.
- An intricate temporal sampling and complex data recombination helps accelerate the temporal domain of 3D dynamic imaging – without compromising spatial resolution.
- An elliptical-centric data sampling helps further increase efficiency.
- Easy to set up, TRICKS rapidly generates time resolved 3D images of blood vessels to meet the challenge of capturing peak arterial phases with minimal venous contamination.

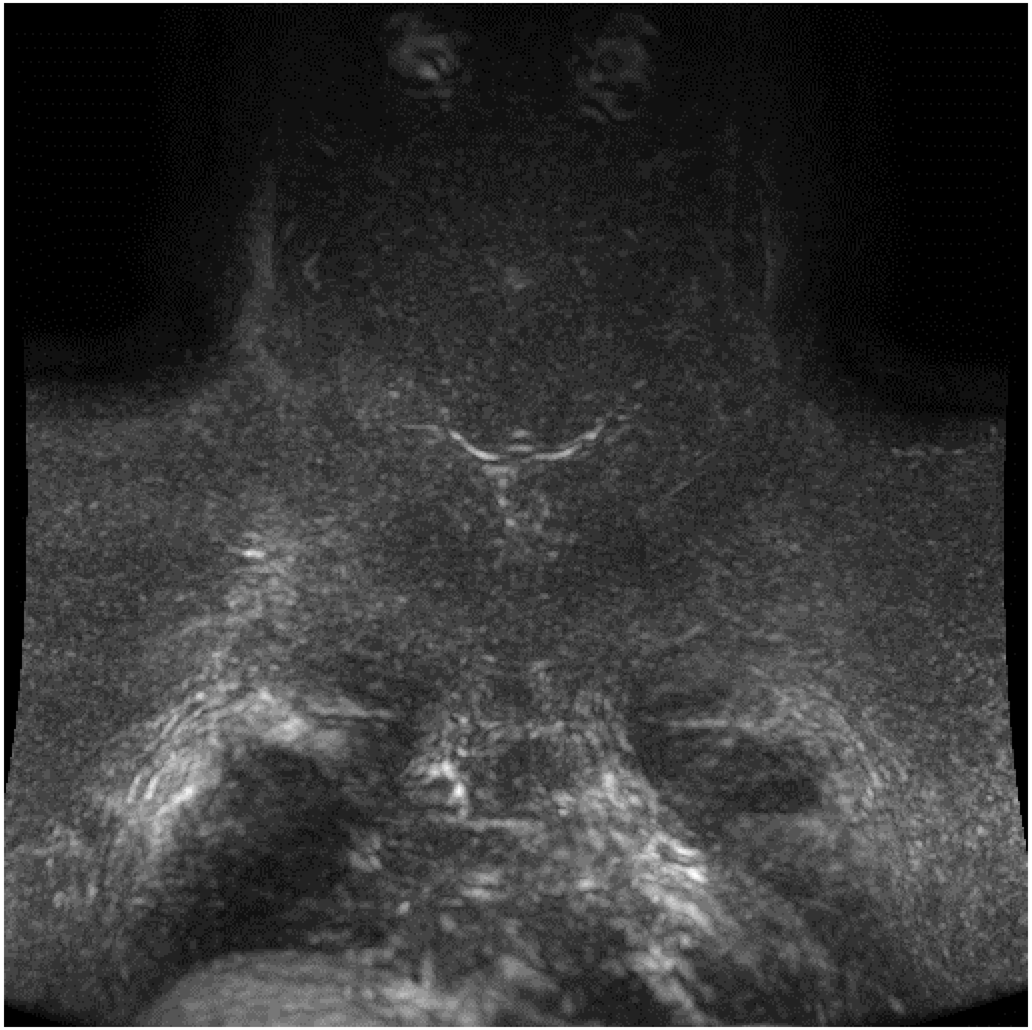


Temporal sharing (TWIST/TRICKS)



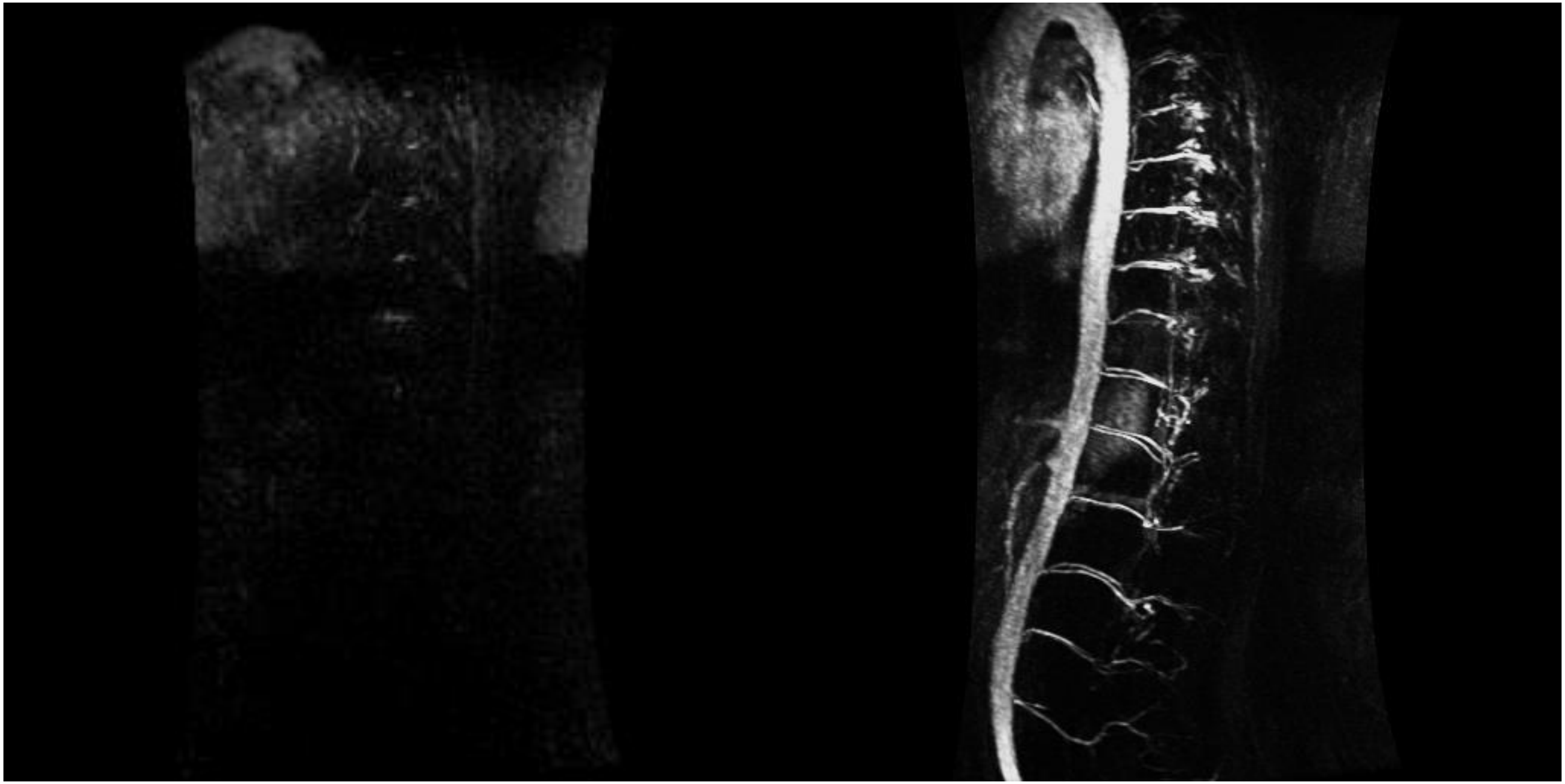
- GE's TRICKS divides k-space into four concentric regions (A-D), sampling them in the order: --A-B-A-C-A-D--A-B-A-C-A-D--

Time Resolved MRA



Temporal sharing (TWIST/TRICKS)

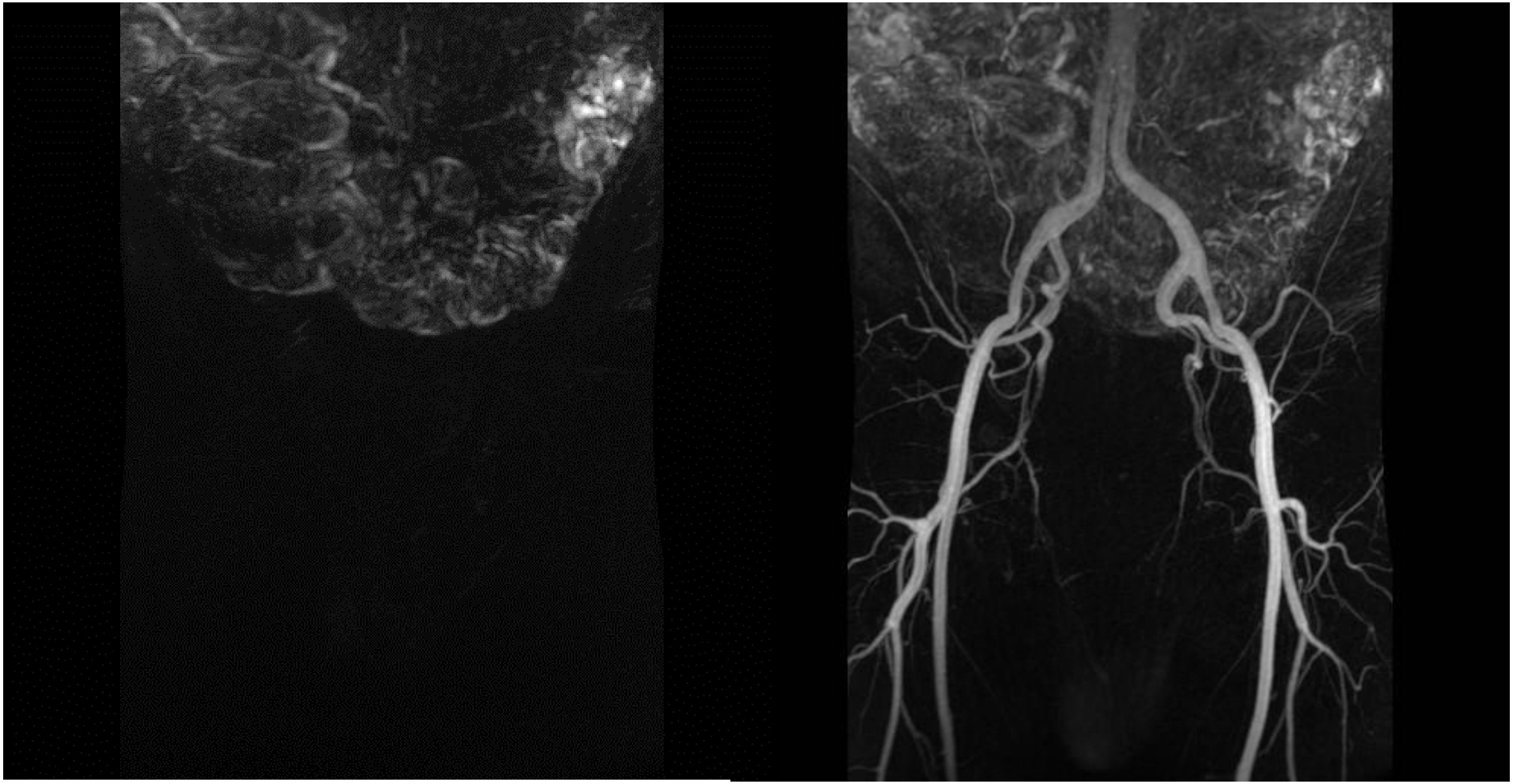
Time Resolved MRA



Temporal sharing (TWIST/TRICKS)

NHS
Hull University Teaching Hospitals
NHS Trust

Time Resolved MRA



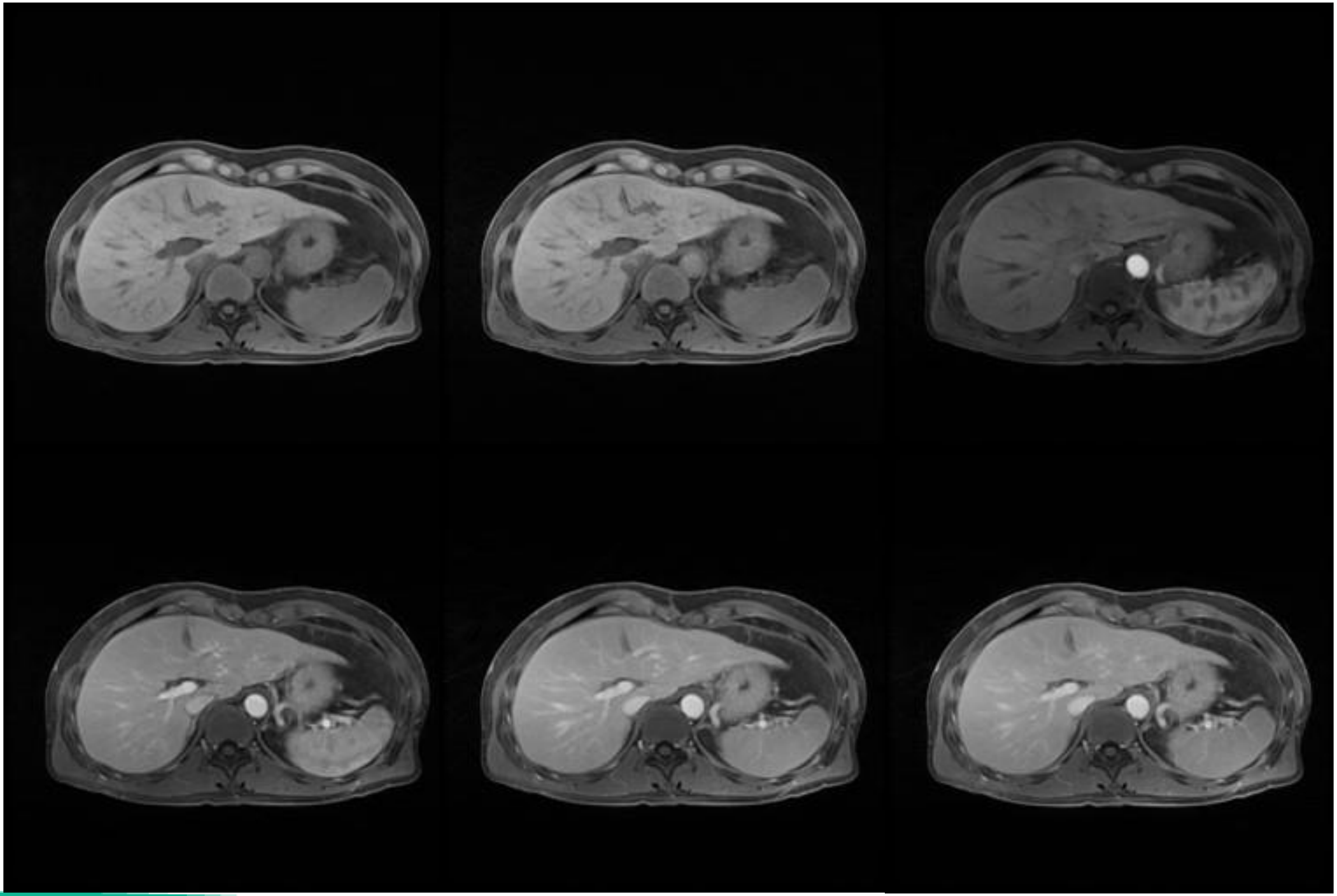
Dynamic T_1 imaging

- Using the same view sharing principles, T_1 DCE data can be rapidly acquired using sequences such as DISCO and TWIST-VIBE with less compromise about spatial resolution

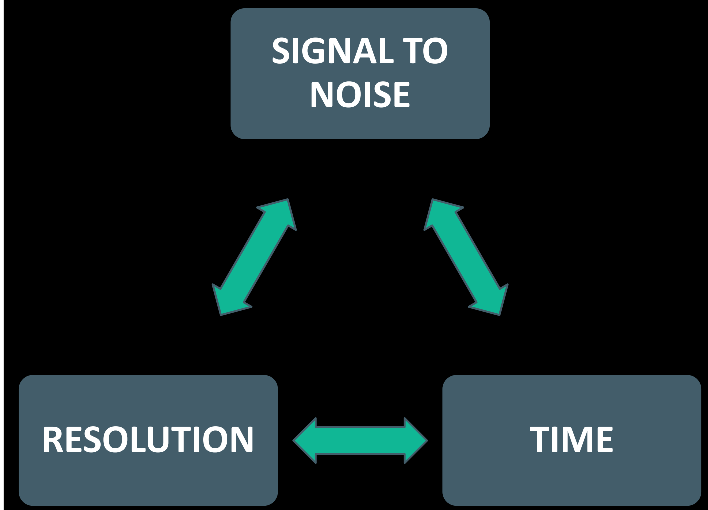
- Motion-insensitive versions (radial stack of stars – similar to PROPELLER but 3D k-space) of these are also now available: DISCO-STAR and GRASP-VIBE

Temporal sharing (TWIST/TRICKS)

TWIST-VIBE / DISCO-STAR



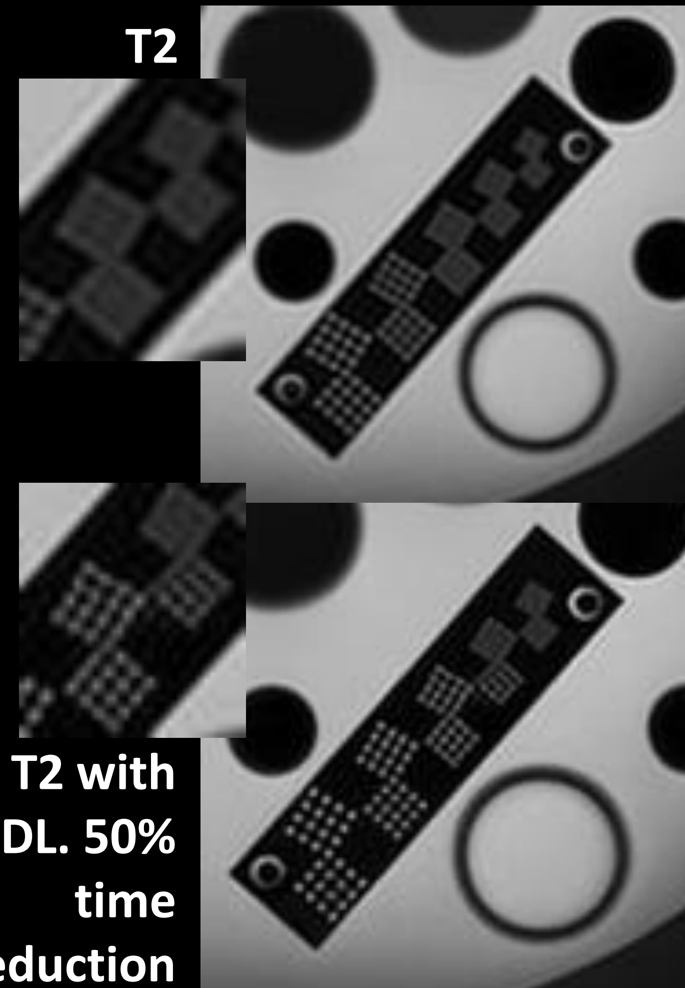
Air Recon DL*



Air Recon DL

- DL-based convolutional neural network for reconstructing MR images
- Denoising
- Sharpening
- Reduction of ringing artefacts

T2



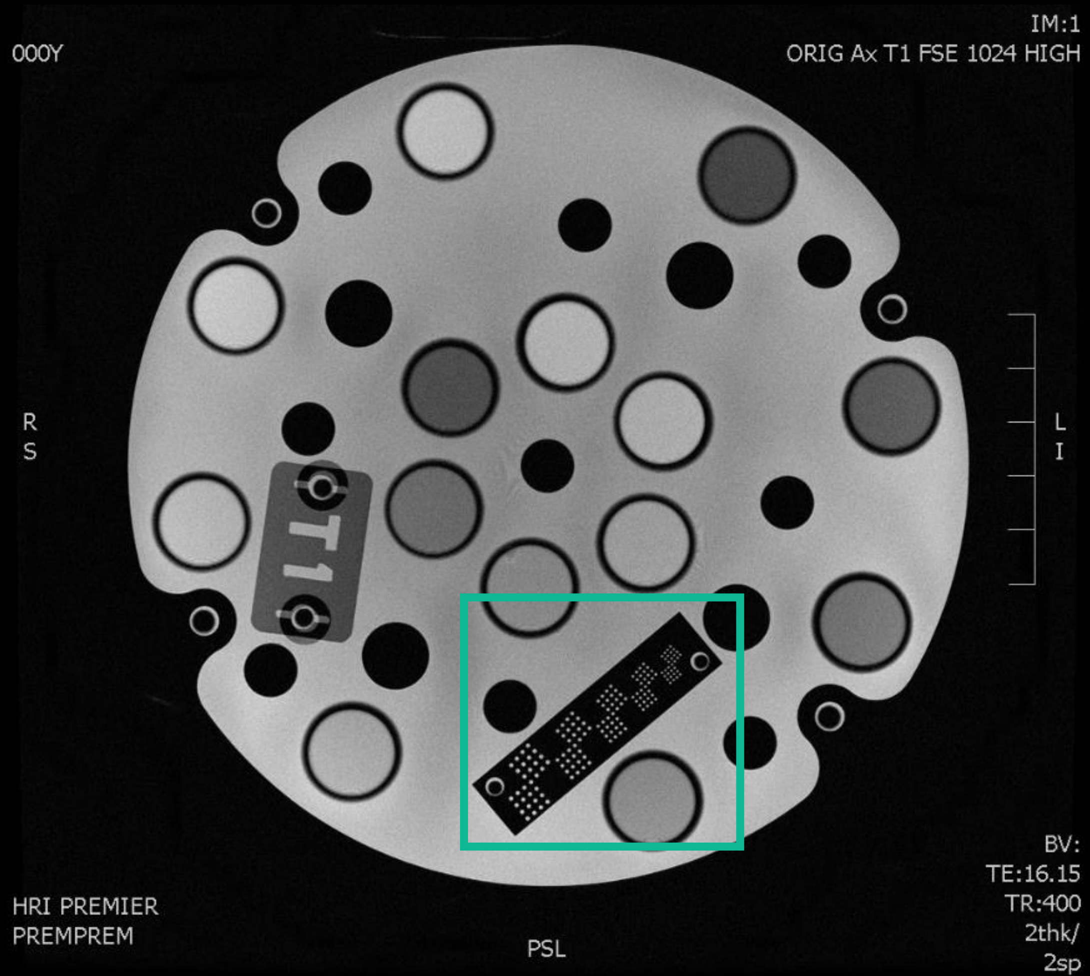
T2 with DL. 50% time reduction

*Other deep learning reconstructions available

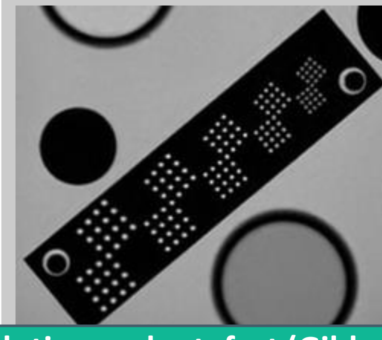
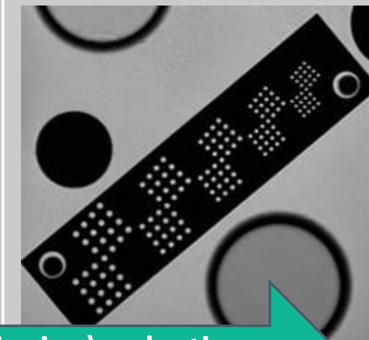
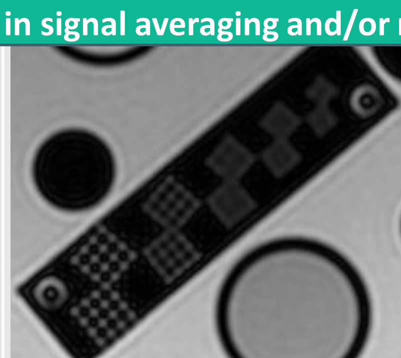
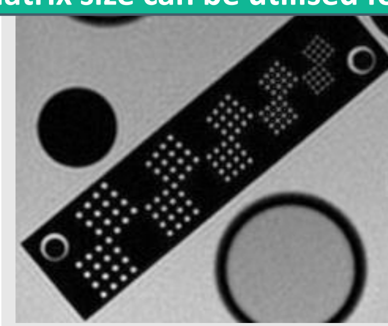
Deep Learning (DL)

- GE 3T Signa Premier
- 48 channel head coil
- 2D FSE Sequence
- Field of View = 200mm
- Slice Thickness = 2mm
- Matrix = 128^2, 256^2, 512^2 & 1024^2
- NEX = 1
- ETL = 3
- TR/TE = 400/10.6ms
- With/Without AirRecon DL (High Denoising)

- CaliberMRI Essential Phantom
- 0.4 – 0.8mm resolution insert



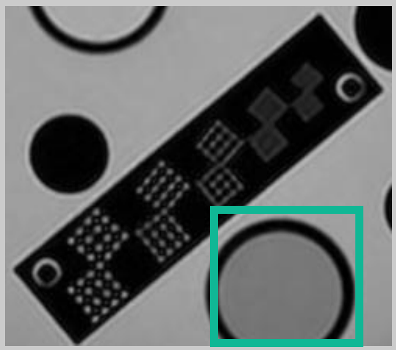
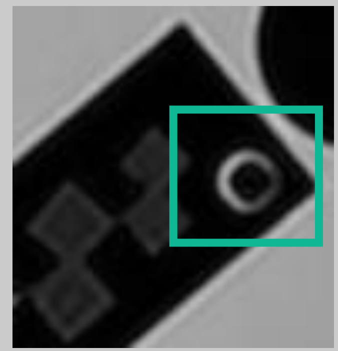
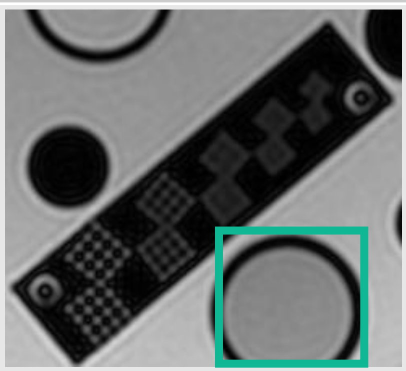
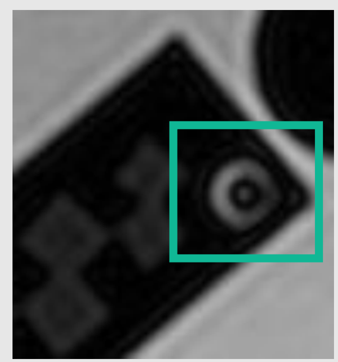
Deep Learning (DL)

Technique/Matrix	128 x 128 (1.56mm inplane) 00:20	256 x 256 (0.78mm inplane) 00:37	512 x 512 (0.39mm inplane) 01:11	1024 x 1024 (0.20mm inplane) 02:19
AirRecon DL (High)				
Original				

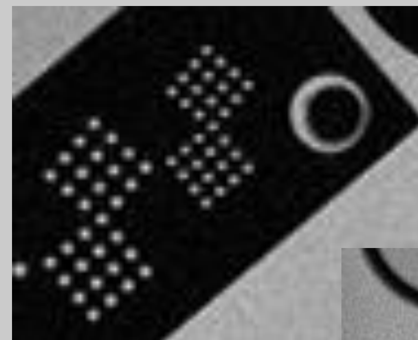
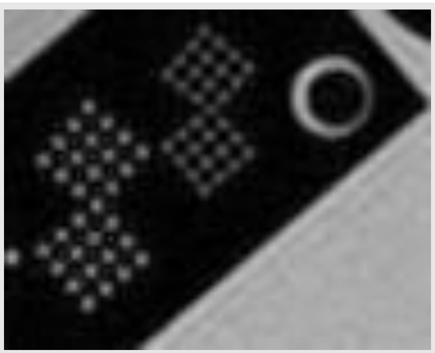
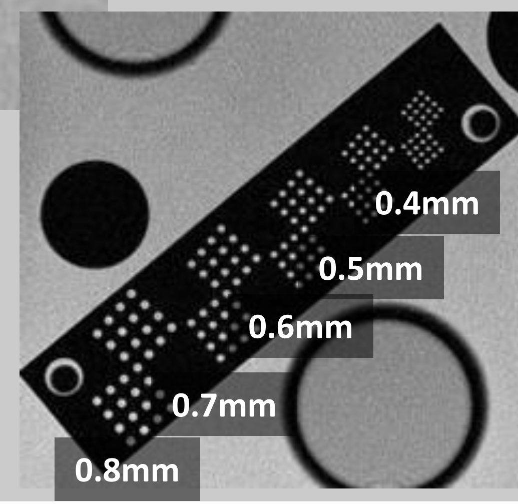
AirRecon DL: Increased SNR, increased resolution and artefact (Gibbs Ringing) reduction. Reduction in signal averaging and/or matrix size can be utilised for time savings.

Deep Learning (DL)

Hull University Teaching Hospitals
NHS Trust

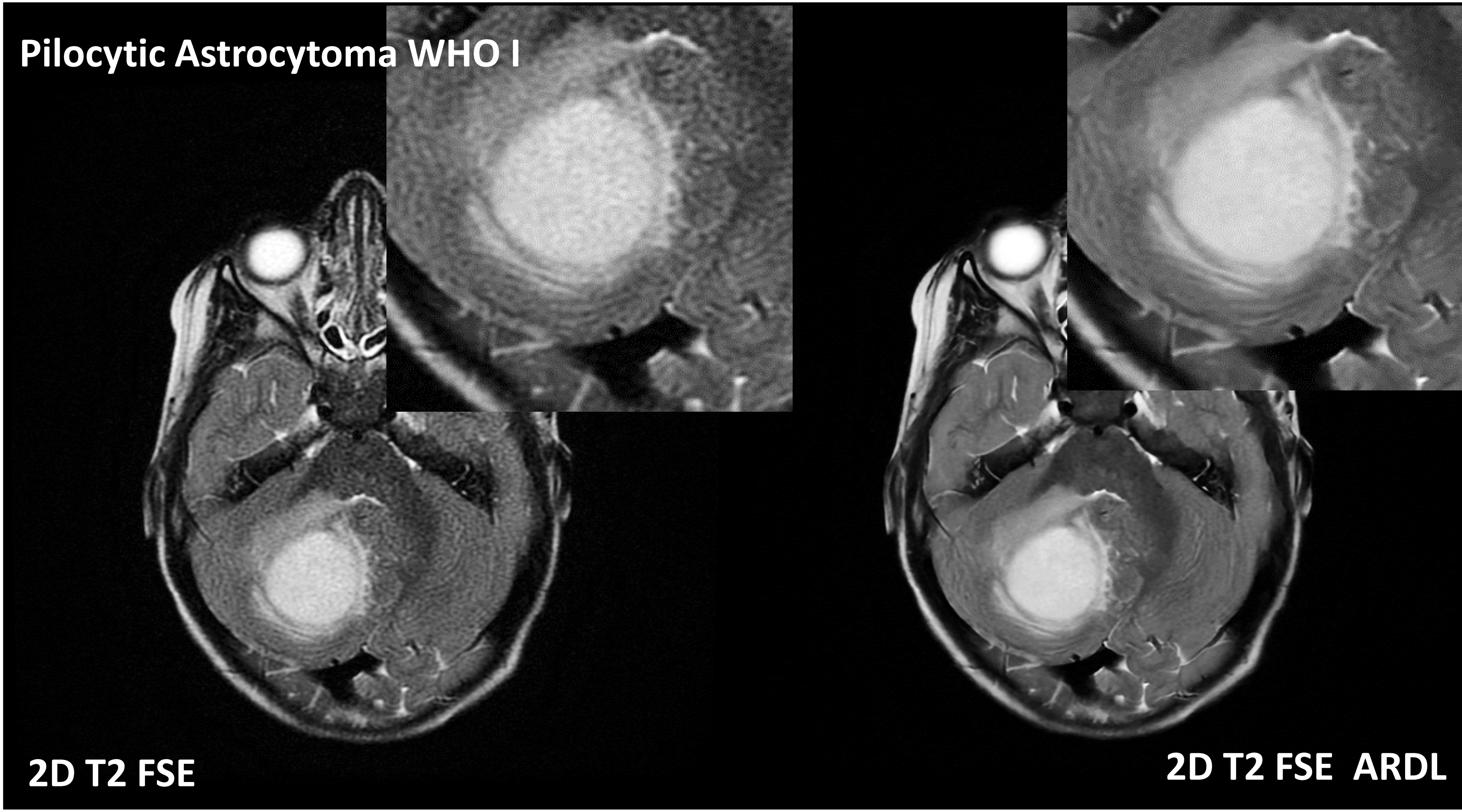
Technique/Matrix	256 x 256 (0.78mm inplane)		
AirRecon DL (High)			Reduction in Gibbs ringing artefact
Original			

Deep Learning (DL)

Technique/Matrix	512 x 512 (0.39mm inplane) 01:11	1024 x 1024 (Original) (0.20mm inplane) 02:19
AirRecon DL (High)	 Better resolution of 0.4 and 0.5mm grid. Closer to 1024 acquired matrix data	
Original		

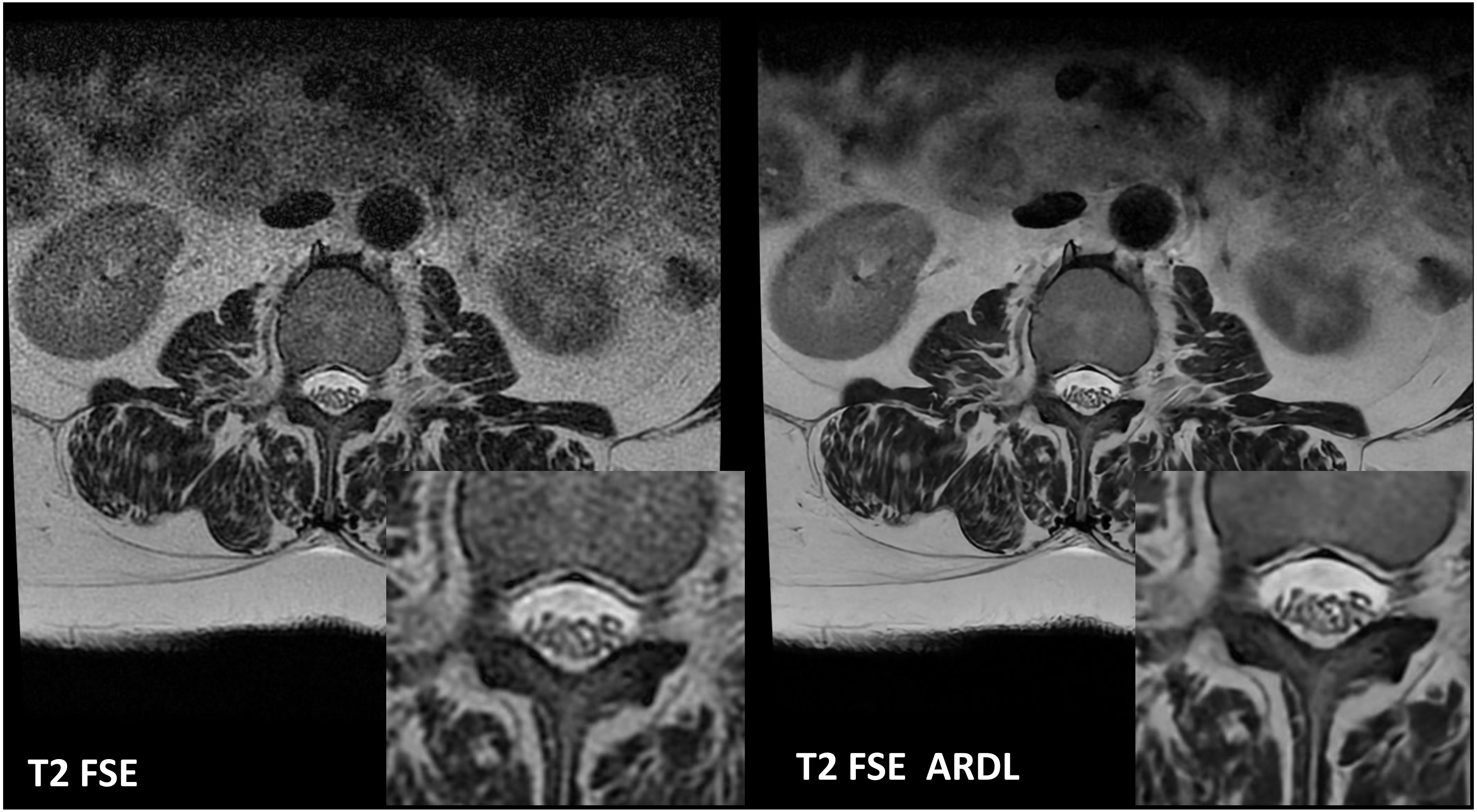
Air Recon DL

NHS
Hull University
Teaching Hospitals
NHS Trust

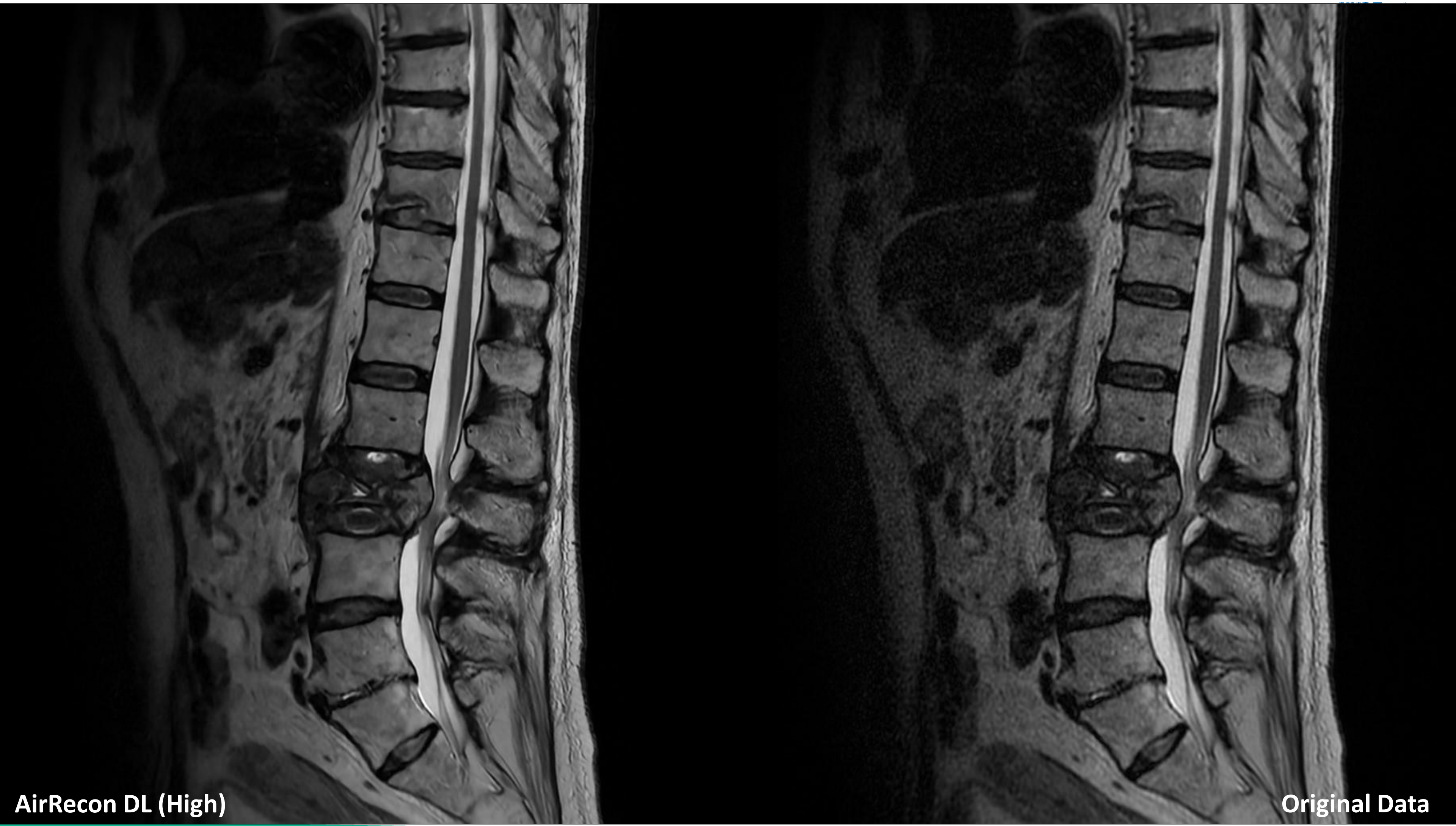


Deep Learning (DL)

Air Recon DL



Deep Learning (DL)



Deep Learning (DL)

Deep Learning (DL)

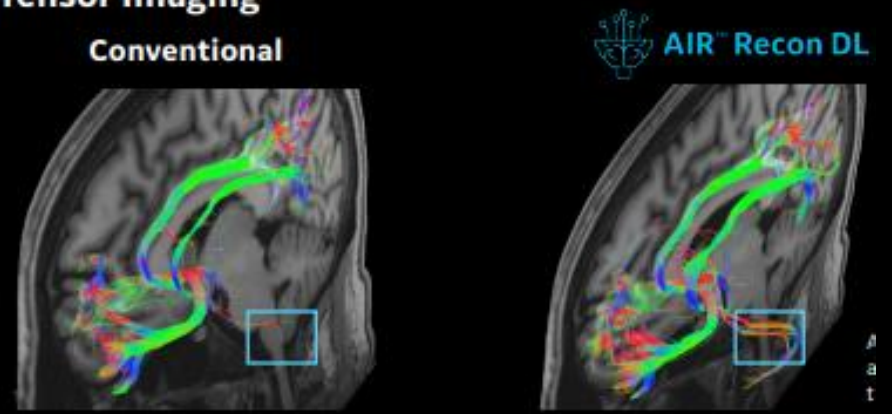
T/R head coil – 2D STIR AirRecon DL (High)

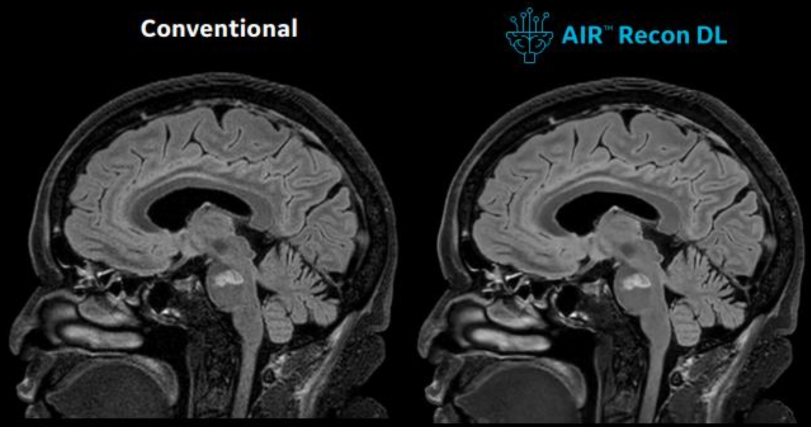
T/R head coil – 2D STIR Original Data

Air Recon DL – the next step

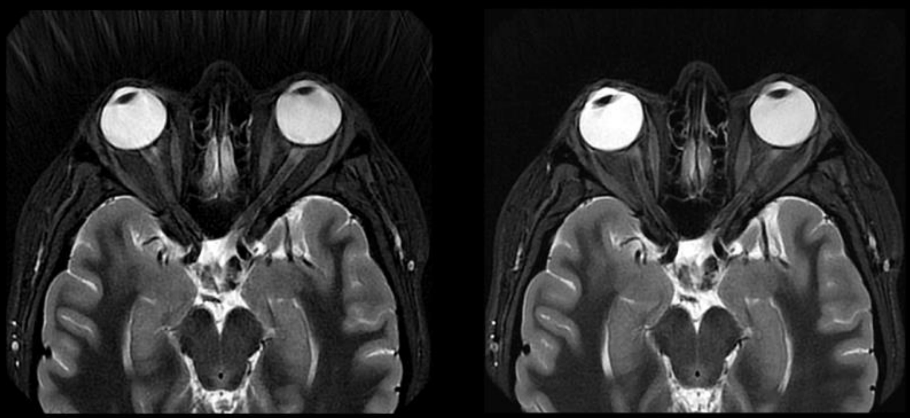
AIR™ Recon DL Diffusion Tensor Imaging

- DTI
- 3D FSE
- 2D Motion insensitive FSE





Sagittal Cube T2 FLAIR HyperSense
1 x 1 x 1 mm
4:34 min



https://www.gehealthcare.com/-/jssmedia/gehc/us/images/products/magnetic-resonance-imaging/mr-30/features---full-width/mr30-r01-sell-sheet-jb21145xx.pdf?rev=-1

7.7 Acceleration techniques, their impact on image quality and potential artefacts

- Zero-filling (interpolation)
  - *Padding k-space with zeroes to speed up reconstruction and improve effective resolution*

- Half-Fourier
  - *Acquire just over half of k-space and use conjugant symmetry to fill in k-space gaps. Reduced SNR compared to complete filling of k-space - square root % of data acquired. E.g. ½ data has 70% SNR compared to full k-space.*

- Parallel imaging
  - *Skip lines of k-space. The ratio of the reduced PE steps is known as the acceleration factor (R). R=2 means half the scan time, R=3 1/3 scan time…*
  - *SENSE/ASSET – use separate low resolution image space calibration data to reconstruct data*
  - *ARC/GRAPPA – internal reference data to reconstruct data. Available in 3D*

7.7 Acceleration techniques, their impact on image quality and potential artefacts

- Simultaneous multislice (multiband)
  - *SMS techniques excite several slices concurrently using multiband radiofrequency pulses. By reducing number of RF pulses required, TR (and scan time) decreases. Exploit differences in coil sensitivity in the slice-encoding direction to unalias the data.*

- Compressed sensing
  - *Pseudo-random under-sampling of k-space to reduce scan time (less phase encodings). Iterative reconstruction methods to fill in k-space and denoise data. Performs better on high contrast, high SNR, 3D acquisitions*

- Temporal sharing (TWIST/TRICKS)
  - *The data from the different partial k-space samplings are combined to create a series of time-resolved images with satisfactory spatial resolution and increases temporal resolution*

7.7 Acceleration techniques, their impact on image quality and potential artefacts

- *Deep Learning Reconstruction*
    - *DL-based convolutional neural network for reconstructing MR images. Denoising. Sharpening. Reduction of ringing artefacts*