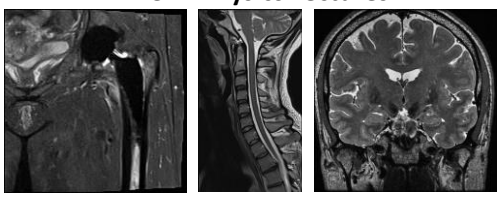
Magnetic Resonance Imaging

F.R.C.R. Physics Lectures



Lawrence Kenning PhD

FRCR MRI Syllabus

Topic area	Main points
7. Magnetic resonance	▪ Creation, detection and spatial localisation of the MR signal
	▪ Basic contrast mechanisms
	▪ Basic MRI sequences & common variants
	▪ Frequency-dependent techniques
	▪ T1-dependent techniques
	▪ Diffusion MRI
	▪ Acceleration techniques
	▪ Flow-related MR techniques
	▪ MR artefacts and artefact reduction techniques
	▪ MR safety
	▪ Quality assurance

https://www.rcr.ac.uk/sites/default/files/guidance_for_the_first_frcr_examination.pdf

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Metal Artefact Techniques

Distortions of the static magnetic field (B_0) due to metallic implants result in:

- Intra-voxel dephasing
  - Signal voids are visible as black areas in the image
- Changes in tissue contrast
  - Failure of fat suppression
- In-plane distortion
  - Shift of image pixels in the frequency encoding direction
- Through-plane distortion
  - The local field offset leads to curved and frayed slices instead of the expected flat



http://clinical-mri.com/wp-content/uploads/new_technologies/WARP_Nittka_MAGNETOM_Flash_RSNA2012.pdf

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Metal Artefact Techniques

The following terms are all techniques to reduce artefacts due to the presence of metal in MR studies:

- WARP (collection of tools)
  - High bandwidth sequence
  - TSE, STIR-TSE
  - Low artefact RF pulses
- **V**iew **A**ngle **T**ilting (VAT)
  - In-plane artefact reduction
- **S**lice **E**ncoding for **M**etal **A**rtefact **C**orrection (SEMAC)
  - In- and through-plane distortion correction
- **M**ulti**A**cquisition with **V**ariable **R**esonance **I**mage **C**ombination (MAVRIC)
  - MAVRIC SL = **MAVRIC SL**ective
  - In- and through-plane distortion correction

ARTEFACT REDUCTION

SCAN TIME

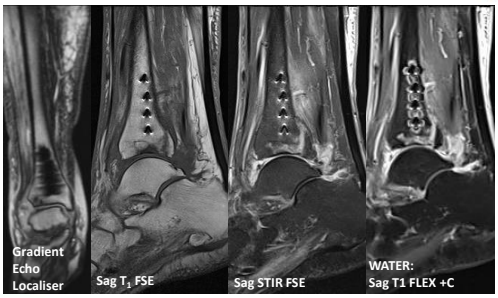
A lower field strength is always better

https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4321802/

Metal Artefact Techniques

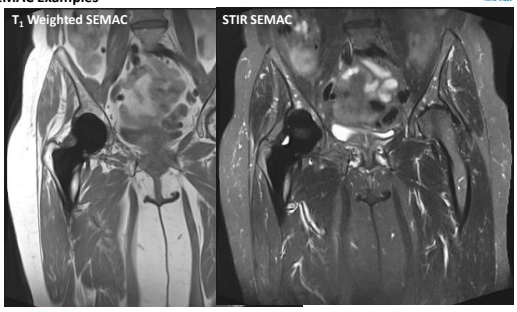


Metal Artefact Techniques



Metal Artefact Techniques

SEMAC Examples



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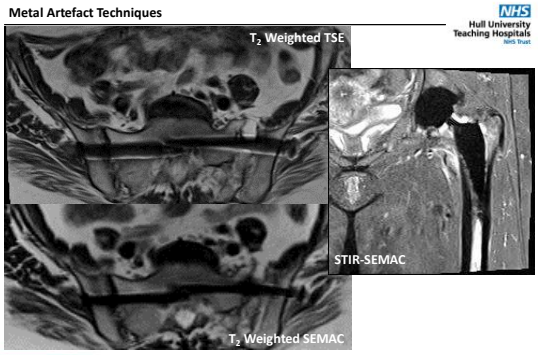
Metal Artefact Techniques



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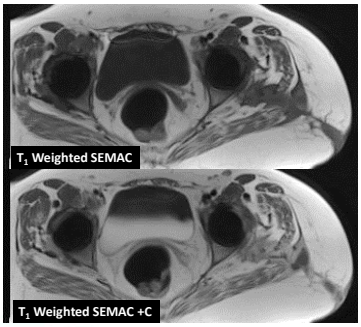
Metal Artefact Techniques



- Limited **MAVRIC SL** and **SEMAC** image contrasts
- T_1
- T_2
- P.D.
- STIR
- No fat-sat!

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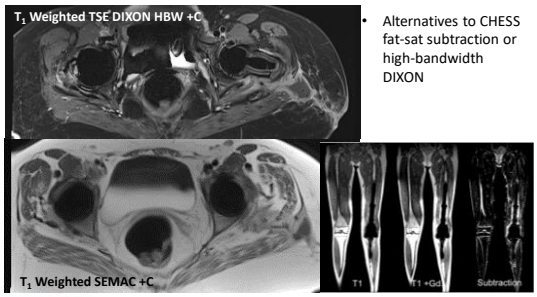
Metal Artefact Techniques



- Alternatives to CHESS fat-sat subtraction or high-bandwidth DIXON

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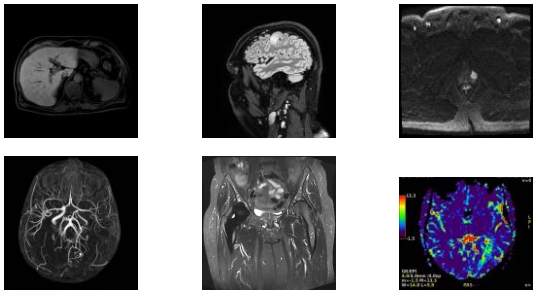
https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4409347/

Acceleration Techniques

Parallel Imaging (PI)



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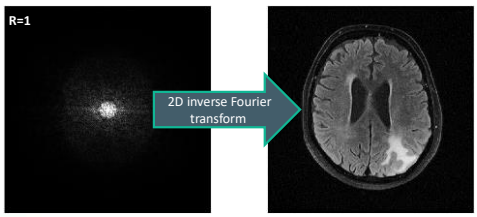
Acceleration Techniques

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



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Acceleration Techniques

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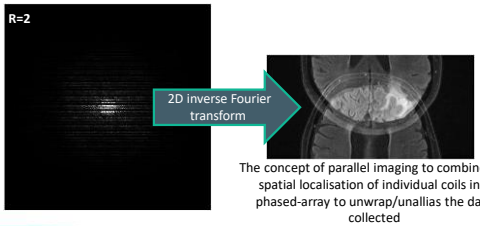
Parallel Imaging

- 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 to combine the spatial localisation of individual coils in a phased-array to unwrap/unallias the data collected

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Acceleration Techniques

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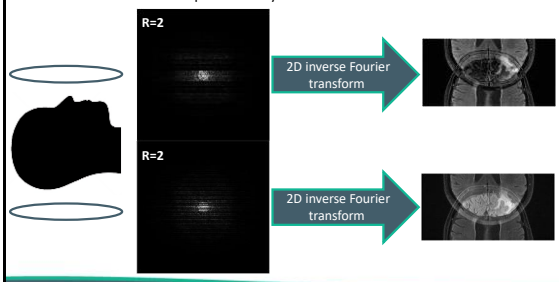
Parallel Imaging

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



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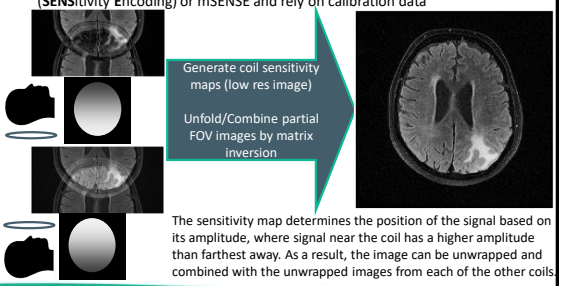
Parallel Imaging - SENSE

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



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.

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http://xrayphysics.com/parallel.html

Acceleration Techniques

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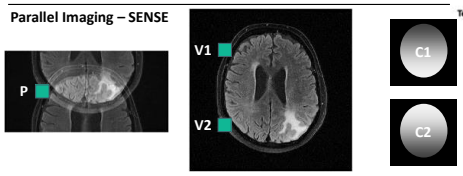
Parallel Imaging – SENSE



- 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 ≤ coils.

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http://xrayphysics.com/parallel.html

Acceleration Techniques

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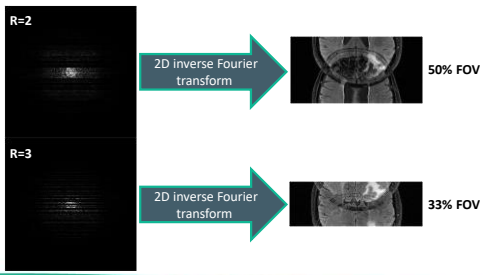
Parallel Imaging - SENSE

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



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Acceleration Techniques

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Parallel Imaging – 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)

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https://mriquestions.com/grappaarc.html

Acceleration Techniques

Parallel 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 mSENSE and GRAPPA work.

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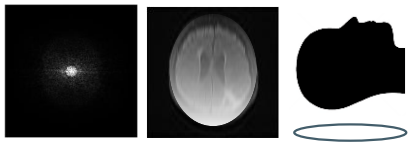
https://mriquestions.com/grappaarc.html

Acceleration Techniques

Parallel Imaging – 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.

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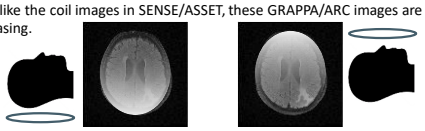
https://mriquestions.com/grappaarc.html

Acceleration Techniques

Parallel Imaging – 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.



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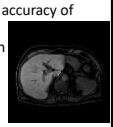
https://mriquestions.com/grappaarc.html

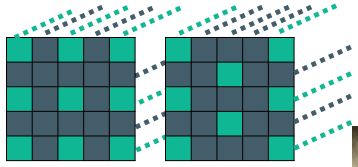
Acceleration Techniques

Parallel Imaging – 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 in **P**arallel **I**maging **R**esults in **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



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https://mriquestions.com/caipirinha.html

Acceleration Techniques

Parallel Imaging

- Just like with traditional reduced field-of-view (and other techniques of reducing acquisition time), the less time you sample the body part, the worse your signal.
- The equation is pretty much the same as traditional reduced field-of-view but with an extra factor g related to coil geometry:

$$SNR = SNR_{initial} / (g * \sqrt{R})$$

- Because of the signal loss (and coil geometry), there is a limit to the acceleration factor you can use, which is usually up to 3-4.

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http://xrayphysics.com/parallel.html

Compressed Sensing

Compressed Sensing (CS)

- Compressed sensing is a signal processing technique built on the fact that signals contain redundant information.
- The initial evidence that image data can be compressed comes from digital photography. To address the issue of storage of large digital image files, several image compression techniques, such as jpeg, were developed.
- The realisation that image compression was possible without loss of detail led to the intriguing question of whether this could be turned around: If all the data is not needed to store the relevant information, why should it be acquired?
- In MR, in which acquisition times are determined by the relaxation properties and proton densities of tissues, the relevant question about compressed sensing is this:
- Can a full image be reconstructed from severely under-sampled data in k-space?

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

Compressed Sensing

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Compressed Sensing (CS)

- In general, compressed sensing can be exploited in clinical practice under the following four conditions:
  - The under-sampling pattern 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

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Compressed Sensing

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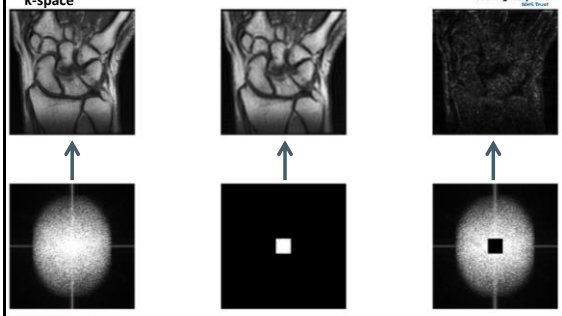
k-space



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Compressed Sensing

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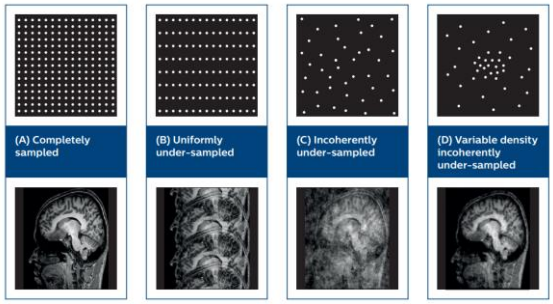

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Compressed SENSE Speed done right. Every time. Liesbeth Geerts-Ossevoort, et al.

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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.

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

Compressed Sensing

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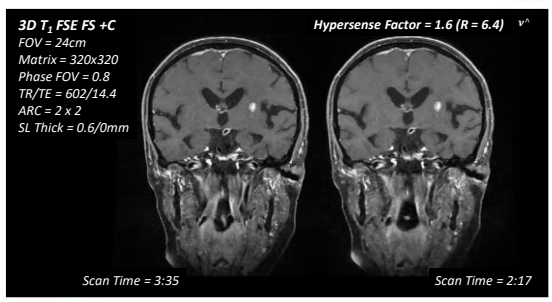

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Compressed Sensing

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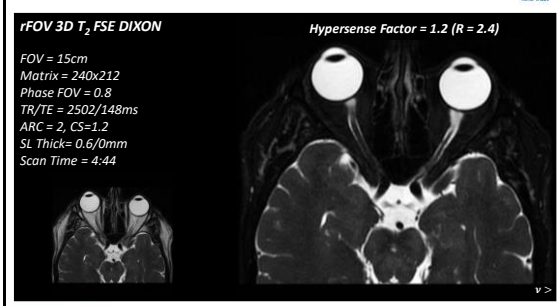

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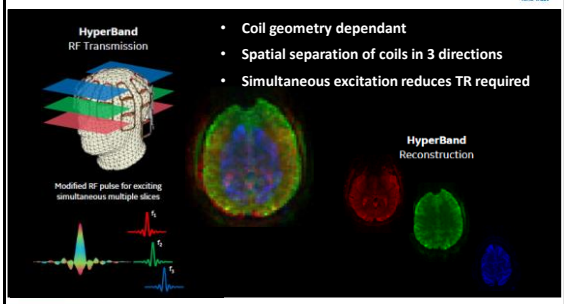
Compressed Sensing

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

Simultaneous Multislice (SMS)

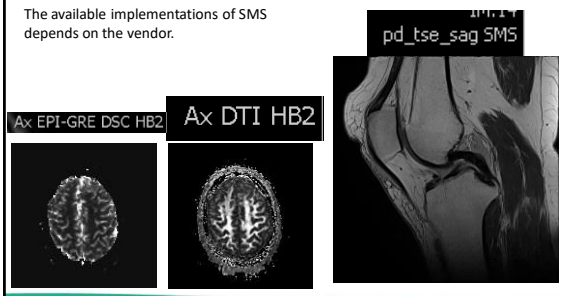


- Coil geometry dependant
- Spatial separation of coils in 3 directions
- Simultaneous excitation reduces TR required

Simultaneous Multislice (SMS)

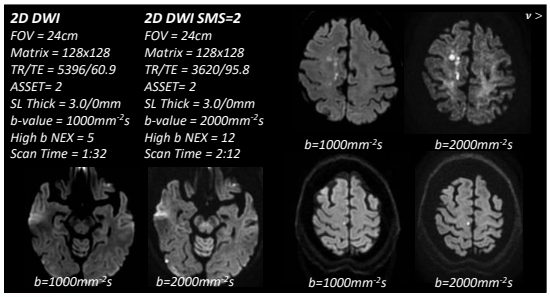
Simultaneous Multislice Acceleration (SMS) / Hyperband (HB)

The available implementations of SMS depends on the vendor.



Simultaneous Multislice (SMS)

2D DWI	2D DWI SMS=2
FOV = 24cm	FOV = 24cm
Matrix = 128x128	Matrix = 128x128
TR/TE = 5396/60.9	TR/TE = 3620/95.8
ASSET= 2	ASSET= 2
SL Thick = 3.0/0mm	SL Thick = 3.0/0mm
b-value = 1000mm^{-2}s	b-value = 2000mm^{-2}s
High b NEX = 5	High b NEX = 12
Scan Time = 1:32	Scan Time = 2:12

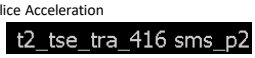


Acceleration Techniques

Acceleration Techniques

- Image domain acceleration
  - ASSET
  - SENSE/mSENSE
- Frequency Domain Acceleration
  - ARC
  - GRAPPA
  - CAIPIRINHA
- Simultaneous Multislice Acceleration
  - SMS
  - Hyperband (HB)
- Compressed Sensing
  - CS
  - Hypersense (HS)







MRI Quality Assurance

Why Test?

- Acceptance Testing
- Sequence Evaluation
- Scanner Evaluation

Quality Assurance (QA) is the overarching system or process to ensure the ongoing delivery, maintenance and improvement in the quality of a service or produce

Quality Control (QC) details the technical procedures and measurements required to demonstrate compliance with standards or specifications.



MRI Quality Assurance

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Acceptance Testing

Opportunity to confirm that the equipment installed is operating in a clinically acceptable manner and to provide a baseline for QA programmes.

Typical tests could include:

- Signal to Noise Ratio (SNR)
- Image uniformity
- Spatial resolution
- Geometric distortion
- Slice thickness and position
- Artefacts (ghosting, RF, tissue-suppression)
- Tissue relaxation measurements
- Specialist QC testing (fMRI, spectroscopy, diffusion, radiotherapy planning)

Non-imaging tests should include confirmatory fringe field measurements.

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MRI Quality Assurance

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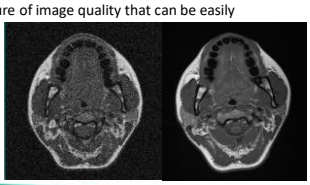
Signal to Noise Ratio (SNR)

The choice of sequence and parameters can have a major effect on the measured SNR, therefore it is necessary to use a standardised protocol for SNR measurements.

SNR measurements provide an overview of the overall system in combination with the designated RF coil (if a separate coil is used)

SNR represent a good signal measure of image quality that can be easily monitored over time.

Is a clinically relatable parameter (visual!)



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MRI Quality Assurance

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Signal to Noise Ratio (SNR)

Ideal scenario is to acquire multiple datasets to minimise errors. (Method 1)

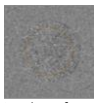
$$SNR(x,y) = \frac{\mu(x,y)}{\sigma(x,y)}$$

- μ = mean signal measured across all acquisitions
- σ = standard deviation of signal measured across all acquisitions

More pragmatic solution is to acquire two identical datasets (Method 2)

$$SNR_{subtraction} = \frac{\sqrt{2}\mu_{phantom}}{\sigma_{subtracted\ image}}$$

- μ = mean signal measured from 1 acquisition
- σ = standard deviation of the subtracted image



The noise in the subtracted image will be Gaussian with variation twice that of the source data (magnitude data)

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MRI Quality Assurance

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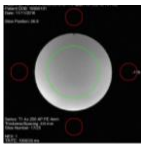
Signal to Noise Ratio (SNR)

Even more pragmatic method for 1 image. (Method 3)



$$SNR_{background} = \frac{f \times \mu_{phantom}}{\sigma_{background}}$$

- μ = mean signal measured from 1 acquisition
- σ = standard deviation of the background noise
- f = correction factor for non-Gaussian nature of the noise distribution (0.66)

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MRI Quality Assurance

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Uniformity

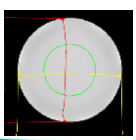
Is a measure of MRI system's ability to produce a contrast signal response over the image volume.

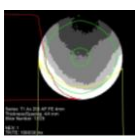
$$(\%)\ Uniformity_{Integral} = 100 \times \left(1 - \frac{S_{max} - S_{min}}{S_{max} + S_{min}}\right)$$

- Integral Uniformity is calculated on smoothed data
- S_{max} / S_{min} = maximum and minimum signal intensities

A perfect uniformity would be 100%







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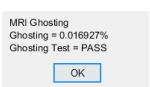
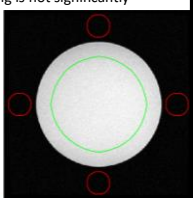
Ghosting

Normally associated with motion arising from patients, can be a sign of RF or gradient instability if observed on phantom studies.

$$(\%)\ \text{Ghosting Ratio} = 100 \times \left(\frac{(top+bottom)-(left+right)}{2 \times signal}\right)$$

- A ghosting ratio close to zero indicates that's ghosting is not significantly above background





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Spatial Resolution and Linearity

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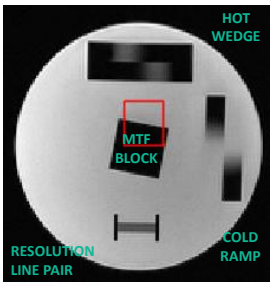

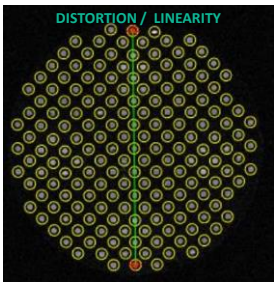

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MR Relaxometry

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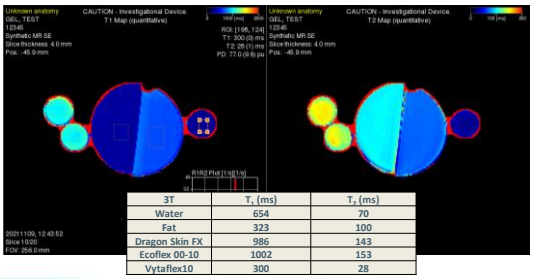

3T	T_1 (ms)	T_2 (ms)
Water	654	70
Fat	323	100
Dragon Skin FX	986	143
Ecoflex 00-10	1002	153
Vytaflex10	300	28

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