MRI Pulse Sequence Optimization

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Protocol Optimization – Modify only when necessary!

- Vendor protocols should *theoretically* be well set-up and 'reasonably' optimized so off-the-cuff uninformed 'tweaking' *should be avoided*.
- Remember that making seemingly harmless parameter changes can have an adverse effect on other aspects of the diagnostic quality of the images or duration of scan time.
- Few MRI anthropomorphic phantoms available and you might not have any.
- Unnecessary *in vivo* tweaking is unethical *(you are using the patient as a phantom)*.
- This lecture is not a licence to tweak, but instead provides direction to take when you do have to optimize a protocol, or when specific patients or pathologies require modifications.

Optimization in MRI

- In terms of sufficiently high image quality for accurate diagnosis at minimum scan time: the subject of this presentation
- In terms of SAR levels: maximum fixed by law based on IEC guidelines, but this maximum can be over-ridden e.g., for specific patients or research. Independent checks of the real SAR levels inside the patient and the temperature distribution should be made – not considered in this presentation.
- In terms of Gadolinium dose: Gd is toxic has been found to deposit in the brain, skin, bone, liver, and other organs. Its safety is a major controversy at the moment. Should use minimum Gd for diagnostic accuracy – not considered in this presentation

Which image quality metrics do you want to optimise?

- For **High Signal** from tissue A $\mathbf{S_A = MPV_A}$ should be high
- **For low mage noise N** in tissue A $\mathbf{SD_A}$ of $\mathbf{MPV_A}$ should be low
- For low **perceived noise** in A $\mathbf{SNR_A = MPV_A / SD_A}$ should be high
- For detection of low tissue contrast between large tissues A and B

  $\mathbf{CNR = (MPV_A - MPV_B)/\sqrt{(MPV_A - MPV_B)}}$ should be high
- For detection of small but high tissue contrast lesions and sharp outlines (including avoiding partial volume effects) need *small voxel size and thin patient slices*

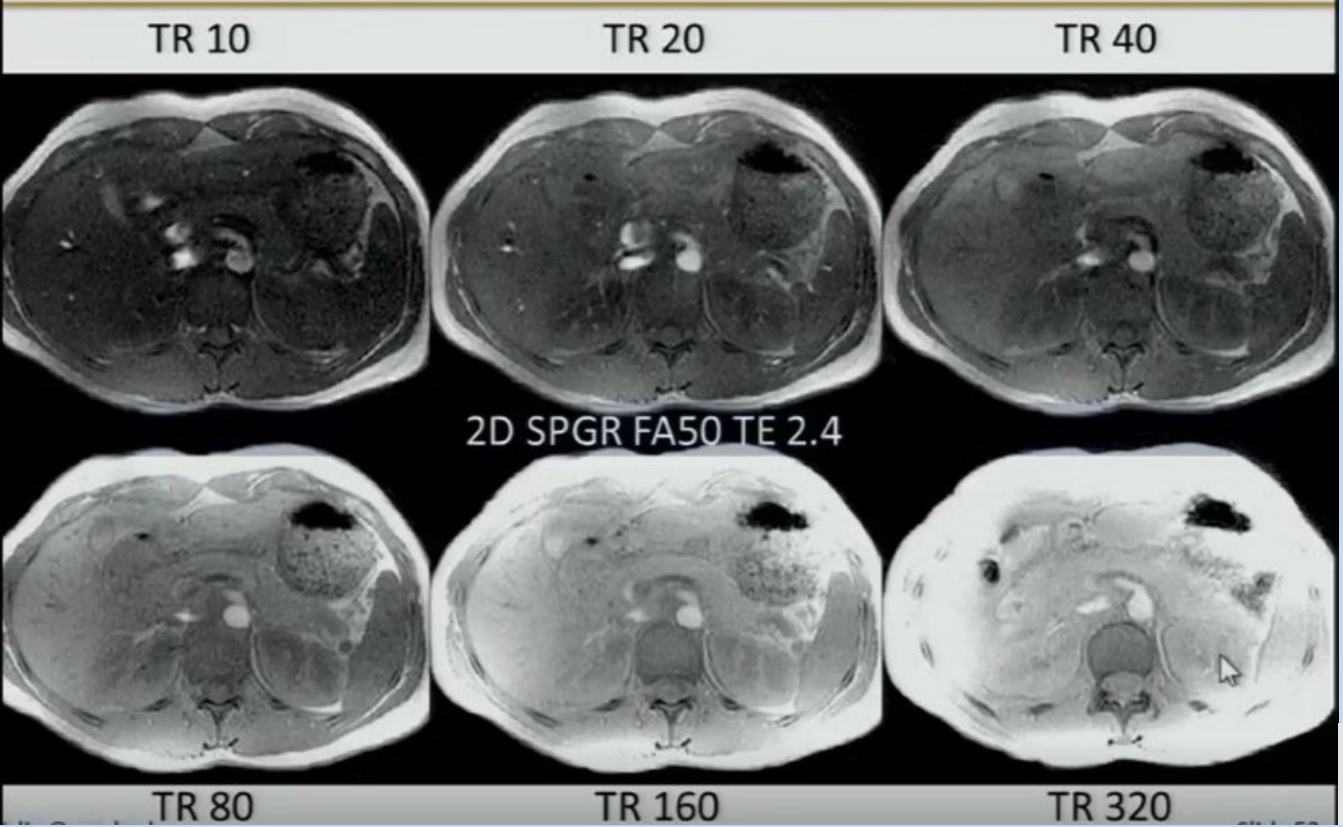
  voxel size $\mathbf{= SFOV/N_{FE}N_{PE}}$ where N = matrix size in frequency encoding and phase directions
- High **geometric accuracy** (absence of distortion)

SNR and small voxel size at short scan time are the metrics mostly used in daily practice. *Trade offs* are part of daily life in MRI. The operator must decide which quality characteristic is the most important for the clinical task in hand and optimize this – *whilst keeping a watchful eye on scan time*.

MRI is much more complex than CT!

Partial list of scanning parameters used today : B_o, 2D/3D, pulse sequence (spin echo, gradient echo, fast spin echo, echo-planar-imaging etc), TE, TR, flip-angle, echo-train-length, receive bandwidth (rBW), SFOV, NSA (NEX), slice thickness, matrix size in 3 dimensions N_{FE} N_{PE}, fat suppression, phase sampling ratio, inversion recovery time, saturation band, cardiac gating, respiratory gating, phase encode ordering, steady state, linear coil, quadrature coil, phased array coil, parallel imaging, spoiling …… etc
This wide range of scanning parameters makes MRI much more flexible than all other imaging modalities combined. However it is also much more complicated! A radiology department without a dedicated MR physicist will have problems!

"The variety of parameters used in MRI is often bewildering" (ref Catherine Westbrook, Handbook of MRI Technique)



Increase TR increases the signal

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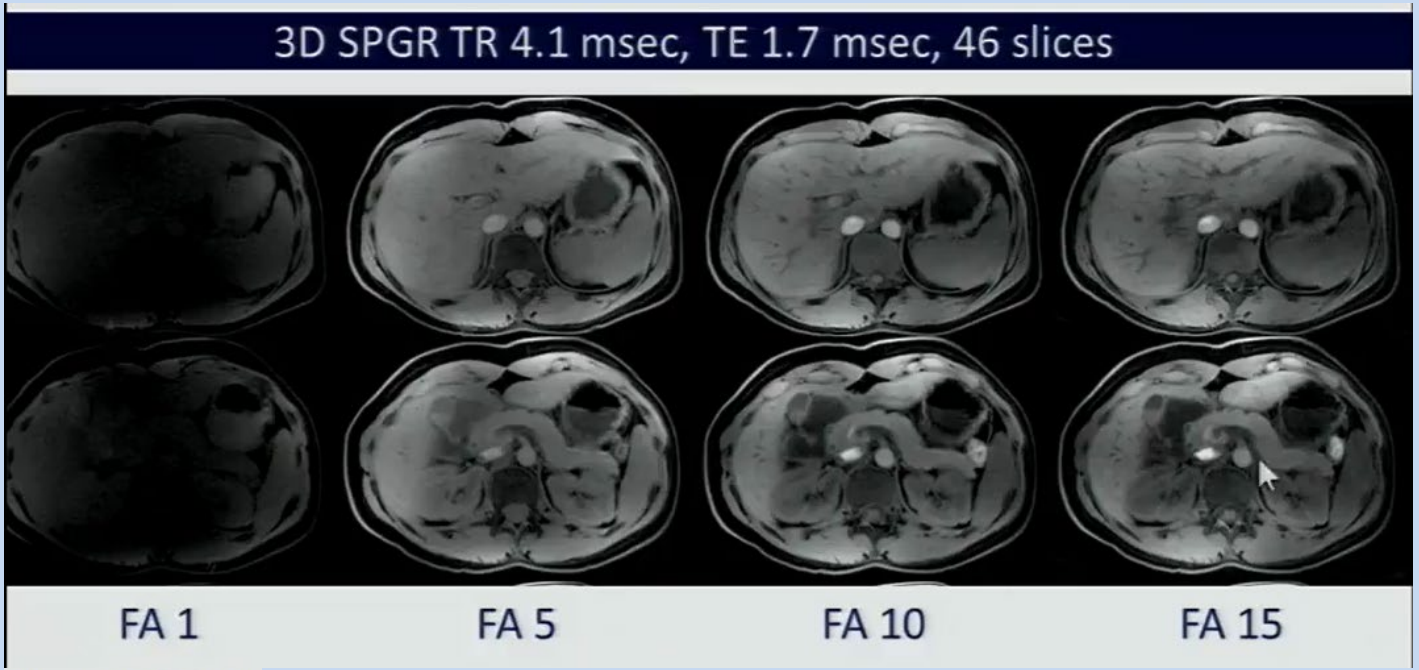
SPGR = SPoiled Gradient imaging sequence using RF spoiling.

Flip Angle effect on signal - Ernst Angle



On moving from FA10 to FA15 we have gone beyond the Ernst angle signal goes down

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Increasing NSA decreases noise

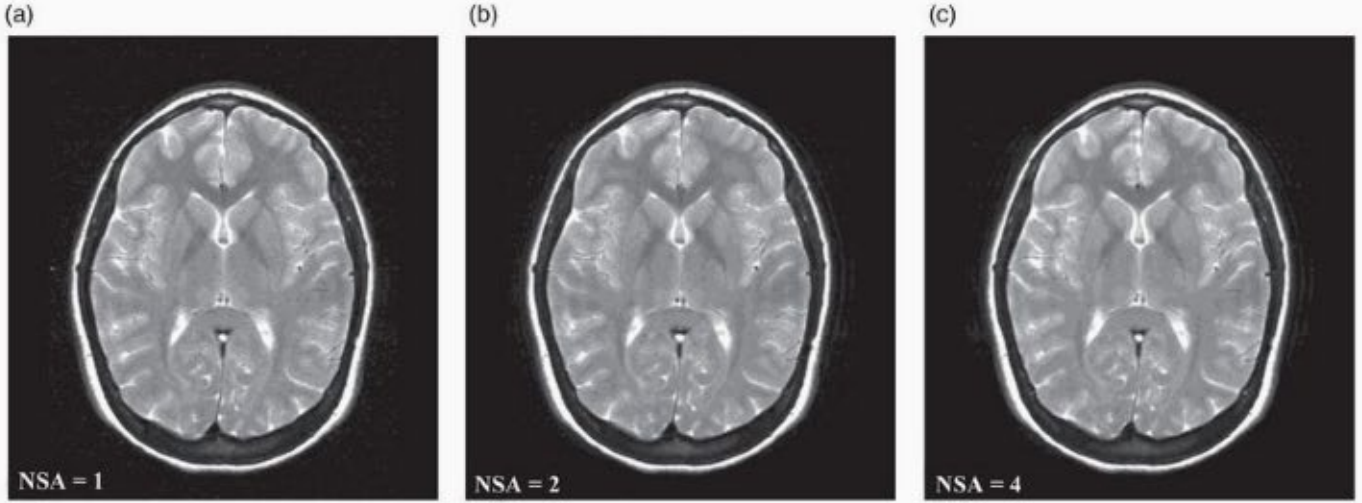
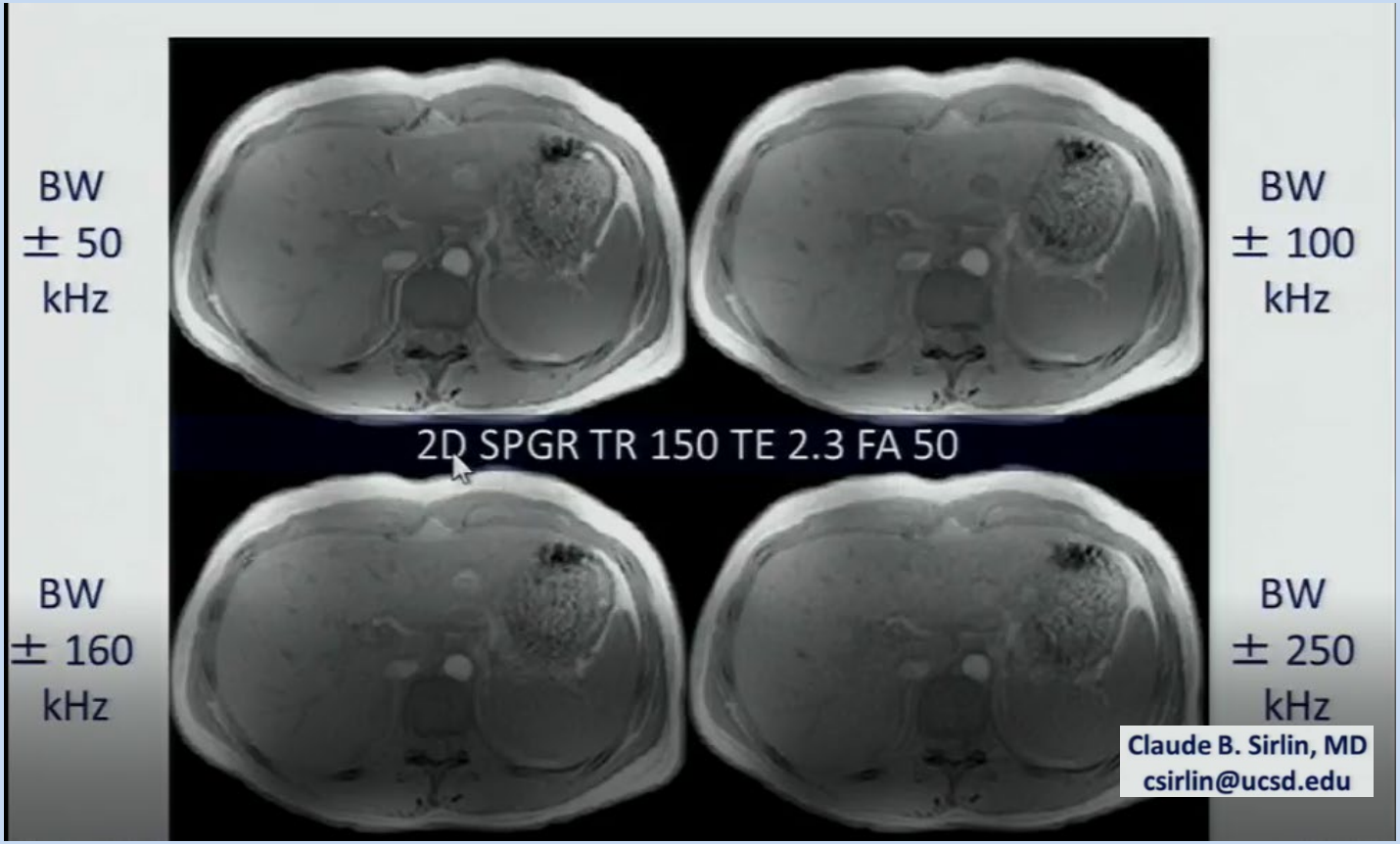


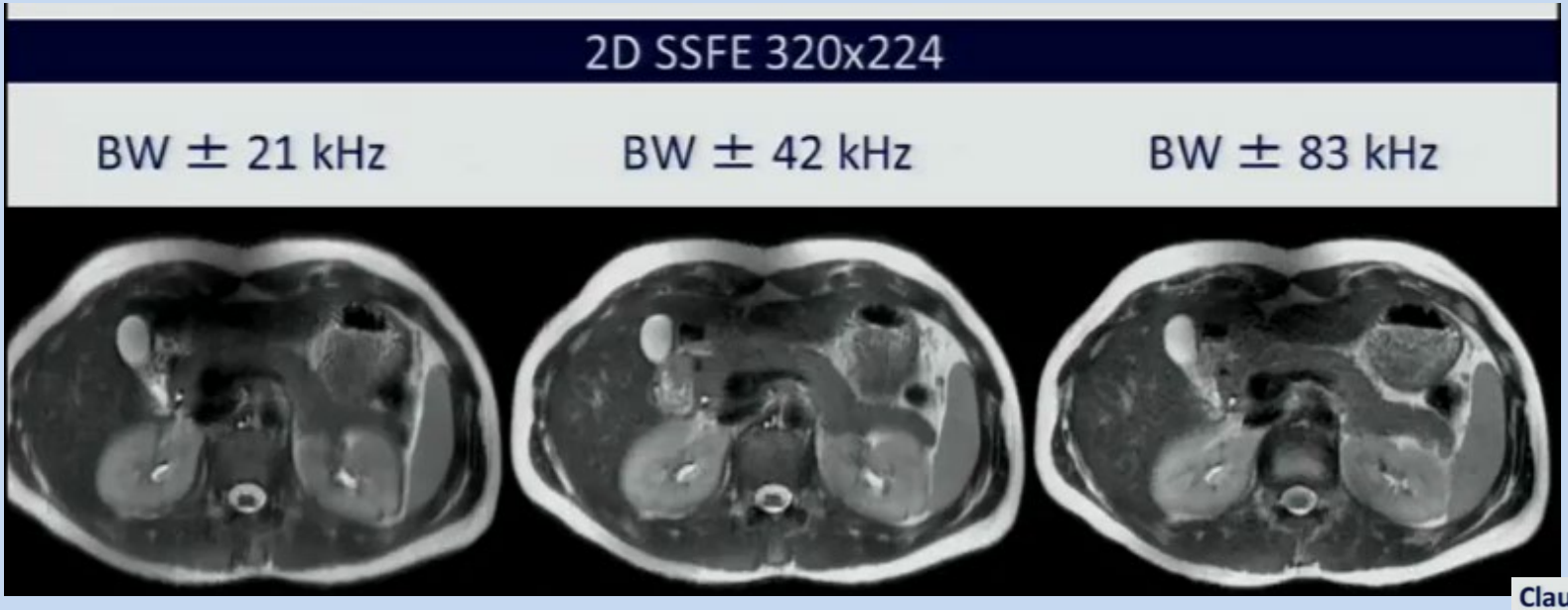
Figure 6.6 Effect of signal averaging (**a**) NSA = 1; (**b**) NSA = 2; (**c**) NSA = 4. Scan times increased proportionately. Image SNR improves with increasing NSA.

McRobbie, Donald W et al MRI from Picture to Proton



Decreasing rBW decreases noise

But! - decreasing rBW also reduces sharpness



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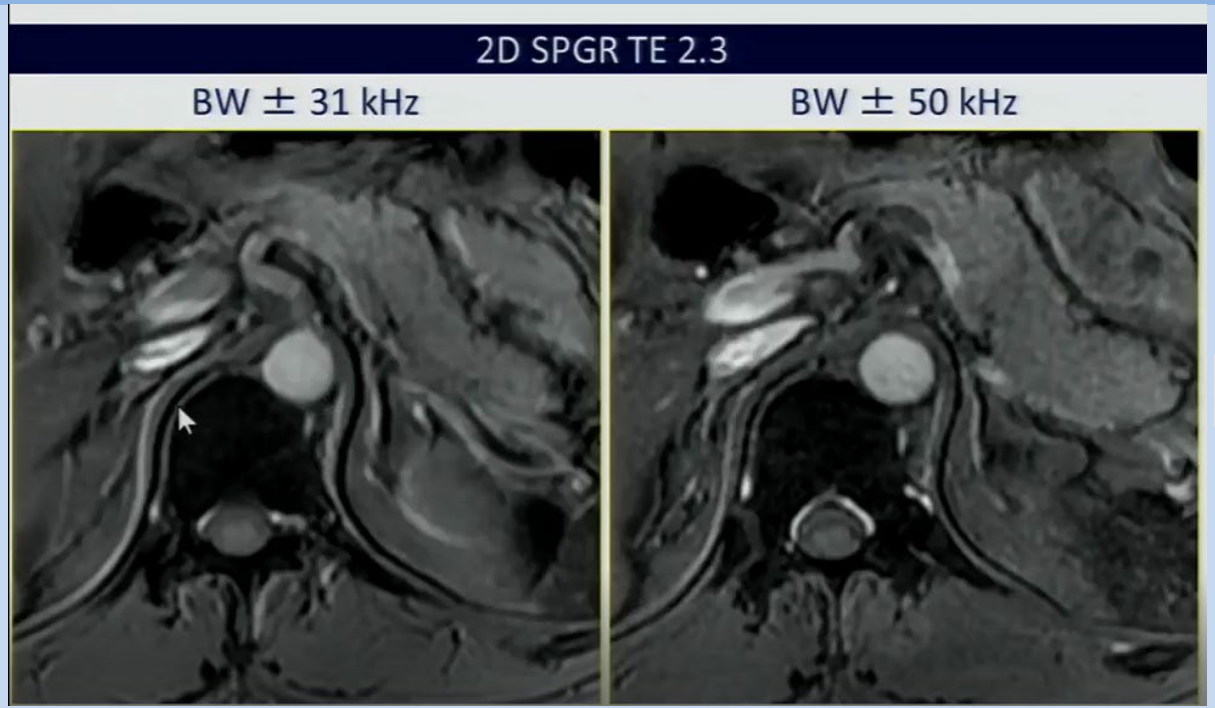
…and increases chemical Shift



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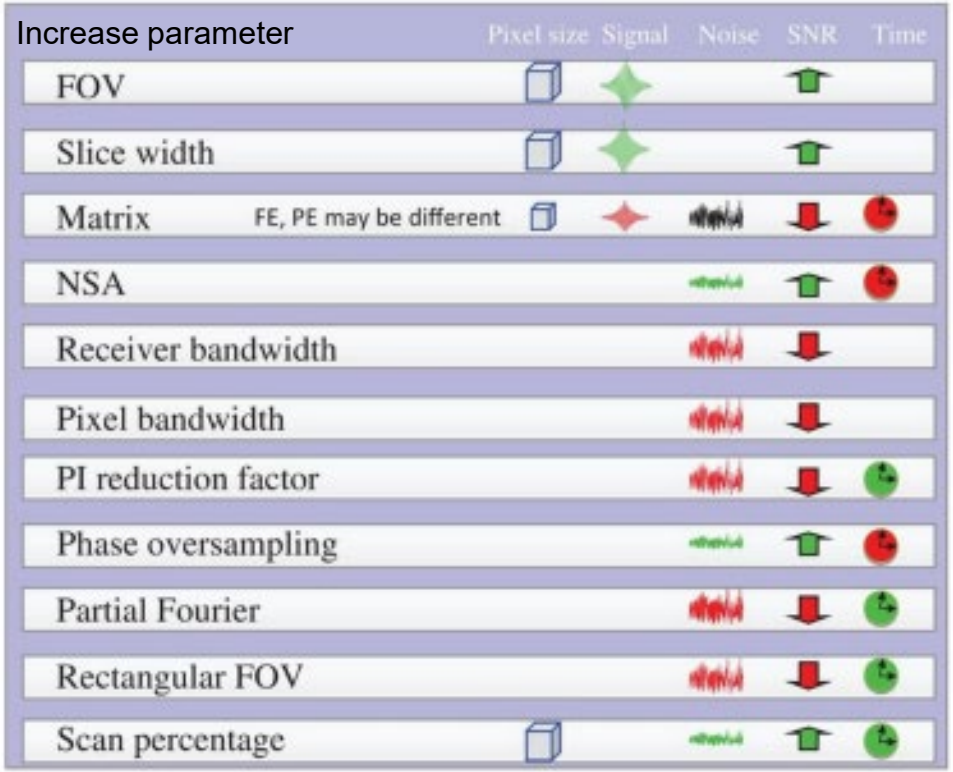
Qualitative optimization in MRI (in vivo optimisation by small tweaks) – radiographers and medical physicists

Summary of imaging parameter trade-offs

Ref: Radiopaedia

Increase Parameters below	SNR	Resolution	Acquisition Time	Distance Covered	Max. Number of Slices
FOV	+	-	nc	nc	nc
NEX	+	nc	+	nc	nc
Slice Thick	+	-	nc	+	nc
Gap	+	-	nc	+	nc
TR	+	nc	+	nc	+
TE	-	nc	nc	nc	-
Matrix size	-	+	+	nc	nc
Bandwidth	-	nc	nc	nc	+
Magnet strength	+	nc	nc	nc	nc

+ increases - decreases nc = no change



Ref:McRobbie, Donald W et al MRI from Picture to Proton

Parameters and Typical Effects

Apply/↑	SNR	Min TR,TE	A.T.	Sharp-ness	Weighting			Artifacts	
					T1	T2(*)	D	CS 1st	χ, Distortion
Gd	↑	–	–	–	↓ T1 & T2		–	–	–
TR	↑	–	↑	–	↓	–	–	–	–
FA	Ernst α	↑	± ↑	–	↑	–	–	–	–
TE	↓	↑	± ↑	–	–	↑	–	–	↑
BW	↓	↓	± ↓	↑	–	–	–	↓	↓
ST	↑	↓	± ↓	↓	–	–	–	–	↑
N_f	↓	↑	± ↑	↑	–	–	–	↓	↓ except EPI
N_p	↓	–	↑	↑	–	–	–		↓ except EPI
N_z (3D)	↑	–	↑	–	–	–	–	–	–
PI	↓	–	↓	↑	–	–	–	–	↓
b-value	↓	↑	± ↑	–	–	–	↑	–	↑

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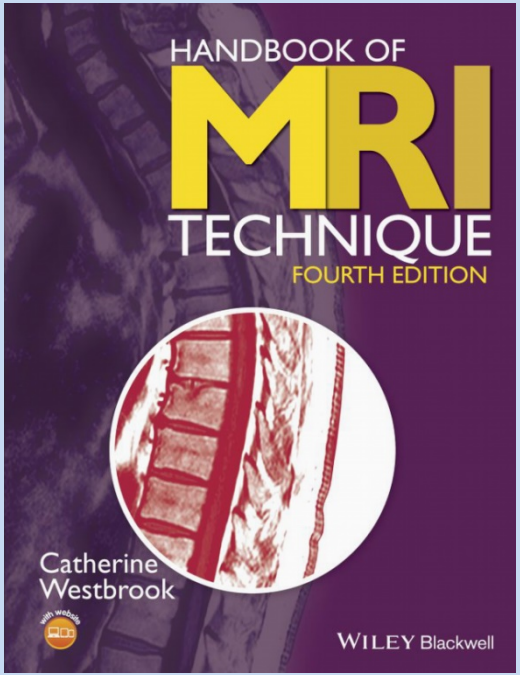
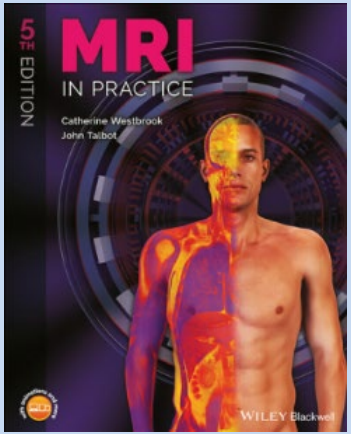
Good basic reference for *qualitative* optimization





Parameter	Advantages	Disadvantages
TR increased (up to 2000 ms in SE)	Increased SNRIncreased number of slices per acquisition	Increased scan timeDecreased T1 weighting
TR decreased (below 2000 ms in SE)	Decreased scan timeIncreased T1 weighting	Decreased SNRDecreased number of slices per acquisition
TE increased	Increased T2 weighting	Decreased SNR
TE decreased	Increased SNR	Decreased T2 weighting
NEX increased	Increased SNR of all tissues	Direct proportional increase in scan time
	Reduced motion artefact due to signal averaging	
NEX decreased	Direct proportional decrease in scan time	Decreased SNR in all tissues
		Increased motion artefact due to less signal averaging
Slice thickness increased	Increased spatial resolution and reduced partial voluming in slice select direction	Decreased SNR in all tissues Decreased coverage of anatomy
FOV increased	Increased SNR Increased coverage of anatomy	Decreased spatial resolution Decreased likelihood of aliasing
FOV decreased	Decreased SNR in all tissues Decreased coverage of anatomy	Increased spatial resolution Increased likelihood of aliasing
Matrix increased	Increased spatial resolution	Decreased SNR if pixel size decreases. If pixel size remains the same, SNR will increase because more phase encodings are performed Increased scan time
Matrix decreased	Increased SNR in all tissues if pixel size increases. If pixel size remains the same, SNR decreases as fewer phase encodings are performed Decreased scan time	Decreased spatial resolution
Receive bandwidth increased	Decrease of minimum TE Decrease in chemical shift	Decreased SNR
Receive bandwidth decreased	Increased SNR	Increase in minimum TE Increase in chemical shift

Qualitative Trade-Offs

Authors' Suggested Parameters based *simply on own experience* – ranges of parameter values for qualitative tweaking

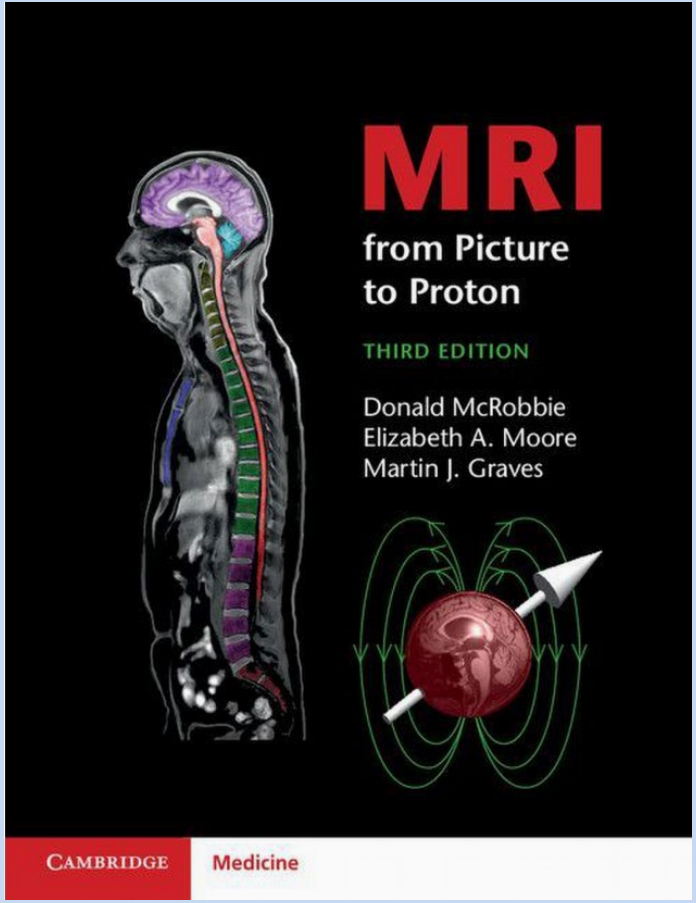
1.5 T		**3 T**	
SE		**SE**	
Short TE	Min–30 ms	Short TE	Min–15 ms
Long TE	70 ms+	Long TE	70 ms+
Short TR	600–800 ms	Short TR	600–900 ms
Long TR	2000 ms+	Long TR	2000 ms+
FSE		**FSE**	
Short TE	Min–20 ms	Short TE	Min–15 ms
Long TE	90 ms+	Long TE	90 ms+
Short TR	400–600 ms	Short TR	600–900 ms
Long TR	4000 ms+	Long TR	4000 ms+
Short TEL	2–6	Short TEL	2–6
Long ETL	16+	Long ETL	16+
IR T1		**IR T1**	
Short TE	Min–20 ms	Short TE	Min–20 ms
Long TR	3000 ms+	Long TR	300 ms+
TI	200–600 ms	TI	Short or null time of tissue
Short ETL	2–6	Short ETL	2–6
STIR		**STIR**	
Long TE	60 ms+	Long TE	60 ms+
Long TR	3000 ms+	Long TR	3000 ms+
Short TI	100–175 ms	Short TI	210 ms
Long ETL	16+	Long ETL	16+
FLAIR		**FLAIR**	
Long TE Long TR	80 ms+ 9000 ms+	Long TE Long TR	80 ms+ 9000 ms + (TR at least 4 × TI)
Long TI	1700–2500 ms (depending on TR)	Long TI	1700–2500 ms (depending on TR)
Long ETL	16+	Long ETL	16+

Coherent GRE		**Coherent GRE**	
Long TE	15 ms+	Long TE	15 ms+
Short TR	<50 ms	Short TR	<50 ms
Flip angle	20–50°	Flip angle	20–50°
Incoherent GRE		**Incoherent GRE**	
Short TE	Minimum	Short TE	Minimum
Short TR	<50 ms	Short TR	<50 ms
Flip angle	20–50°	Flip angle	20–50°
Balanced GRE		**Balanced GRE**	
TE	Minimum	TE	Minimum
TR	Minimum	TR	Minimum
Flip angle	>40°	Flip angle	>40°
SSFP		**SSFP**	
TE	10–15 ms	TE	10–15 ms
TR	<50 ms	TR	<50 ms
Flip angle	20–40°	Flip angle	20–40°

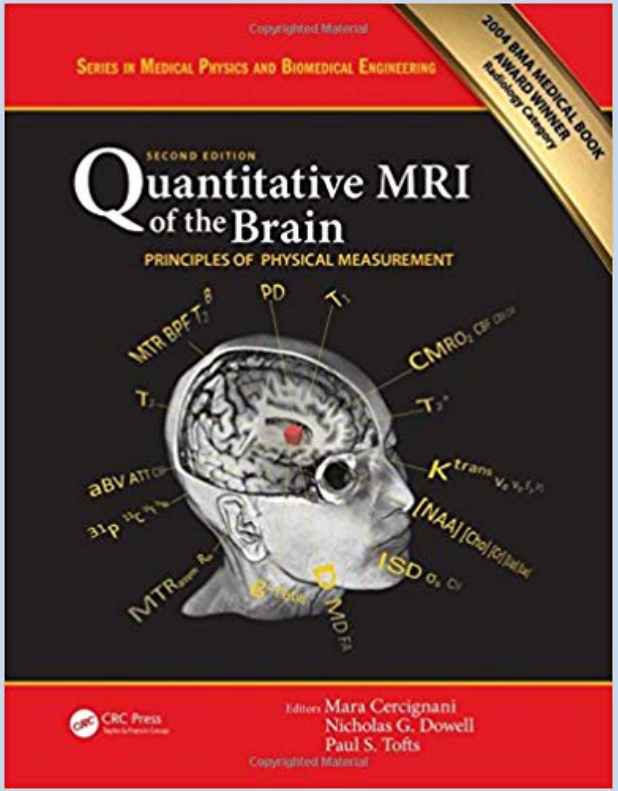
PC-MRA 2D and 3D		**TOF-MRA 2D**	
TE	Minimum	TE	Minimum
TR	25–33 ms	TR	28–45 ms
Flip angle	30°	Flip angle	40–60°
VENC venous	20–40 cm/s	**TOF-MRA 3D**	
VENC arterial	20–40 cm/s60 cm/s	TE	Minimum
		TR	25–50 ms
		Flip angle	20–30°

Slice thickness 2D		**Slice thickness 3D**	
Thin	2–4 mm	Thin	<1 mm
Medium	5–6 mm	Thick	>3 mm
Thick	8 mm		
FOV		**Matrix**	
Small	<18 cm	Coarse	256 × 128 / 256 × 192
Medium	18–30 cm	Medium	256 × 256 / 512 × 256
Large	>30 cm	Fine	512 × 512
		Very fine	>1024 × 1024
NEX/NSA		**Slice number 3D**	
Short	1	Small	<32
Medium	2–3	Medium	64
Multiple	>4	Large	>128

Quantitative optimization – medical physicists



Unfortunately very few books out there.



Absolute signal from a given voxel

$F_{sequence}$ = signal per unit voxel size

SE = spin echo sequence

GE = gradient echo sequence

IR = inversion recovery sequence

Spin Echo (assuming **TE<<TR**)

$$F_{SE} \propto \left[1 - \exp\left(\frac{-TR}{T_1}\right)\right] \cdot \exp\left(\frac{-TE}{T_2}\right)$$

Inversion Recovery

$$F_{IR} \propto \left[1 - 2\exp\left(\frac{-TI}{T_1}\right) + \exp\left(\frac{-TR}{T_1}\right)\right] \cdot \exp\left(\frac{-TE}{T_2}\right)$$

also provided $TE \ll TR$; or if $TR > 5 \times T_1$ this simplifies to

$$F_{IR} \propto \left[1 - 2\exp\left(\frac{-TI}{T_1}\right)\right] \cdot \exp\left(\frac{-TE}{T_2}\right)$$

Gradient Echo

$$F_{GE} \propto \frac{\sin\alpha \cdot (1 - \exp(-TR/T_1)) \cdot \exp(-TE/T_2^*)}{1 - \cos\alpha \exp(-TR/T_1)}$$

for a 'spoiled' gradient echo (possibly called 'SPGR', 'FLASH' or 'T1-FFE' on your scanner).

Noise (SD)

2D

$$\text{noise} \propto \frac{\sqrt{BW}}{\sqrt{NSA \cdot N_{PE} \cdot N_{FE}}}$$

$$\text{noise} \propto \frac{\sqrt{bw}}{\sqrt{NSA \cdot N_{PE}}}$$

BW = total rBW across the whole echo used by GE Healthcare
bw = rBW/pixel used by Siemens and Philips

3D Replace N_{PE} with N_{PE1} x N_{PE2} (since there are two phase encoding directions)

SNR

2D

$$\mathrm{SNR} \propto \frac{\mathrm{FOV}_{FE} \cdot \mathrm{FOV}_{PE} \cdot \Delta z \cdot F_{sequence} \sqrt{NSA}}{\sqrt{BW \cdot N_{FE} \cdot N_{PE}}}$$

For systems which utilize the 'bandwidth per pixel' concept we get the following equation:

$$\mathrm{SNR} \propto \frac{\Delta x \cdot \Delta y \cdot \Delta z \cdot F_{sequence} \cdot \sqrt{NSA \cdot N_{PE}}}{\sqrt{bw}}$$

3D

$$\mathrm{SNR} \propto \frac{\Delta x \Delta y \Delta z \cdot F_{sequence} \cdot \sqrt{NSA \cdot N_{\mathrm{FE}} \cdot N_{\mathrm{PE1}} \cdot N_{\mathrm{PE2}}}}{\sqrt{BW}}$$

$$\mathrm{SNR} \propto \frac{\Delta x \Delta y \Delta z \cdot F_{sequence} \cdot \sqrt{NSA \cdot N_{\mathrm{PE1}} \cdot N_{\mathrm{PE2}}}}{\sqrt{bw}}$$

As a rule-of-thumb an SNR higher than 20: 1 offers little image quality advantage to the observer and excess SNR would be best converted to either a larger matrix or reduced scan time.

Acquisition Time

2D Acquisition Time = TR x N_{PE} x NSA

3D Acquisition Time = TR x N_{PE1} x N_{PE2} x NSA

Physics Quantitative Optimization - a case study from Greece

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journal homepage: www.elsevier.com/locate/ejmp

Original paper

Neonatal brain: Fabrication of a tissue-mimicking phantom and optimization of clinical T1w and T2w MRI sequences at 1.5 T

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Clinical Problem

- Relaxation times T1 and T2 of neonatal brain tissues differ greatly from those of children and adults (mainly owing to incomplete myelination, more water therefore longer T1 and T2).
- Using adult TR and TE leads to low contrast (RC) between white and grey matter
- *In vivo* optimisation is not ethically acceptable particularly in neonates (neonates have undeveloped thermoregulation and cannot speak up if SAR too high and overheated)
- Such optimisation had been done at 3T but not at 1.5T. The clinic where the authors work had only 1.5T and moreover for safety reasons they would prefer to use 1.5T on neonates
- Advices from other centres etc not scientifically optimised – mainly based on opinion
- Needed to optimise own SE protocols at 1.5T themselves

Optimising the values of TE and TR for SE T1w sequences for max signal contrast between WM and GM

Spin Echo (assuming **TE<<TR**)

$$F_{SE} \propto \left[1 - \exp\left(\frac{-TR}{T_1}\right)\right] \cdot \exp\left(\frac{-TE}{T_2}\right)$$

- Since T1w choose small TE = 10ms for low T2 weighting, need to find optimal TR
- Choose T1 and T2 values from the literature for WM and GM:
  - WM: T1 = 1653ms T2 = 376ms
  - GM: T1 = 1136ms T2 = 200ms
- Set up two equations for S_{GM} and S_{WM}
- Set up equation for relative contrast = $S_{GM} - S_{WM}$
- Find $d(S_{GM} - S_{WM})/d(TR)$
- Set $d(S_{GM} - S_{WM})/d(TR) = 0$ for TR giving max relative contrast

Literature search for T1 and T2 values of neonatal brain

TABLE I	T1 and T2 Relaxation Times for Six Anatomic Regions and White and Gray Matter	
Region	T1 (msec)	T2 (msec)
Frontal white matter	1,771 ± 227	435 ± 50
Centrum semiovale	1,726 ± 201	385 ± 45
Forceps major	1,627 ± 266	360 ± 30
White matter (average)	1,712 ± 235	394 ± 52
Thalamus	1,116 ± 223	191 ± 28
Putamen	1,095 ± 207	207 ± 26
Cortical gray matter	1,216 ± 275	214 ± 19
Gray matter (average)	1,144 ± 245	206 ± 26

Choose values of tissues you want to increase the relative contrast of, say WM and GM

Ref: Jones et al MRI of the neonatal brain: optimization of SE parameters

Further Tweaking – to avoid in vivo optimization you need a phantom

- Set up a phantom consisting of two vials with Gd-DTPA doped Agarose gel one having T1 and T2 of the neonatal GM and one with T1 and T2 of neonatal WM
- Tweak the optimised TR obtained by calculation using ROI measurements on the images for both tubes for maximum contrast

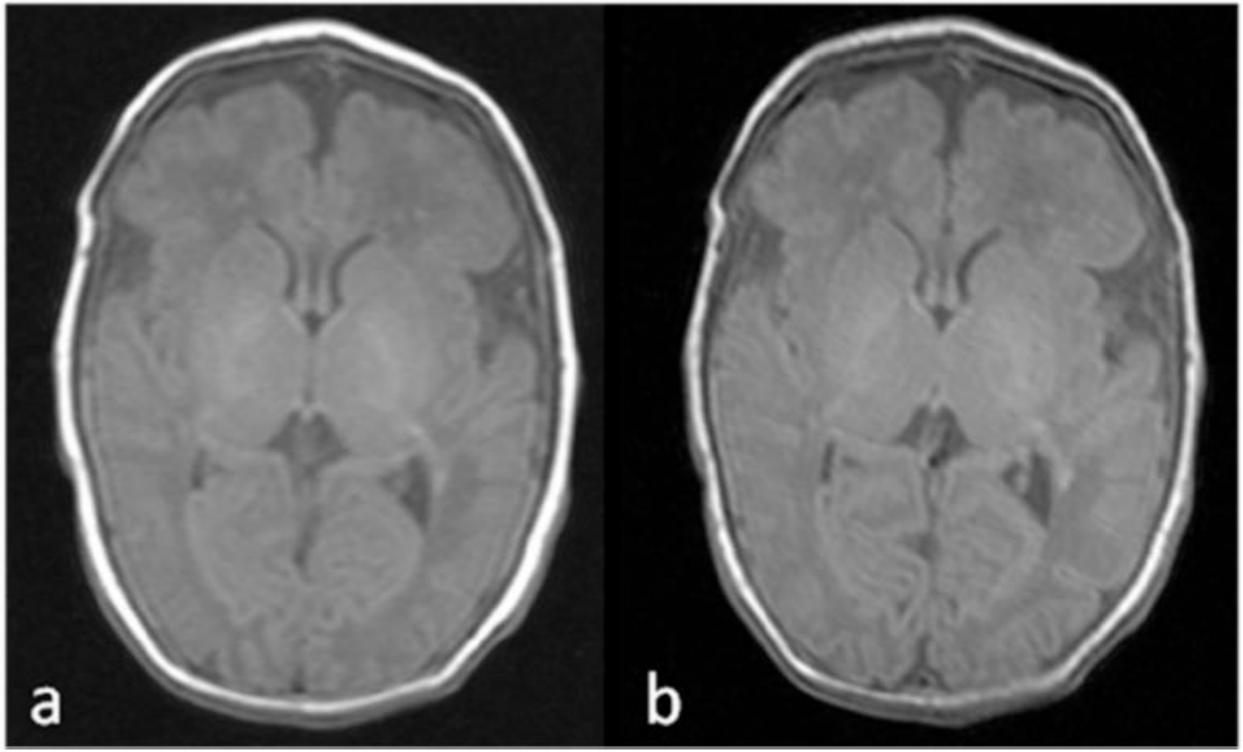

Fig. 9. MRI of a male neonate of 41 weeks' gestational age. (a) Standard T1w image at the level of basal ganglia with TR/TE values 800/10 ms and (b) optimised T1w image at the same level with TR/TE values 1200/10 ms.

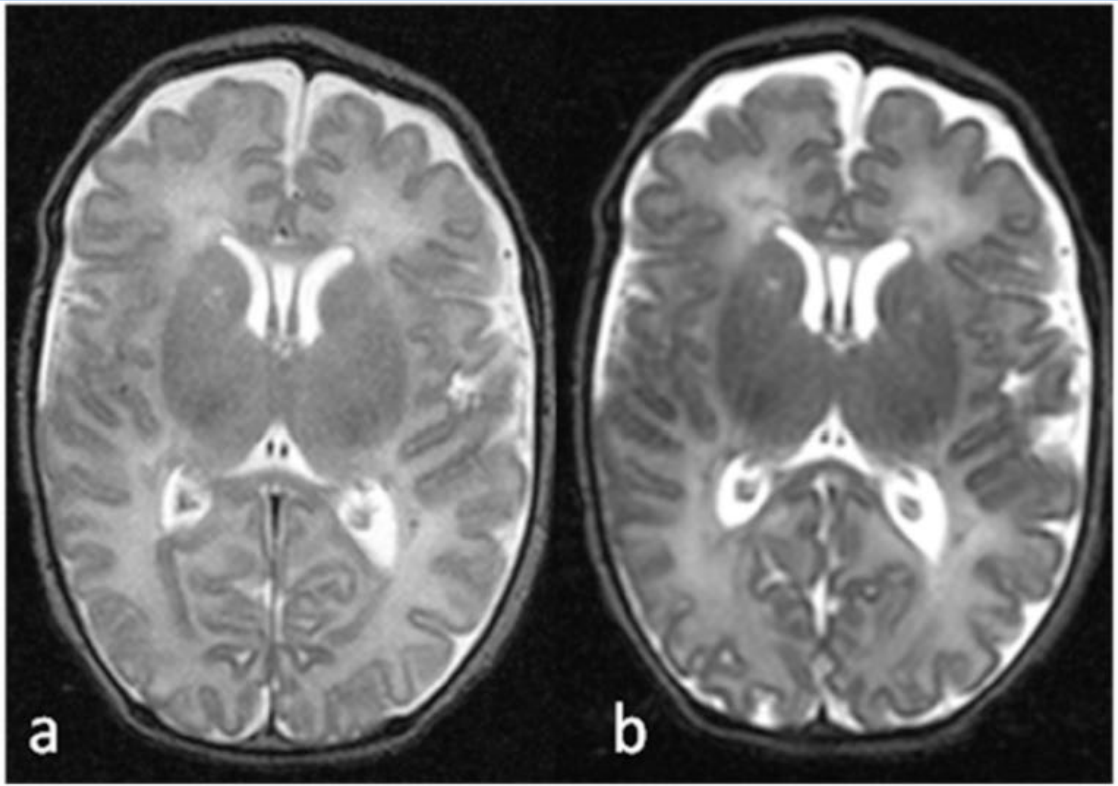

Fig. 10. MRI of a female neonate of 41 weeks' gestational age. (a) Standard T2w image at the level of basal ganglia with TR/TE values 4200/209 ms and (b) optimised T2w image at the same level with TR/TE values 7890/274 ms.

References

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Thank you for your attention!

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