MRI – Tissue Characteristics and Image Production

Radiotherapy Lecture

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Memorial Sloan Kettering Cancer Center

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MRI has superior soft tissue contrast

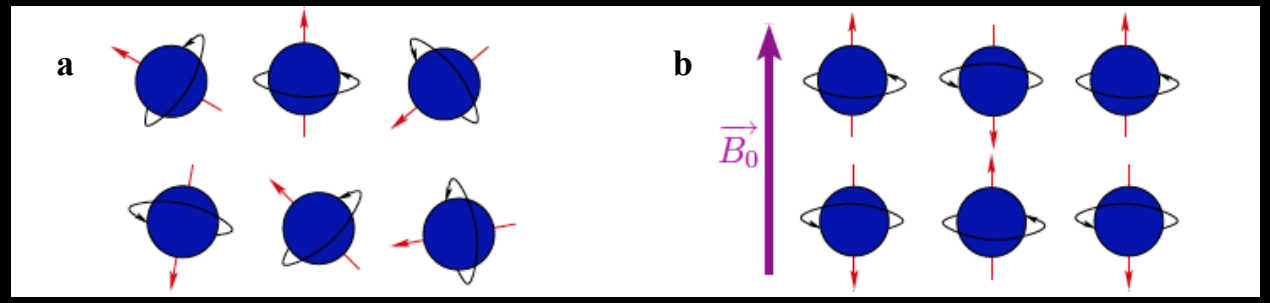
- T1 relaxation
- T2 relaxation
- Proton density
- FLAIR
- Diffusion weighted Imaging
- Perfusion weighted Imaging

Source: Citation

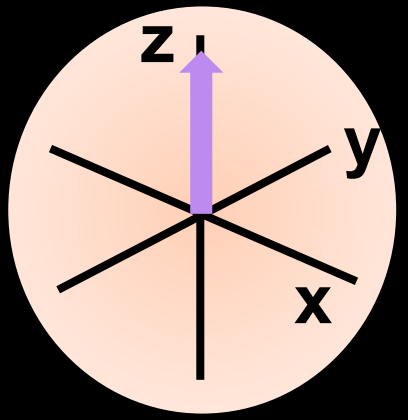
Basic MRI physics Recap

H atoms randomly orientated

H atoms align B field

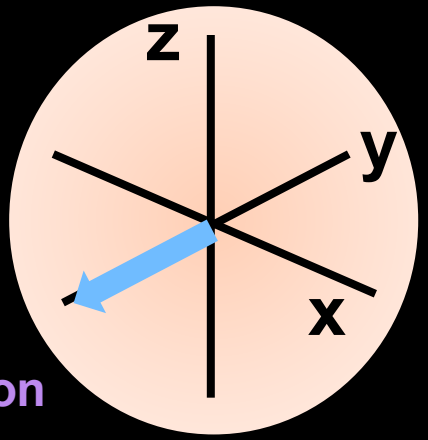


Magnetization in the direction of B field



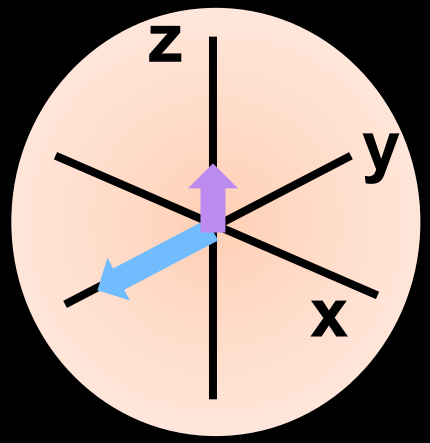
Longitudinal Magnetization

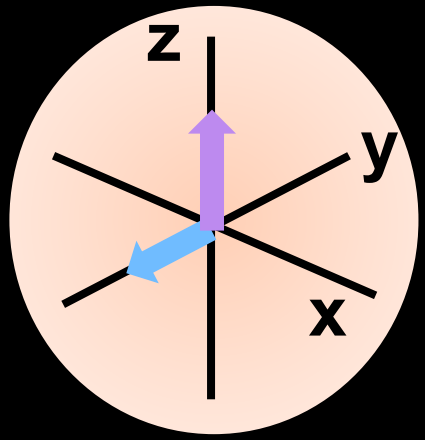
Apply a RF field

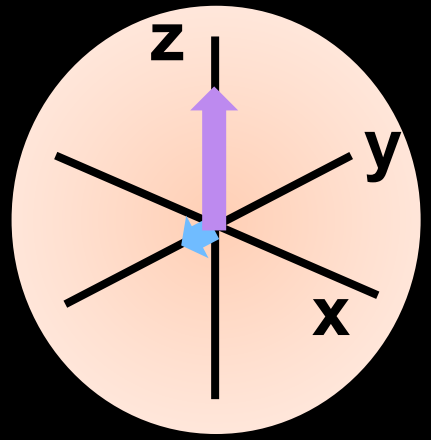


Transverse Magnetization

RF field off, H atoms go through **Relaxation**



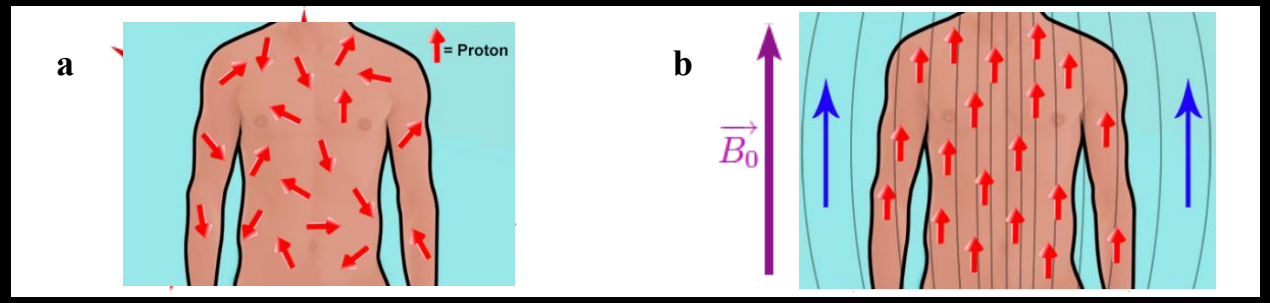




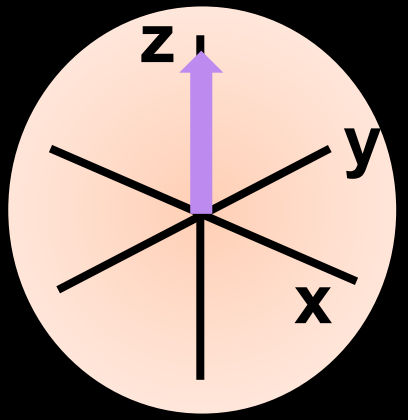
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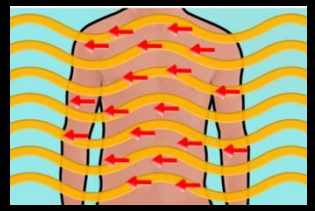
H atoms align B field



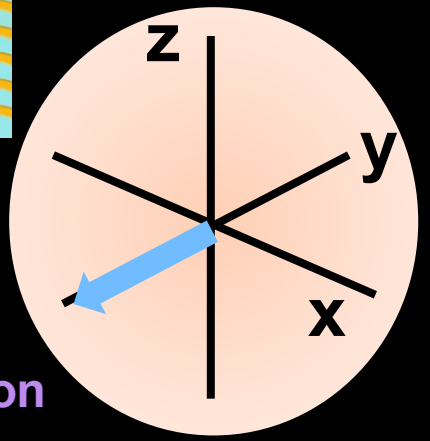
Magnetization in the direction of B field



Longitudinal Magnetization

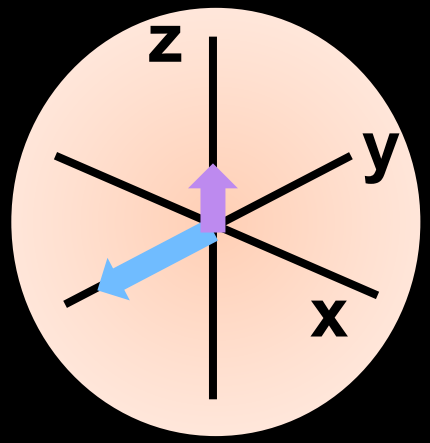


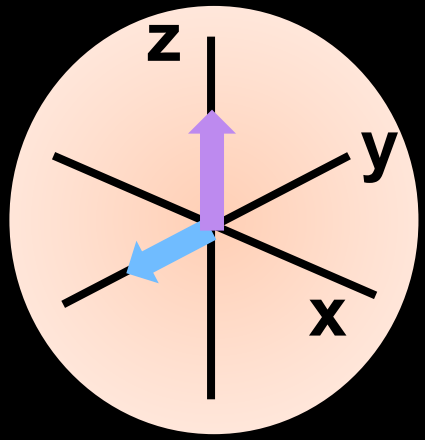
Apply a RF field

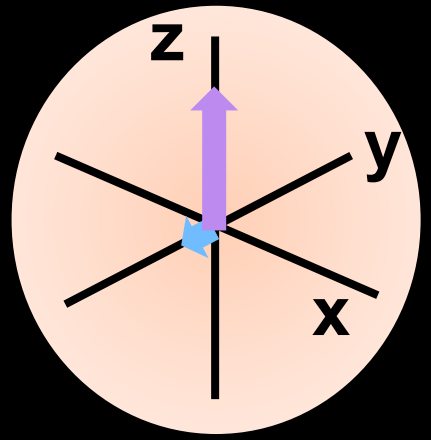


Transverse Magnetization

RF field off, H atoms go through **Relaxation**

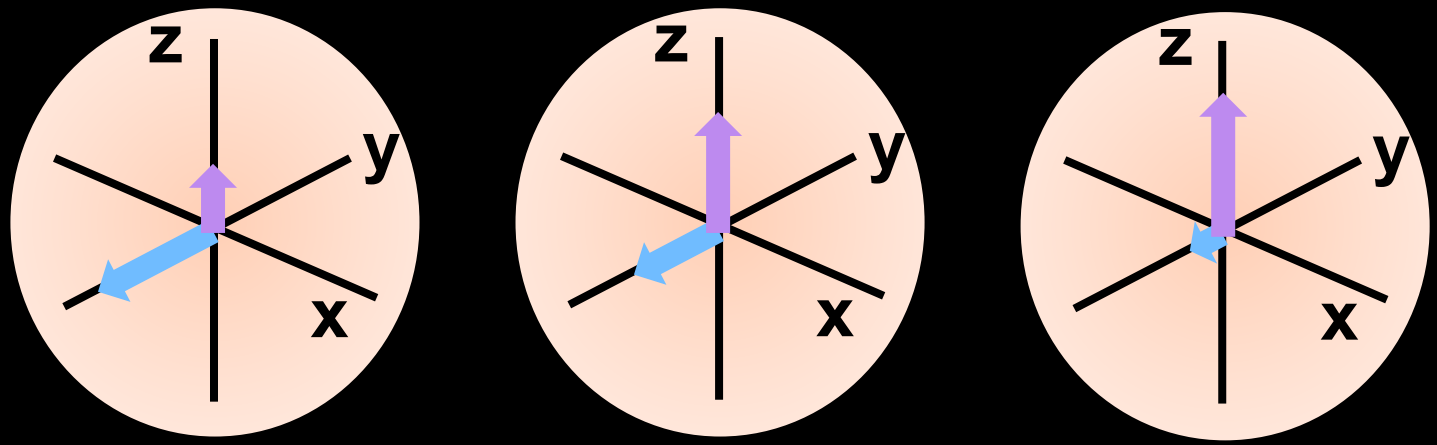






Basic MRI physics Recap

RF field off, H atoms go through **Relaxation**



Time to recovery the longitudinal magnetization ↑ → Spin lattice relaxation time T1 (ms)

Time to lose the transverse magnetization ↙ → Spin-spin relaxation time T2 (ms)

T1 relaxation

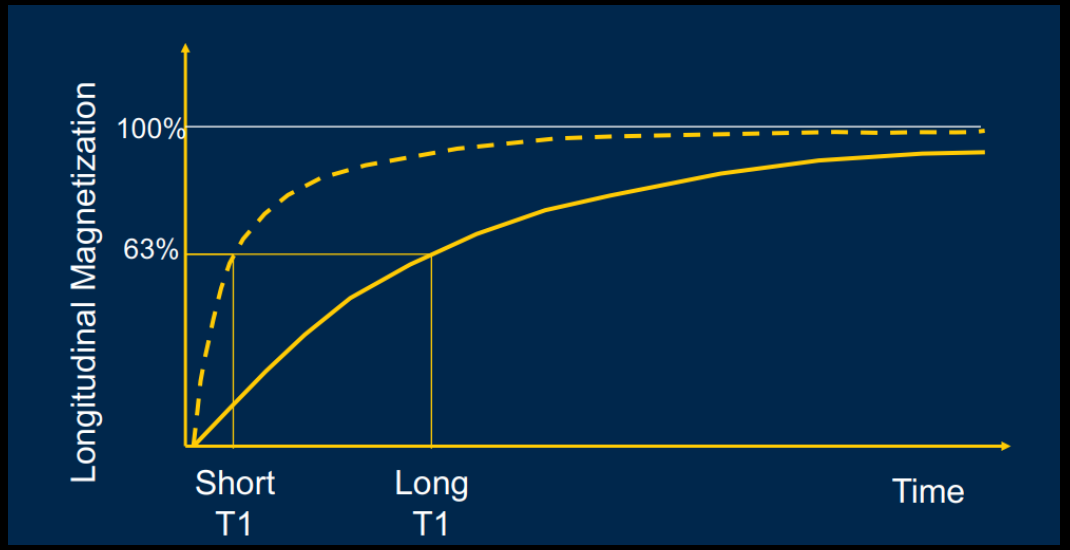
T1 = time it takes for 63% of longitudinal magnetization to recover

Different tissue has different T1 (ms or s)

Slightly different depending on scanner and B field

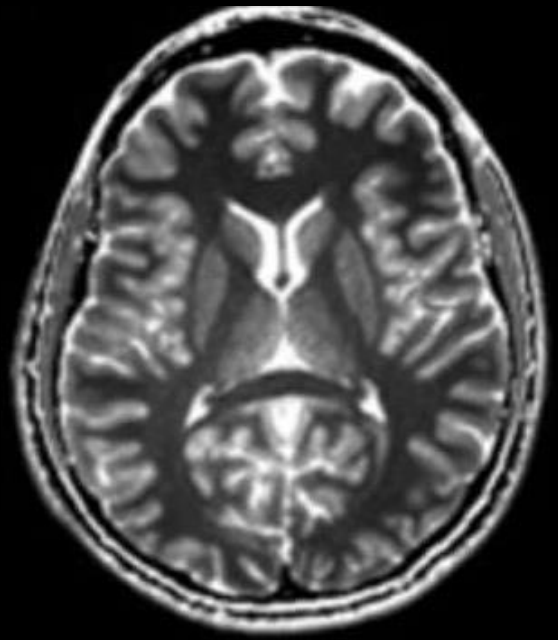
Water → longest T1

Fat → short T1



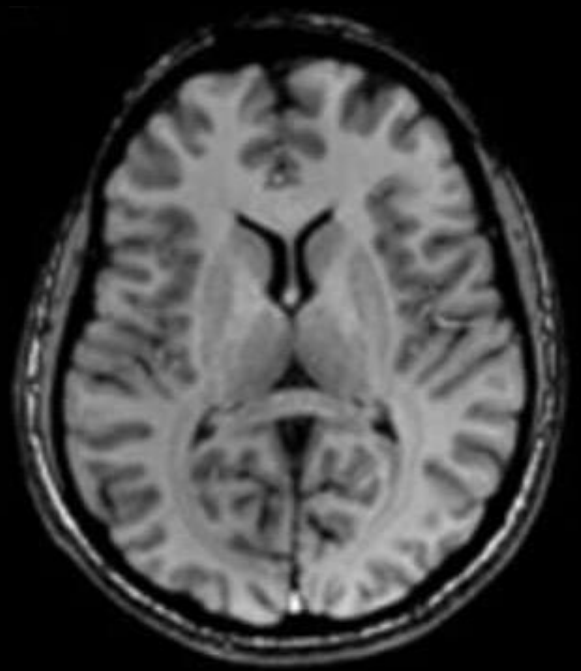
Tissue	T1 (msec)
Water/CSF	4000
Gray matter	900
Muscle	900
Liver	500
Fat	250
Tendon	400

T1 relaxation



T1 map ~ $T1$

- CSF: very bright
- Fat: dark
- Grey Mater: light grey
- White matter: dark grey

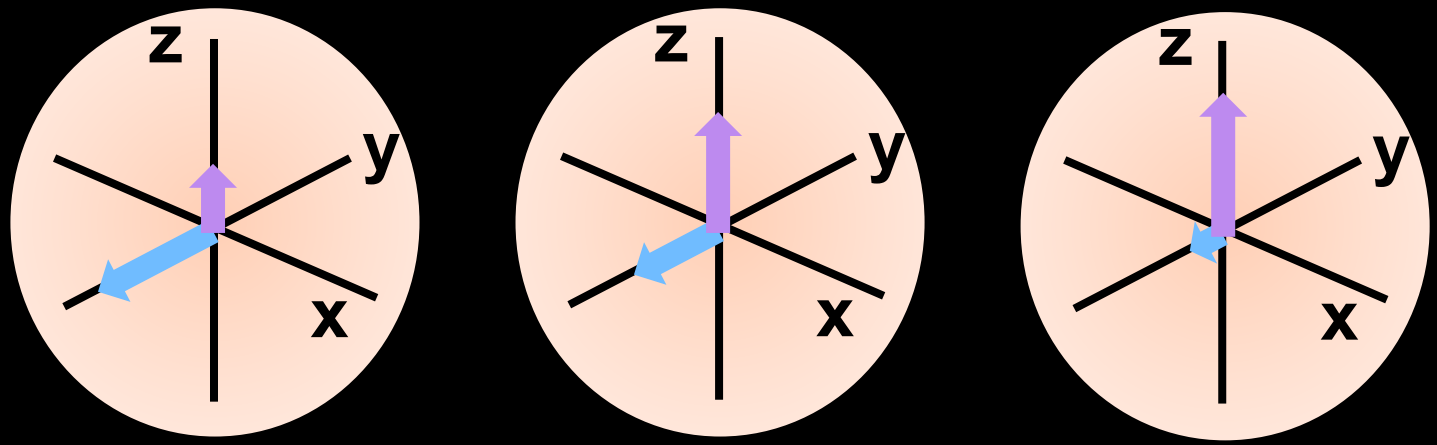


T1-weighted Image ~ $1 - exp(1 - t/T1)$

- CSF: very dark
- Fat: light
- Grey Mater: dark grey (more water content)
- White matter: light grey (myelin, fatty substance)

Basic MRI physics Recap

RF field off, H atoms go through **Relaxation**



Time to recovery the longitudinal magnetization ↑ → Spin lattice relaxation time T1 (ms)

Time to lose the transverse magnetization ↙ → Spin-spin relaxation time T2 (ms)

T2 relaxation

T2 = time it takes to lose 63% of transverse magnetization

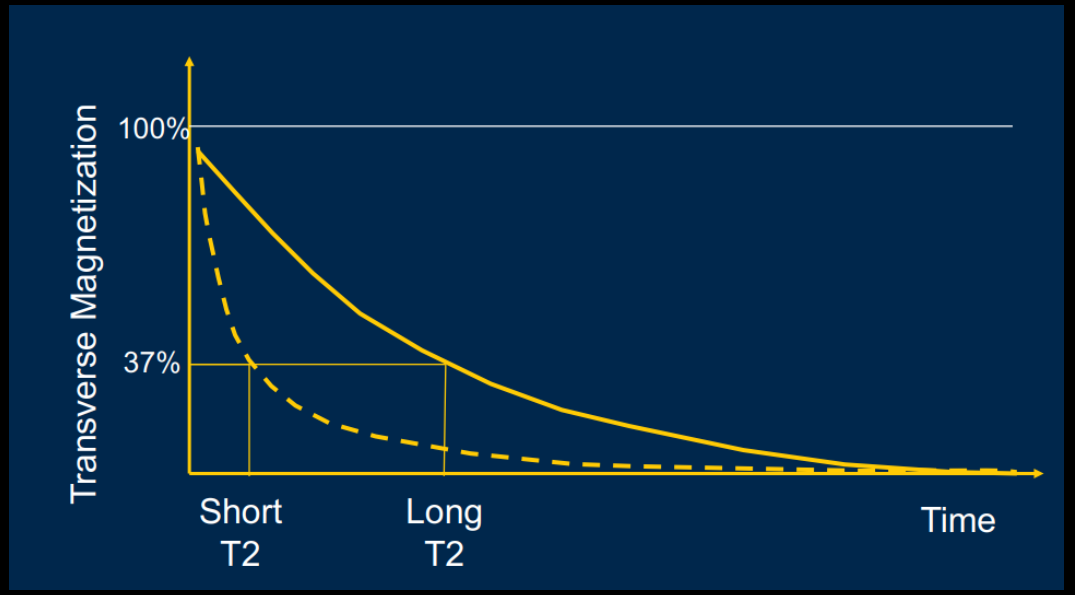
Different tissue has different T2 (ms or s)

Slightly different depending on scanner and B field

Water → long T2

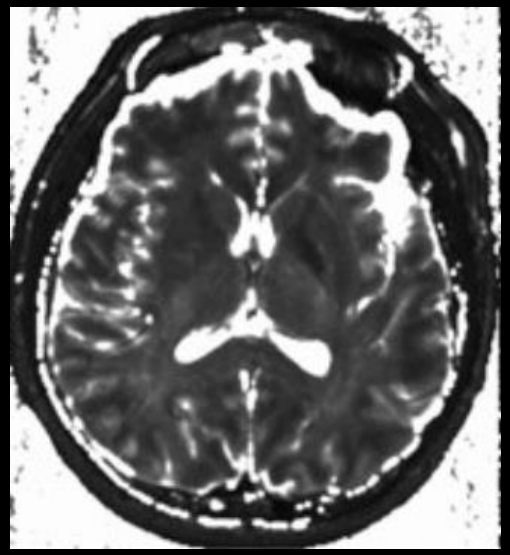
Fat → short T2

Occurs at the same time, but much faster than T1 relaxation



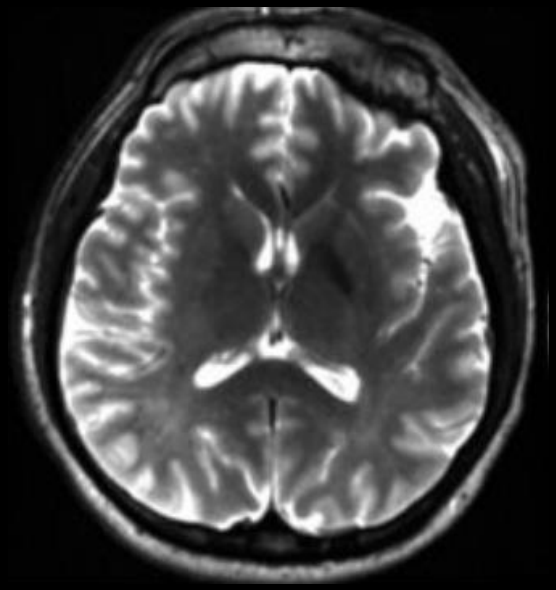
Tissue	T1 (msec)	T2 (msec)
Water/CSF	4000	2000
Gray matter	900	90
Muscle	900	50
Liver	500	40
Fat	250	70
Tendon	400	5

T2 relaxation



T2 map ~ $T2$

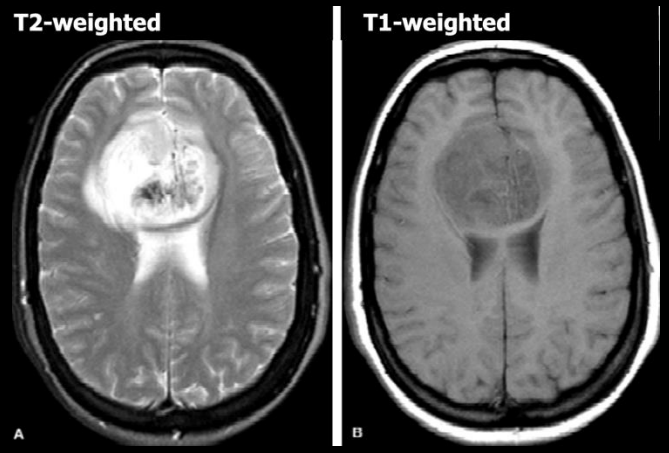
- CSF: very bright
- Fat: light
- Grey Mater: light grey
- White matter: dark grey

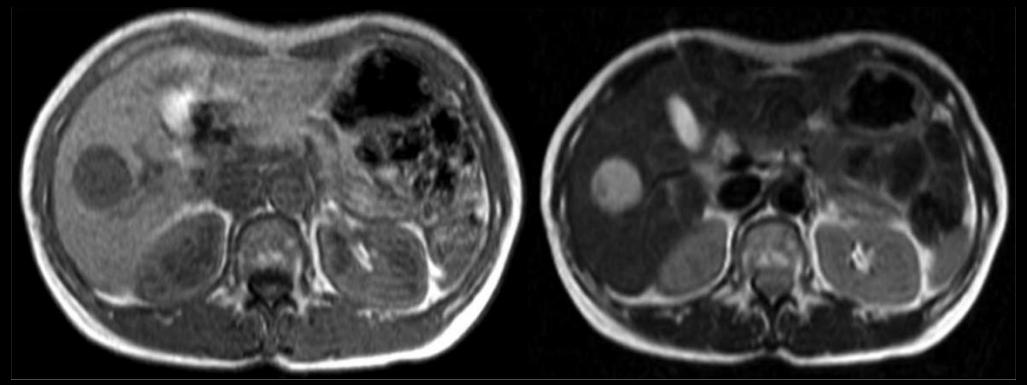


T2-weighted Image ~ $exp(-t/T2)$

- CSF: Bright
- Fat: light
- Grey Mater: light grey (more water content)
- White matter: dark grey (myelin, fatty substance)

Clinical application for T1 and T2 w MRI

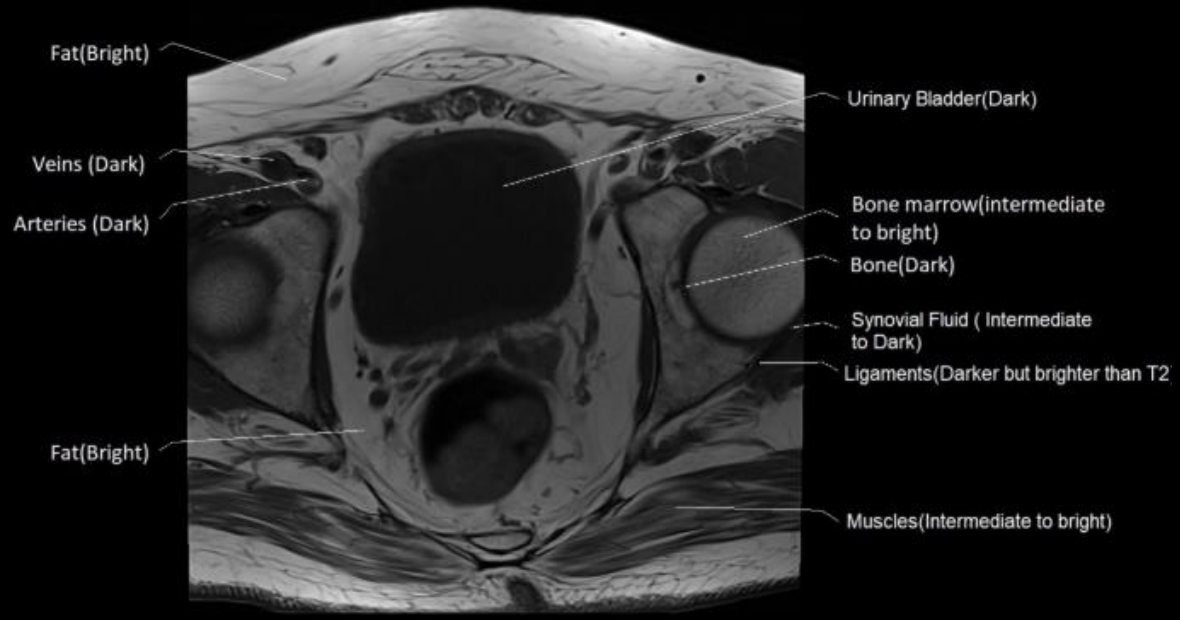


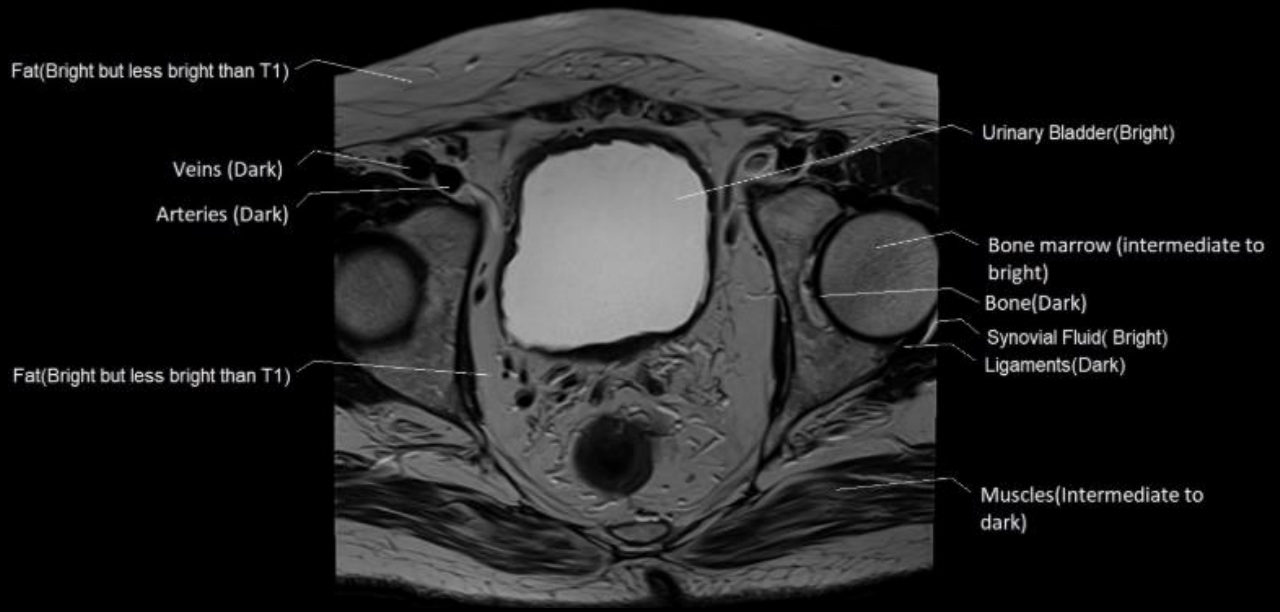


T1w T2w

- No clear rules, T1 and T2w MRI are both often acquired
- T2 weighting shows pathology, fluid filled, edema, necrosis better
- T1 weighting better delineates anatomy in Brain, Musculoskeletal and contrast enhancement

Clinical application for T1 and T2 w MRI





Proton density contrast

Proton = H atom content

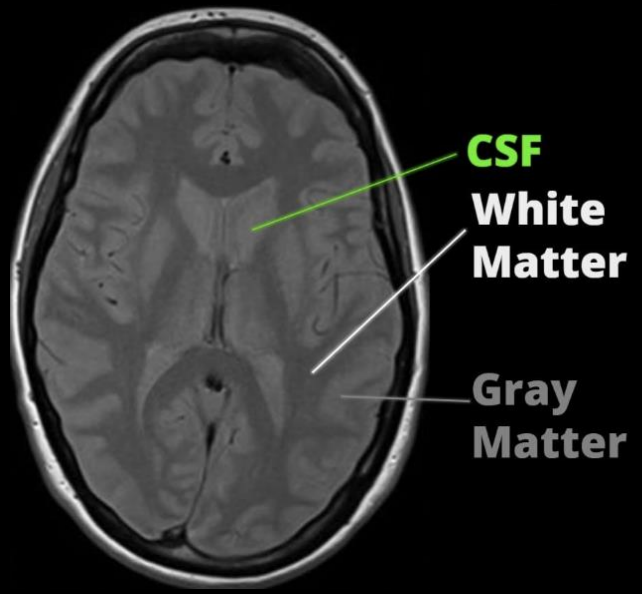
The more H we have, the brighter it is on Proton density weighted images

Water → Bright

Grey matter → light grey

White matter → dark grey

Low soft tissue contrast: most soft tissue have similar water contents, good for musculoskeletal imaging, can differentiate fluid from cartilage





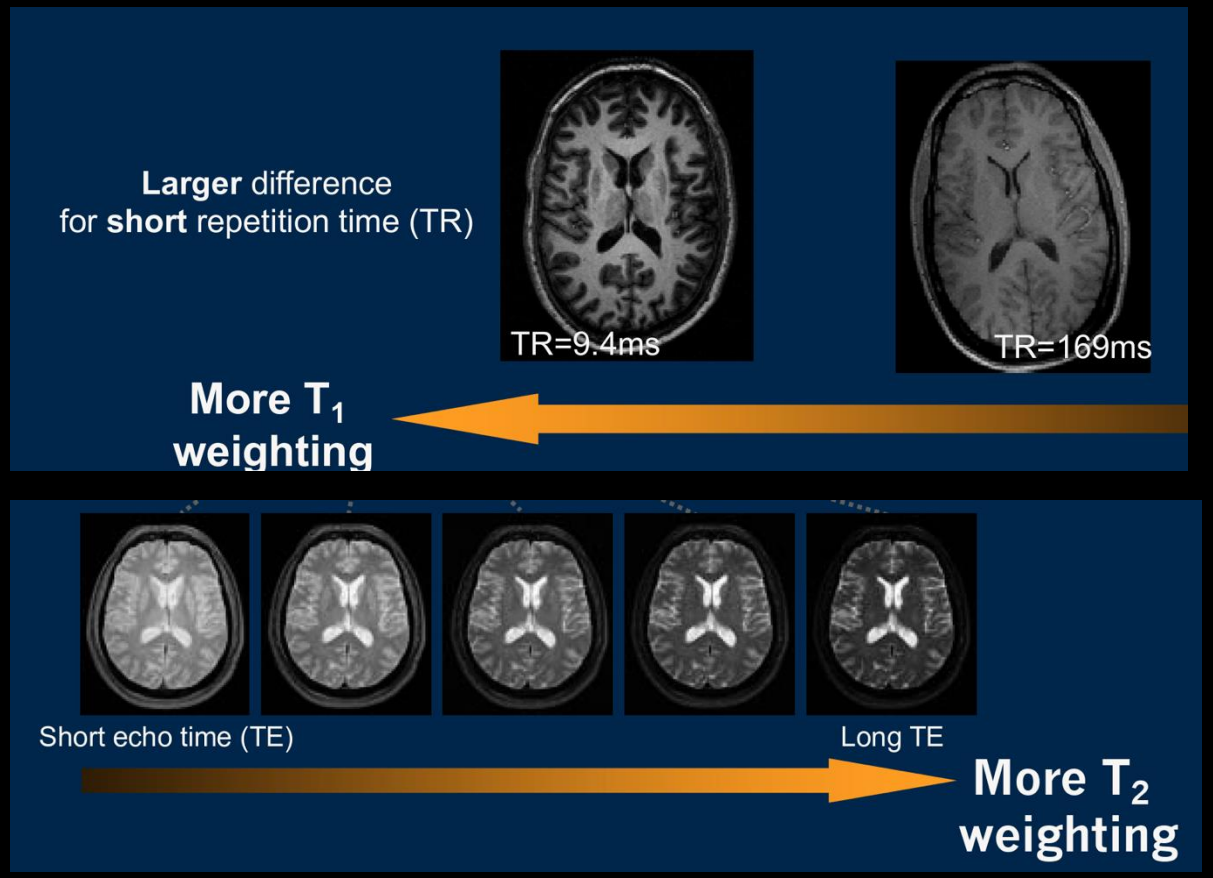
How do we choose the “weighting”?

We typically do not make images of T1 and T2 values in tissue clinically (common in research)

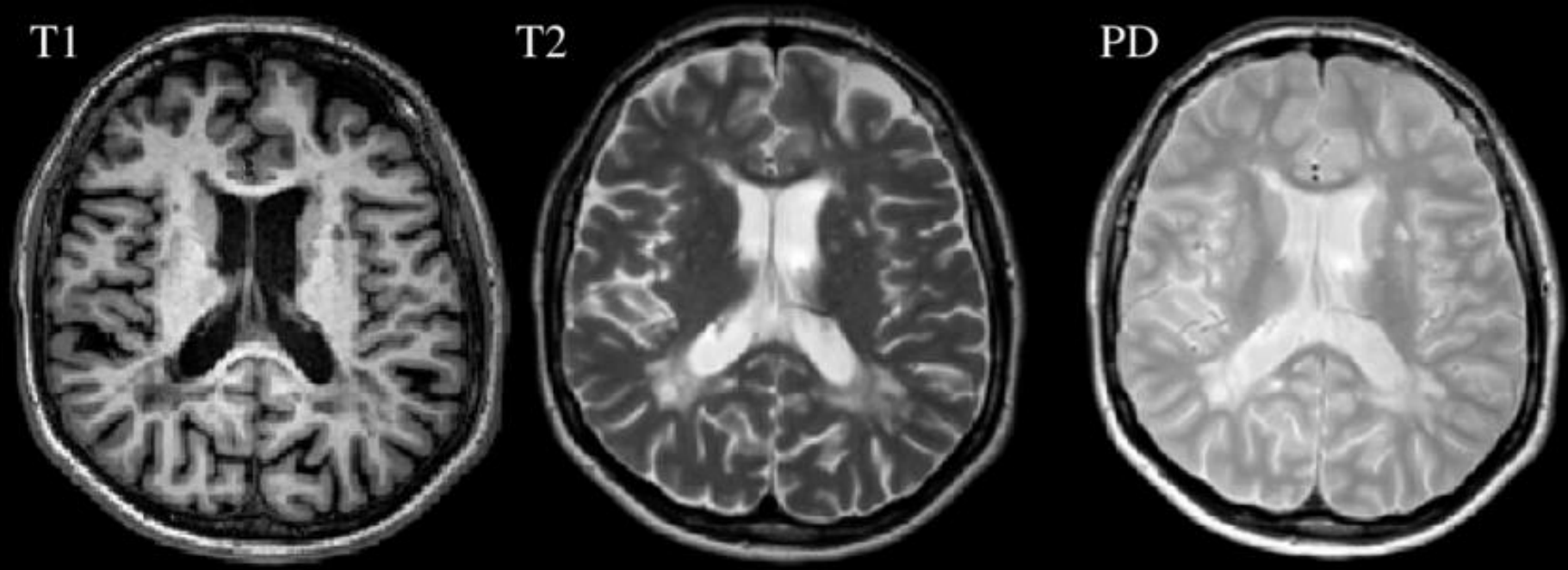
We make images that **emphasize** T1 or T2 contrast difference in tissue

Scanner Parameters

- TR: Repetition time controls T1 contrast
- TE: Echo time controls T2 contrast



How do we choose the “weighting”?



Shorter TR, better T1 contrast, longer TE, better T2 contrast

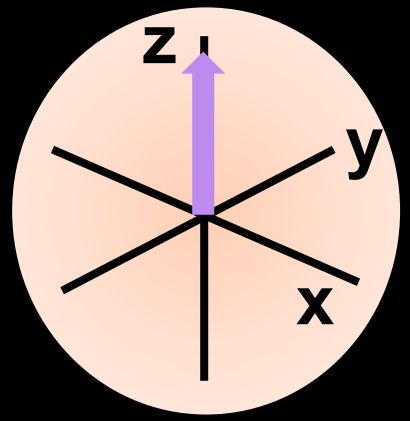
T1w: short TR, short TE

T2w: long TR, long TE

PD: long TR, short TE

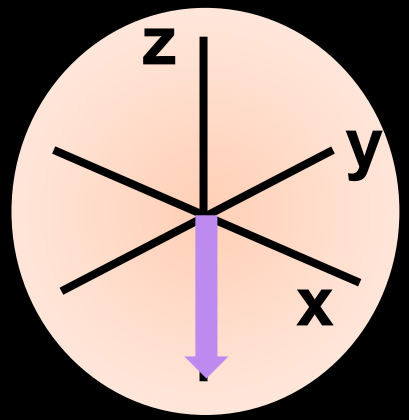
FLAIR (Fluid attenuating inversion recovery)

Magnetization in the direction of B field

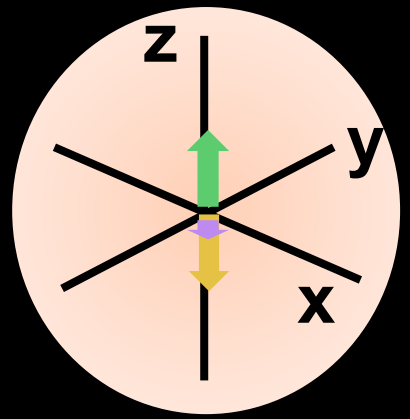


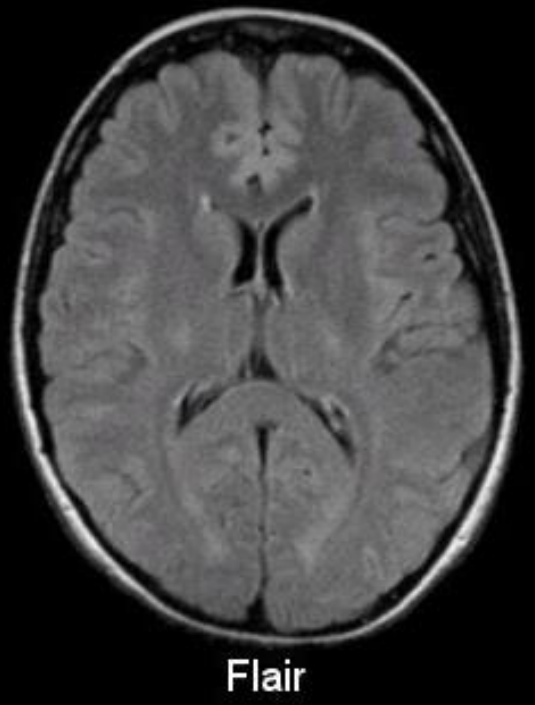
Longitudinal Magnetization

Apply RF

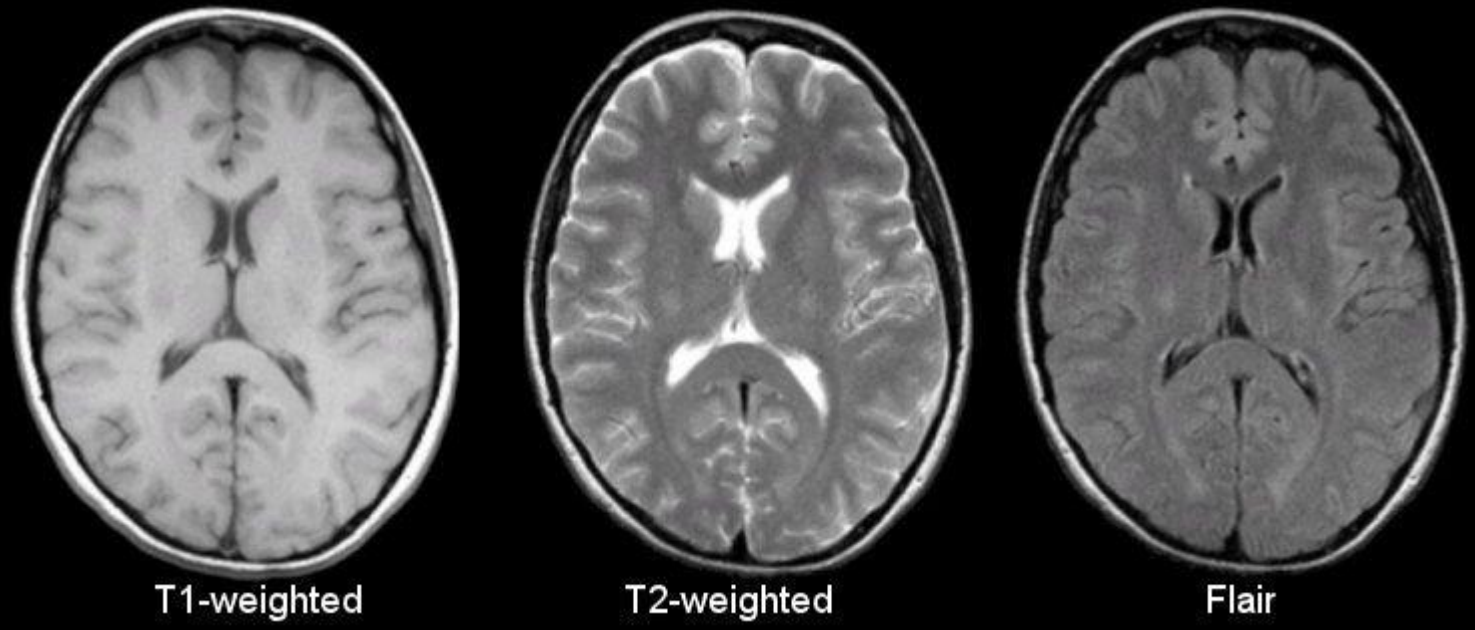


Different tissue recovers at different rate, measure when magnetization of fluid is at 0





FLAIR (Fluid attenuating inversion recovery)



Tissue	T1w	T2w	Flair
CSF	Dark	Bright	Dark
White matter	Light grey	Dark grey	Dark grey
Grey matter	Dark grey	Light grey	Light grey
Fat	Bright	Light	light

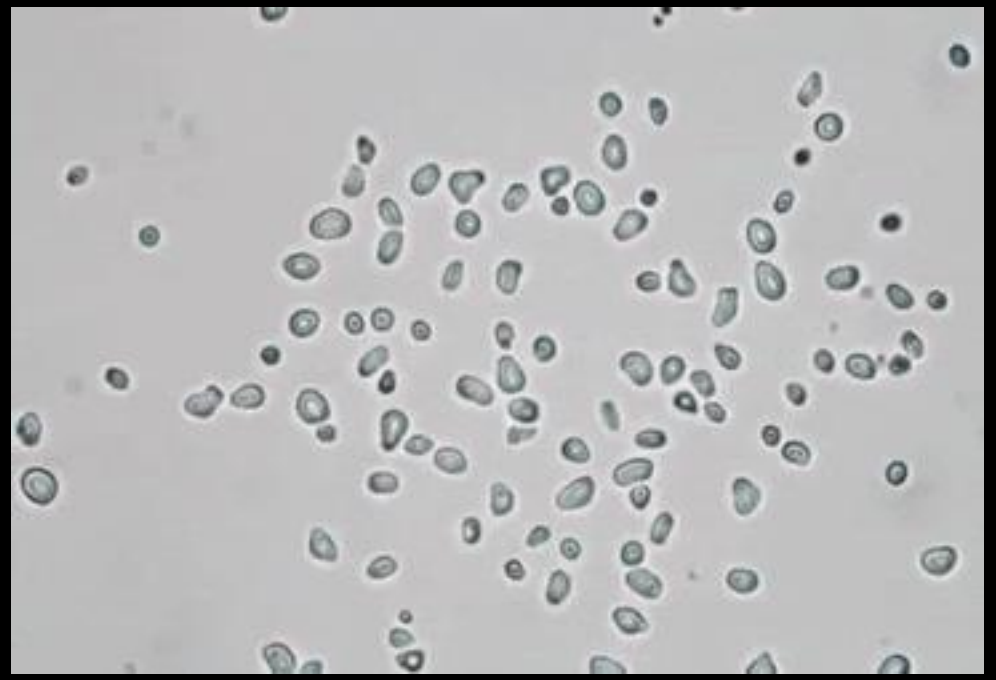
Diffusion weighted MRI

What is diffusion?

In 1827, botanist **Robert Brown** observed a curious random migration of pollen grains in water under the microscope → **Brownian motion**

Diffusion is associated with Brownian motion

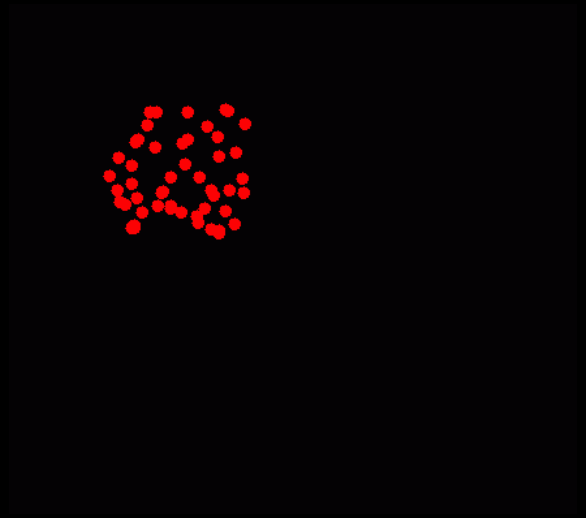






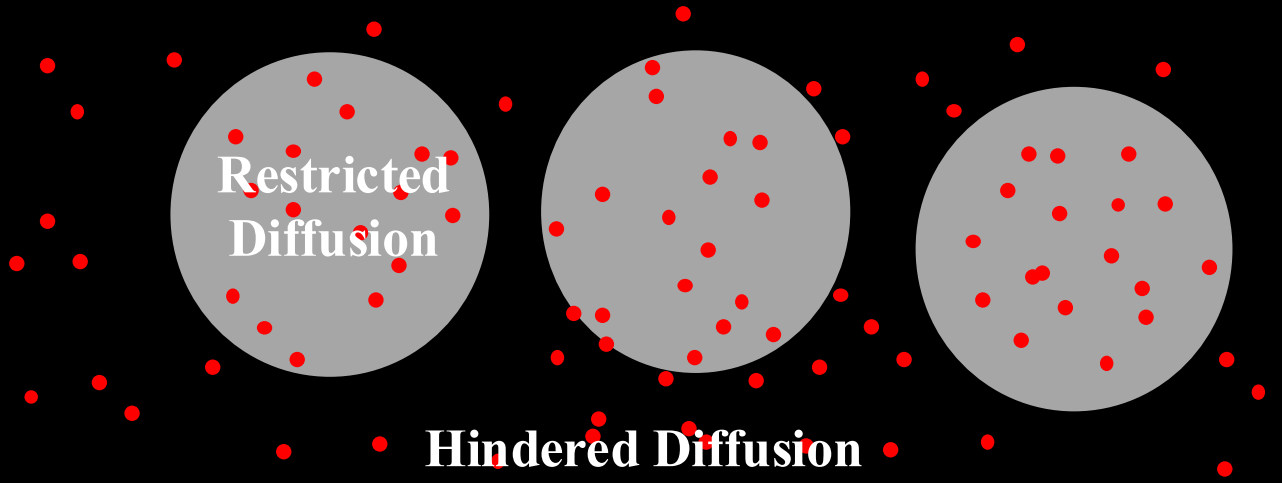
Diffusion weighted MRI

Free Diffusion



Brownian motion
Random walk

2-compartment Diffusion



Extracellular hindered diffusion: delay in motion as water molecules navigate around obstacles
Intracellular restricted diffusion: trapping of water molecules within an enclosed compartment

Diffusion weighted MRI

Diffusion weighting can be adjusted by b-value, increase b, increase weighting to restricted diffusion

$$S = S_0 e^{-\boldsymbol{b}\cdot D}$$

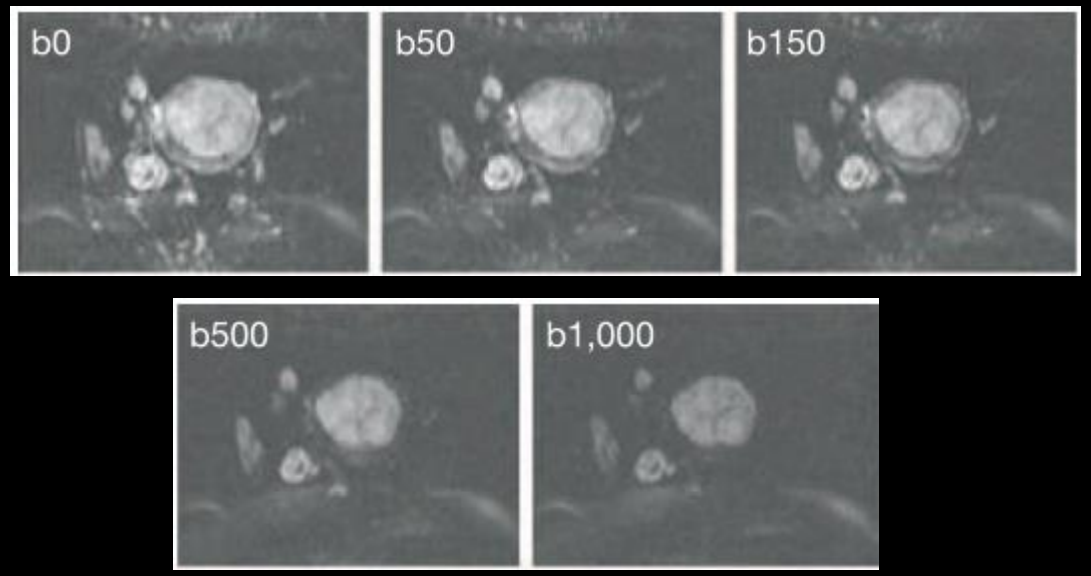


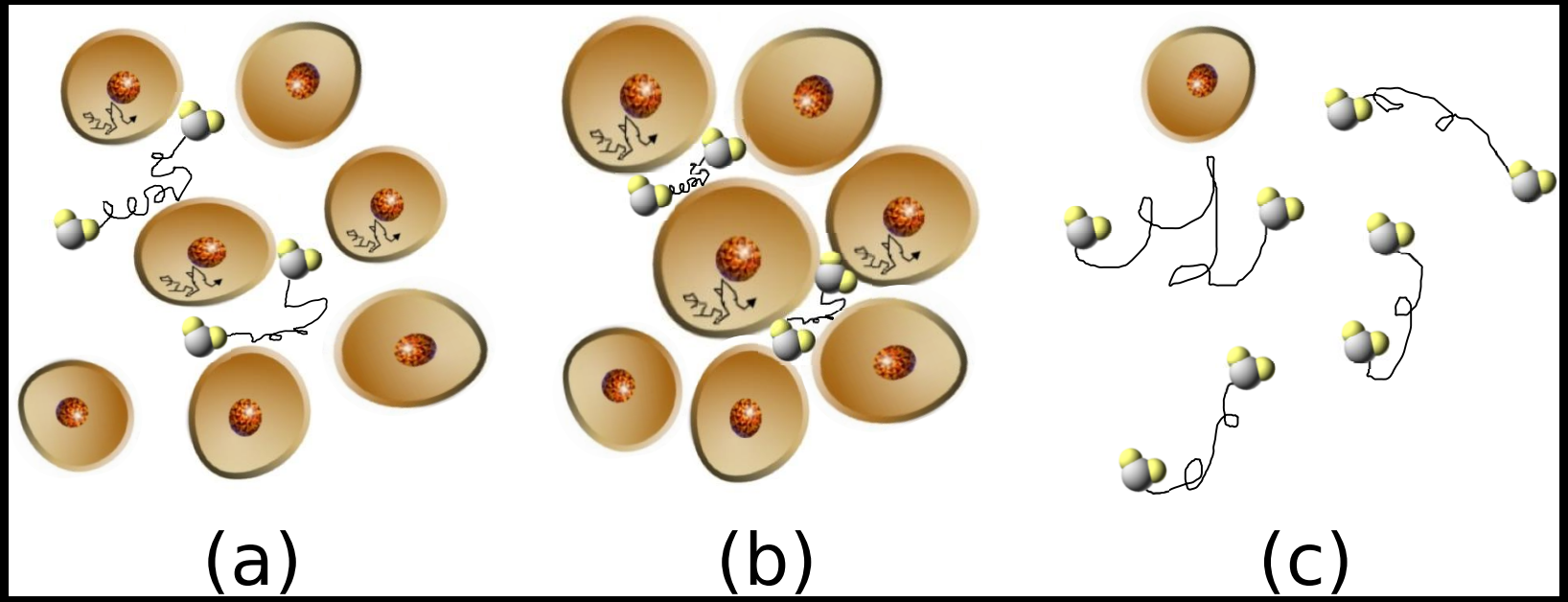
Table 2 Interpretation of tumor diffusion-weighted images.

Intensity of image on T_2W	Intensity of image on DW-MRI (b800–b1,000 s/mm^2)[a]	Intensity of image on ADC (b0–1,000 s/mm^2)[b]	Interpretations
High–intermediate	High	Low	Tumor generally of high cellularity; rarely coagulative necrosis or abscess
High intensity	High	High	T2-shine through; often proteinaceous fluid
Low–intermediate	Low	Low	Fibrous tissue with low water content with/without viable tumor cells
High	Low	High	Fluid; liquefactive necrosis; lower cellularity; gland formation

[a]Obtained at b-values greater than 800–1,000 s/mm^2; [b]Generated using b-values from 0–1,000 s/mm^2. Abbreviations: ADC, apparent diffusion coefficient; DW-MRI, diffusion-weighted MRI; T_2W, T_2-weighted.

Diffusion weighted MRI in Cancer

ADC is of particular interest for cancer application because it reflects cellularity



Loosely packed cells, could be normal tissue

Densely packed cells, could be cancerous tissue

Free diffusion, could be necrosis, fluid (CSF)

Diffusion weighted MRI in cancer

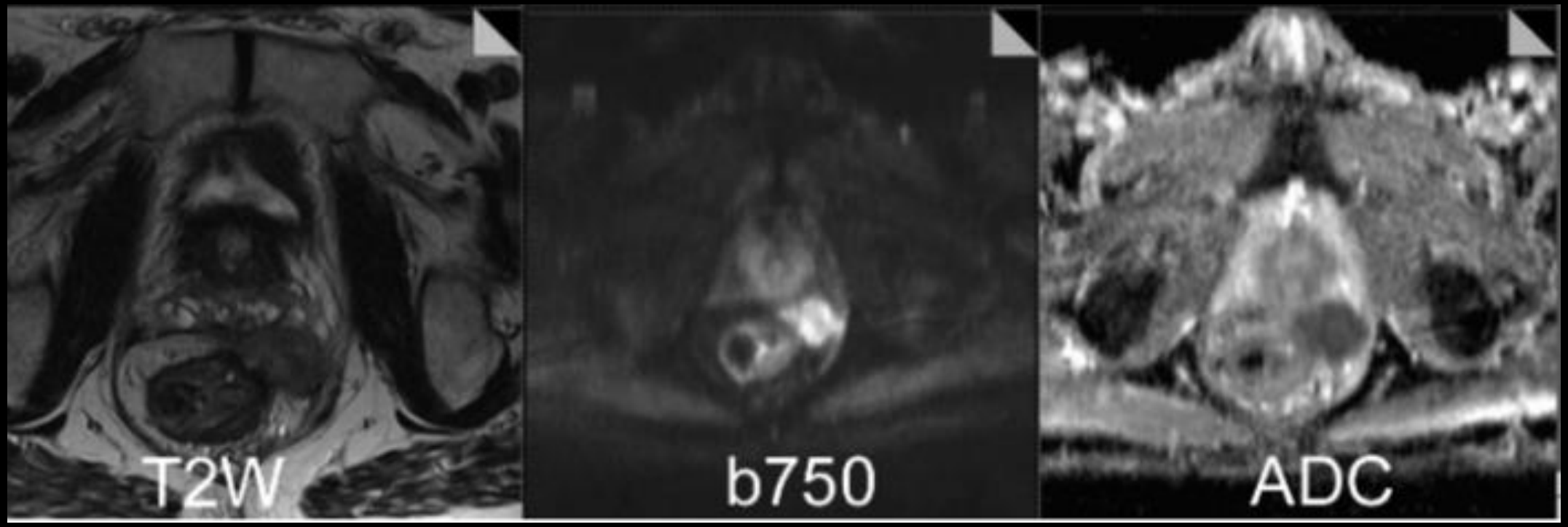


Figure shows Restricted diffusion within rectal cancer (Padhani et al 2009)

Diffusion weighted MRI in cancer

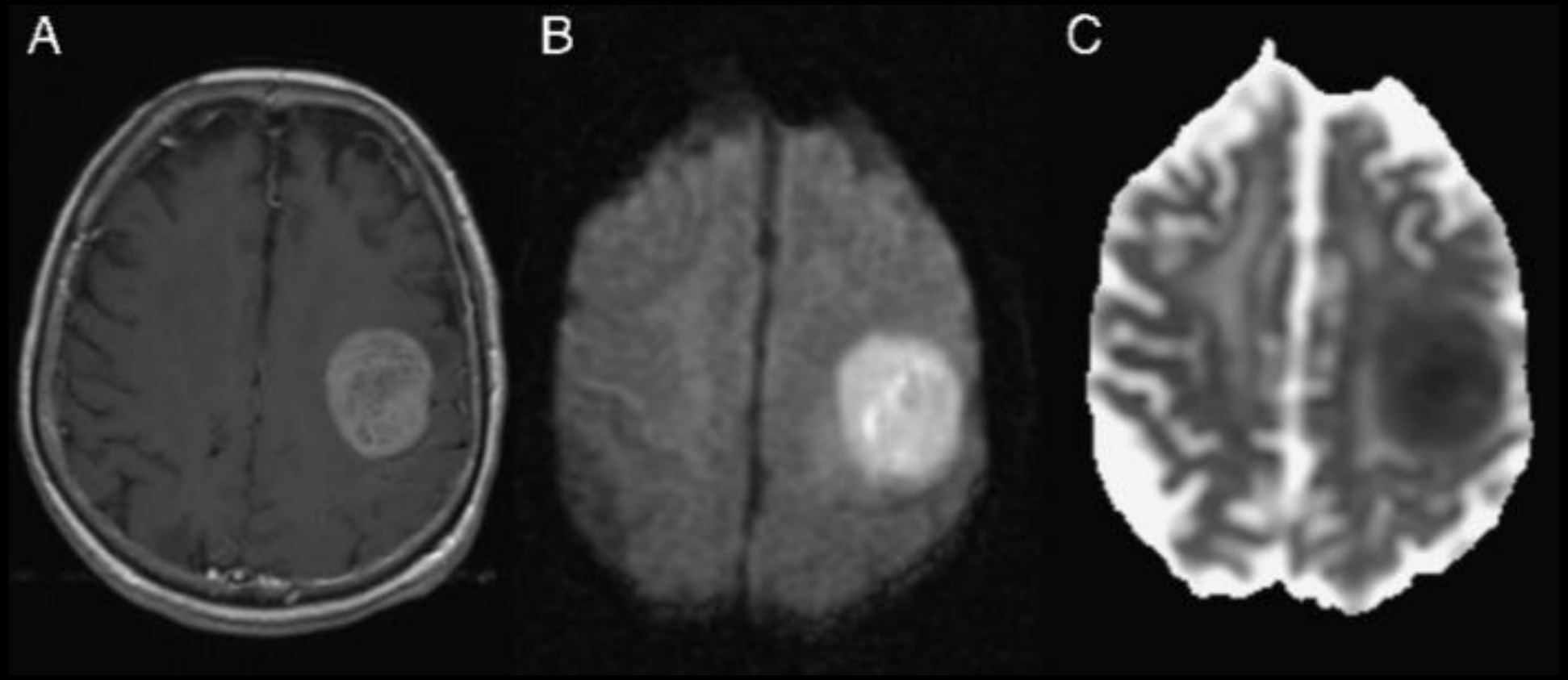
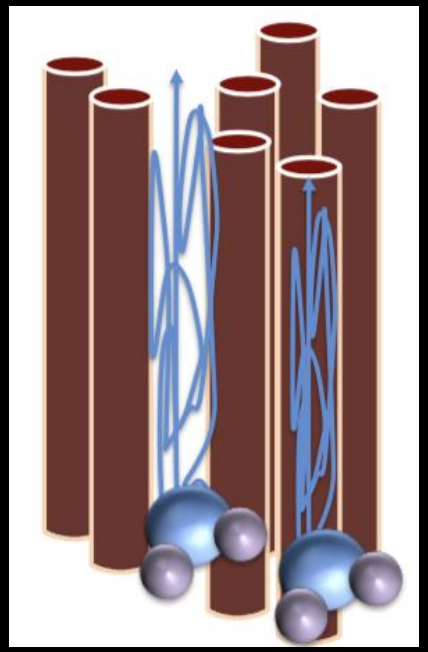


Figure shows Restricted diffusion in CNS lymphoma (Padhani et al 2009)

Diffusion tensor imaging

Path of diffusing water molecules

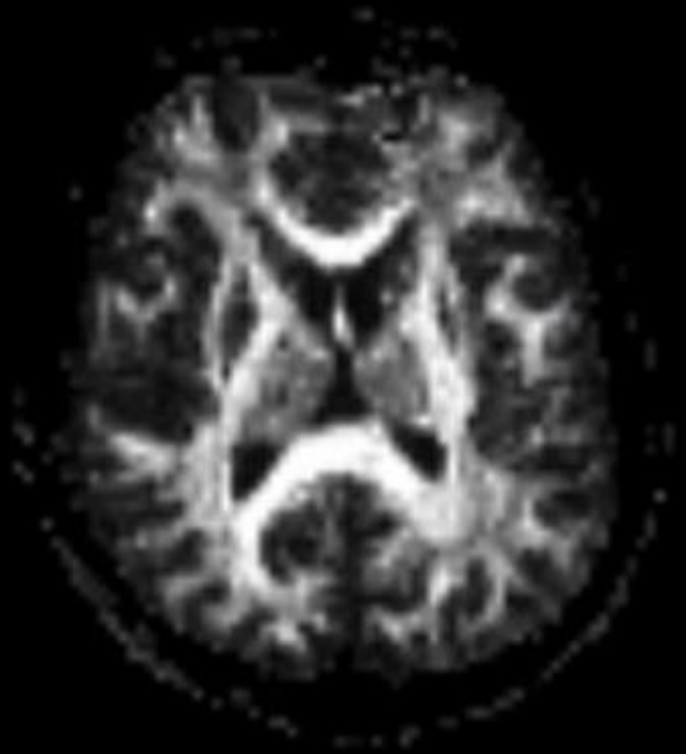


Water displacement distribution

$$D_{xx} = D_{yy} \ll D_{zz}$$

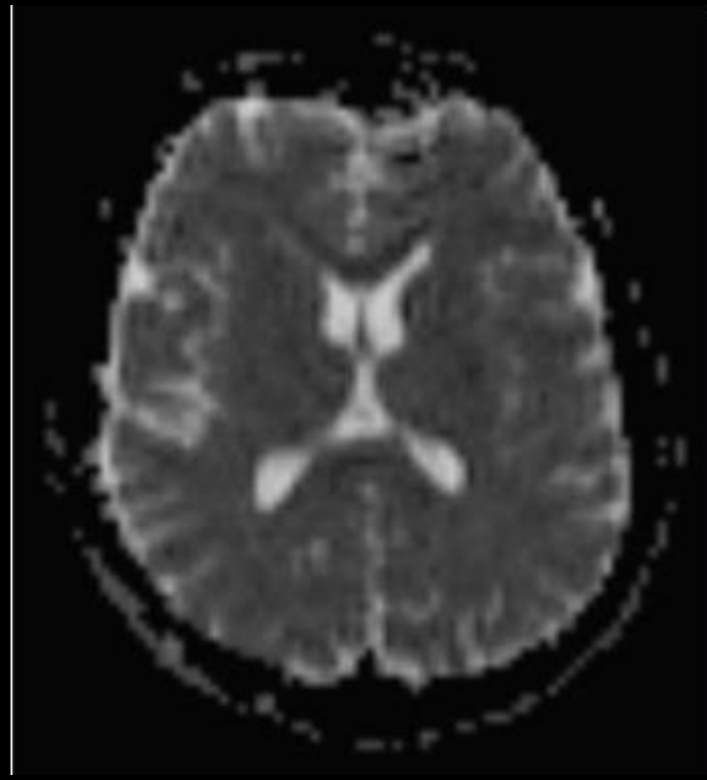
$$[D] = \begin{bmatrix} D_{xx} & D_{xy} & D_{xz} \\ D_{yz} & D_{yy} & D_{yz} \\ D_{zx} & D_{zy} & D_{zz} \end{bmatrix}$$

Application in the brain

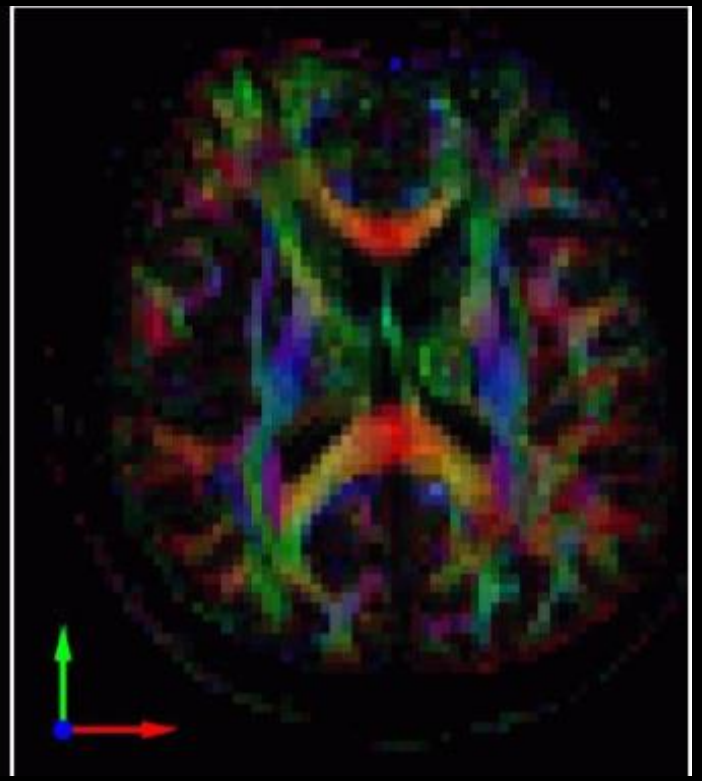


Fractional anisotropy (FA)

Measures How anisotropic water diffusion is



Mean diffusivity (MD)



Principal diffusion directions scaled by FA

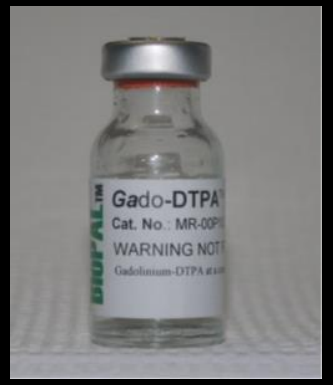
Application in Tractography

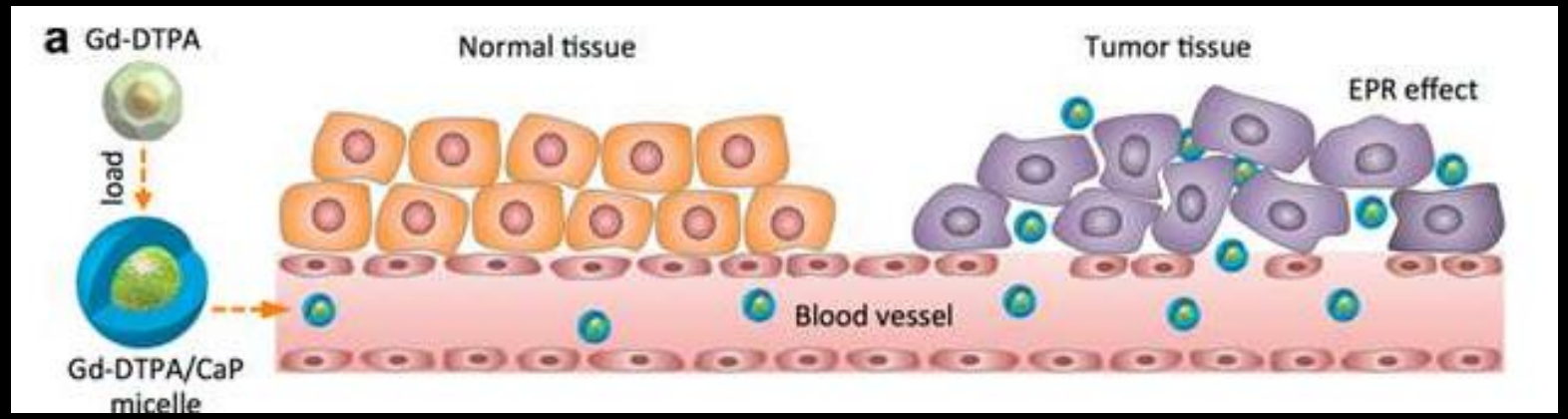


Contrast enhanced MRI

Contrast agent Gd-DTPA

- Prior to imaging, Gadolinium (Gd) is injected as a contrast agent
- Shortens T1 relaxation times of H atoms → increase in T1 contrast
- Gadolinium preferentially accumulates in the tumor based on the enhance permeability and retention effect (EPR)

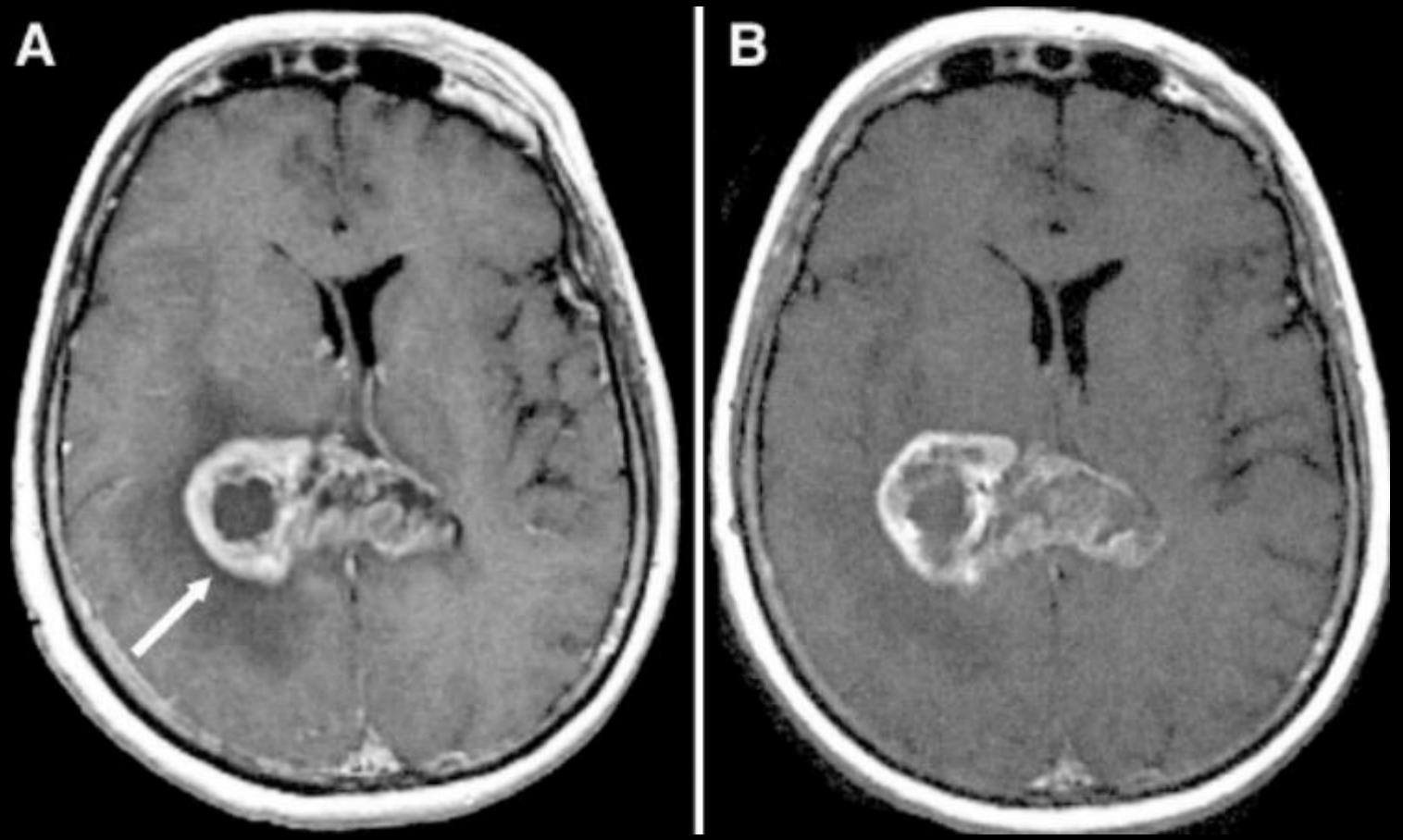




Contrast enhanced MRI

9 min post Gd contrast

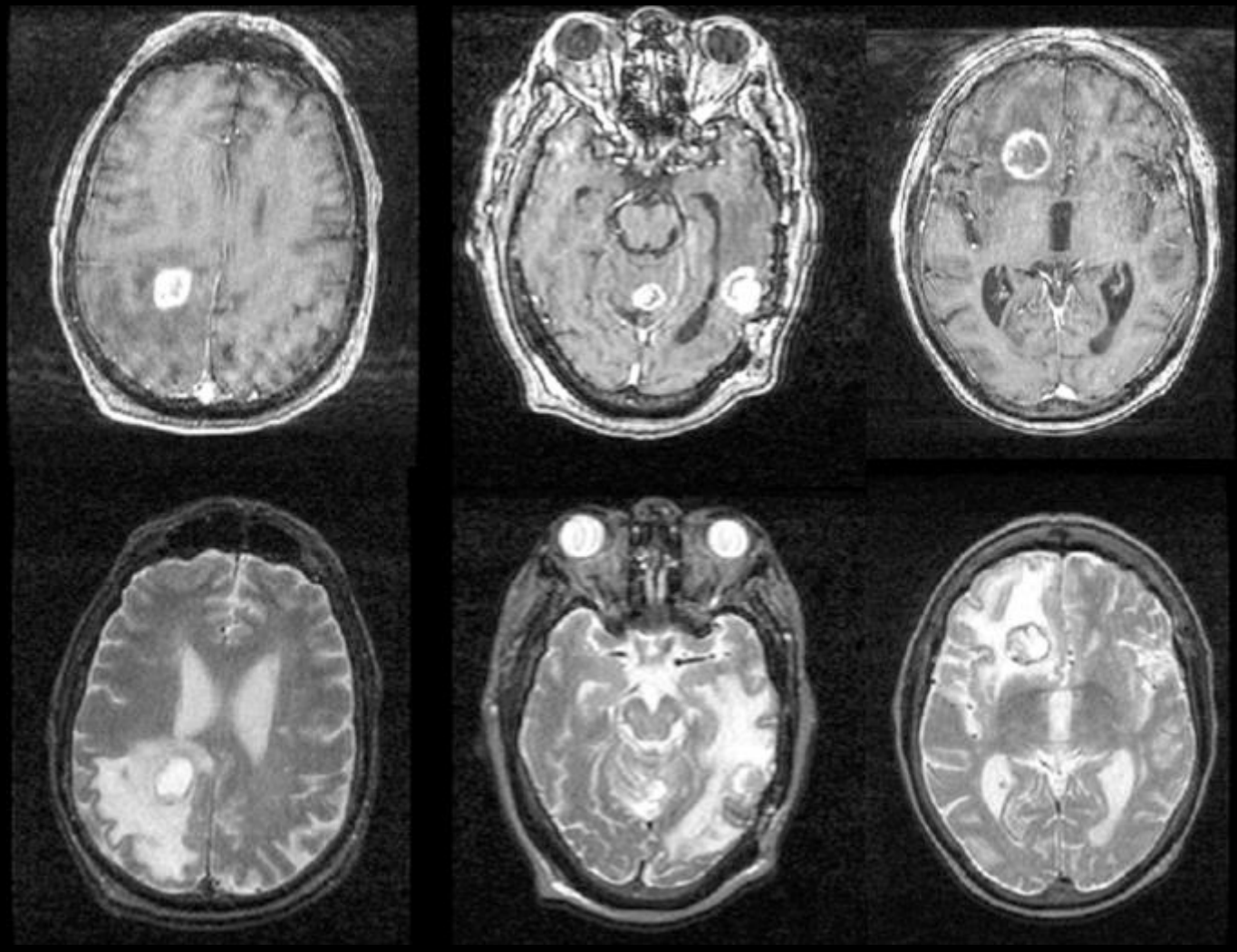
T1-weighted MRI



Contrast enhanced MRI

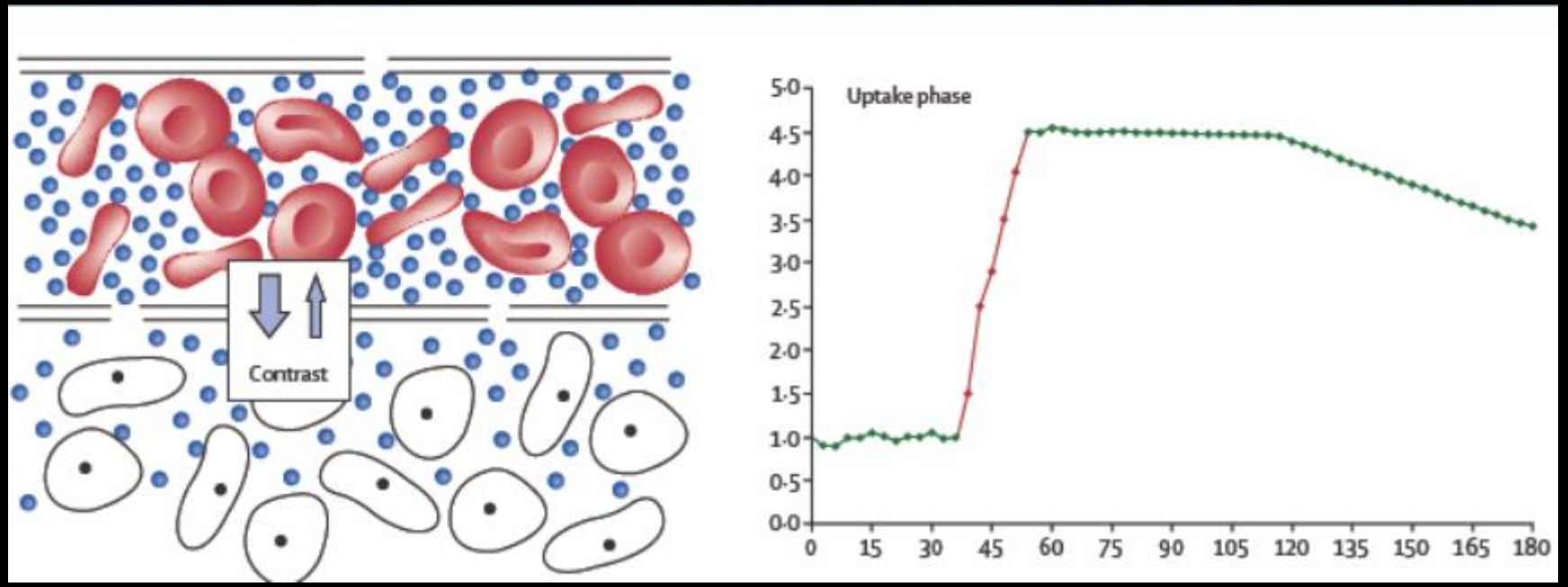
Contrast enhanced MRI

T2-weighted MRI



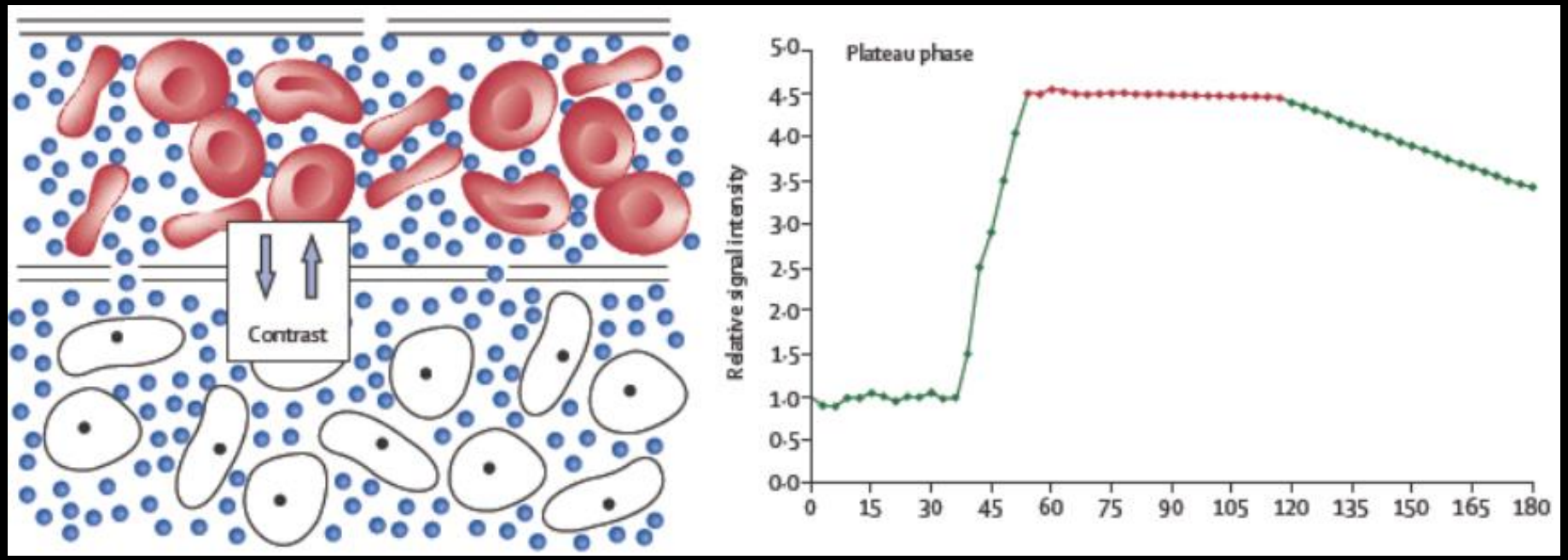
Contrast enhanced with time

Uptake phase: signal intensity rise above baseline and there is a net leakage of contrast from the blood vessels into the interstitial space



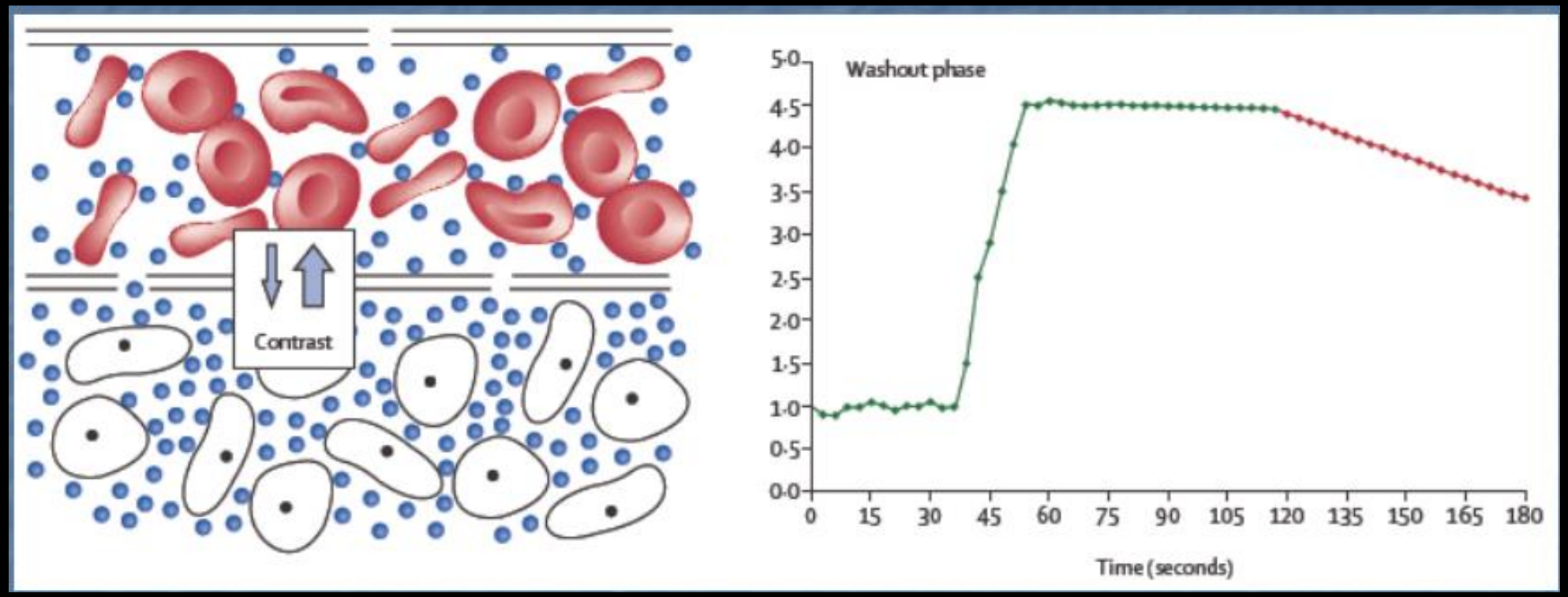
Contrast enhanced with time

Plateau phase: maximum enhancement with an equilibrium in the movement of contrast between the blood vessel and the interstitial space



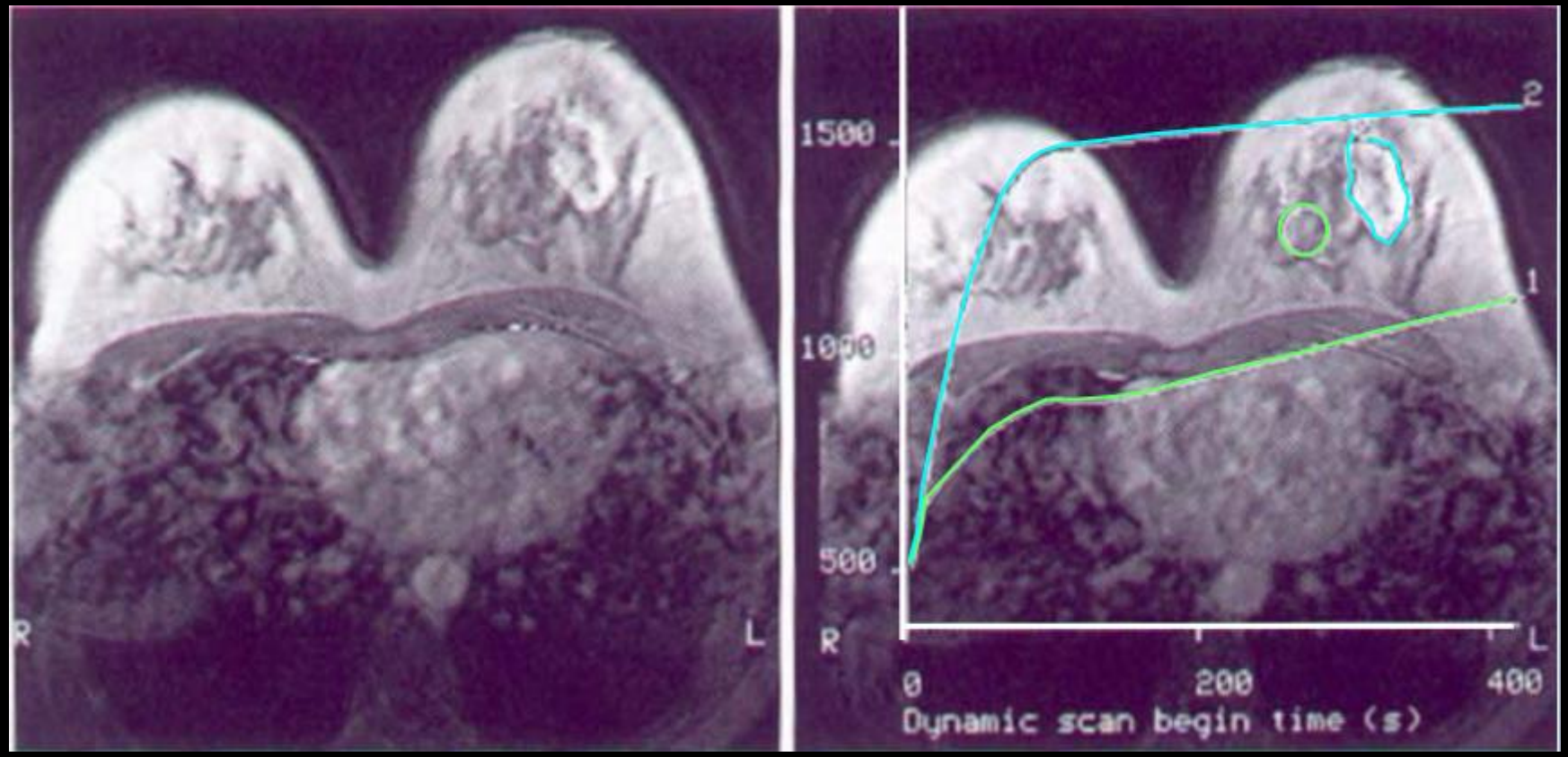
Contrast enhanced with time

Washout phase: contrast starts to leave tissue and goes back into the blood vessels.



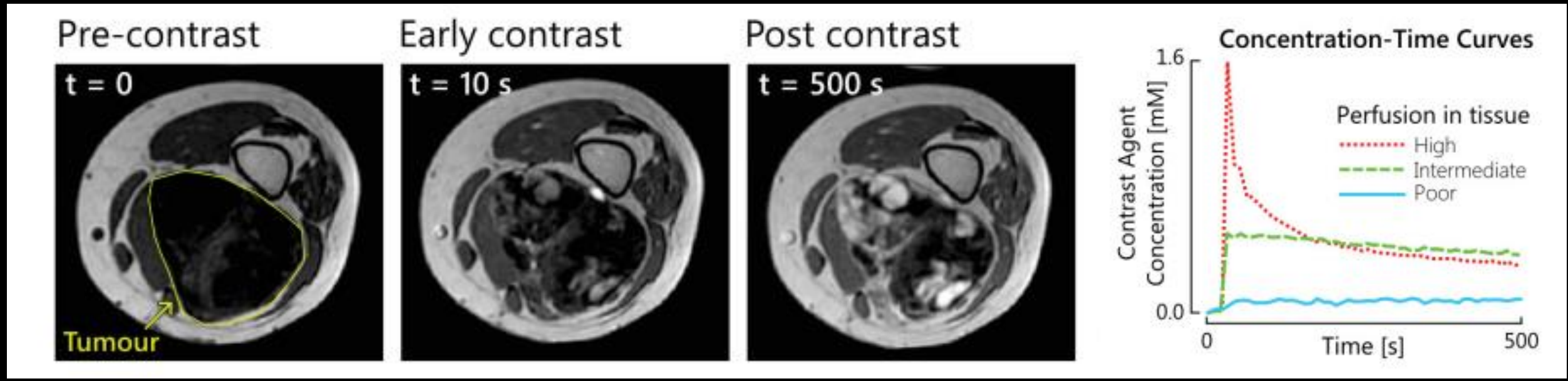
Contrast enhanced with time

Different tissue has different uptake curve. Blue is lesion and green is normal glandular tissue



Contrast enhanced with time

Identify different components in the tumor. Tumor tends to have high perfusion due to increased blood flow



Summary

- RF pulse timing (TE, TR) can be used to manipulate soft tissue T1 and T2 contrast in MRI
- Inversion recovery MRI (FLAIR) can be used to eliminate signal from CSF
- These images can be used to evaluate tumor size, contouring
- Diffusion MRI is used to evaluate tumor cell integrity
- Tumor tends to have lower diffusivity than normal tissue
- Contrast agents Gd can be used to reduce tissue T1 for dynamic contrast enhanced perfusion imaging (DCE-MRI)
- DCE MRI are used to better visualize the tumor, improve diagnosis

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