Structural MRI (1):
Basic Principles and Introduction

구조 자기공명영상 (1):
원리 및 소개

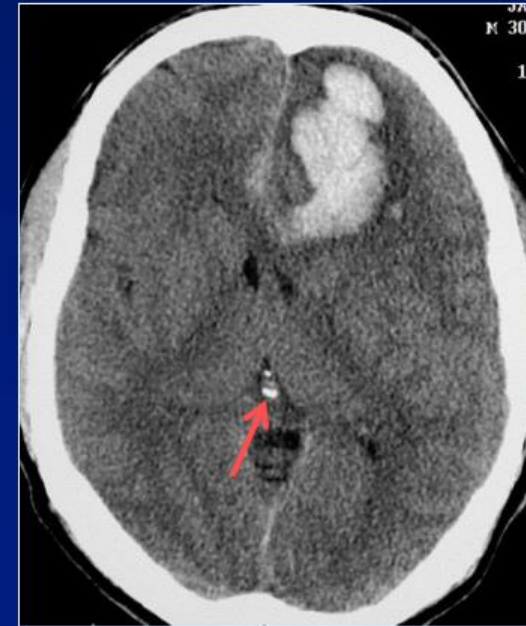- MRI > CT

  (almost all disease)
  - infarct, tumor, inflammation, infection
  - degeneration, atrophy
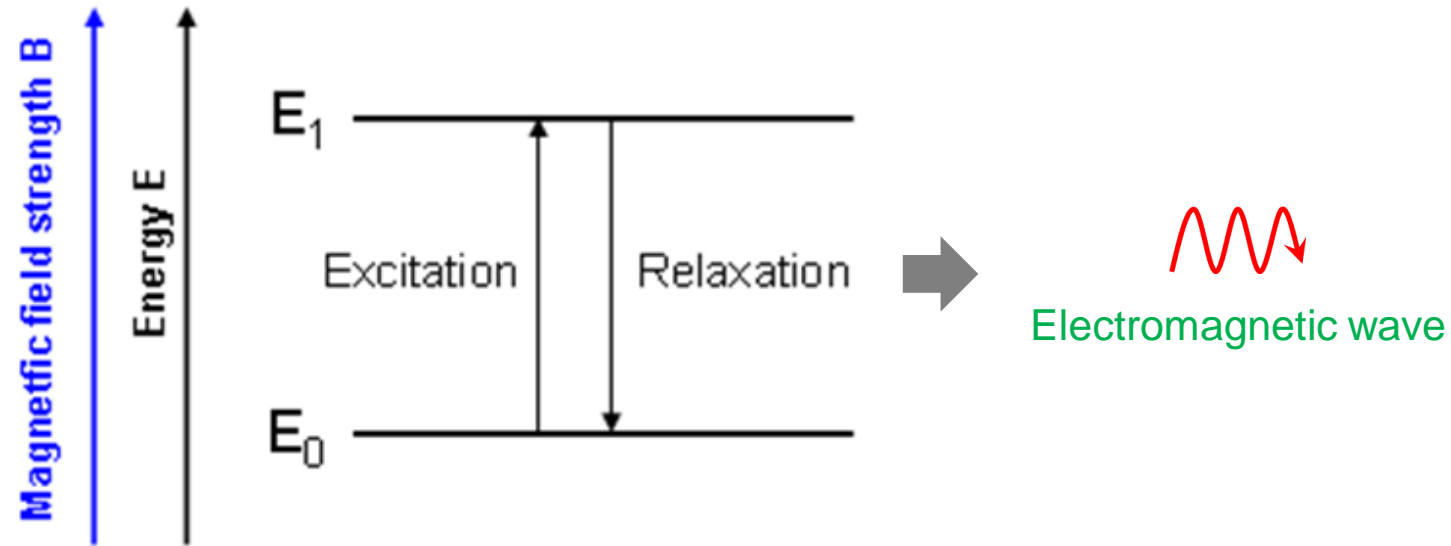 - hemorrhage, trauma
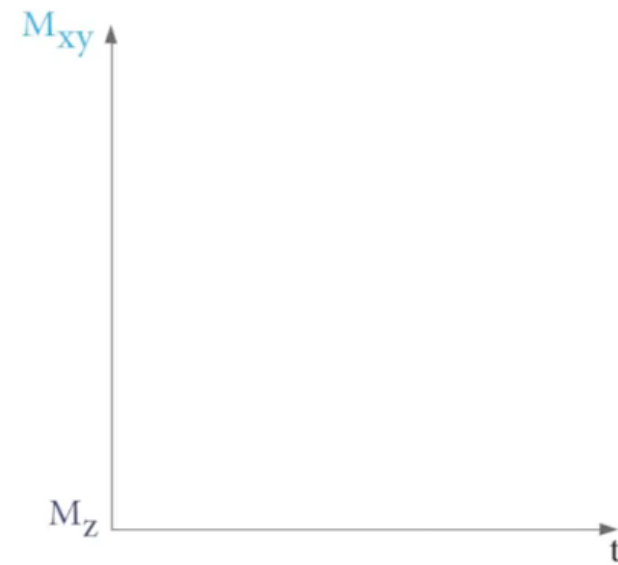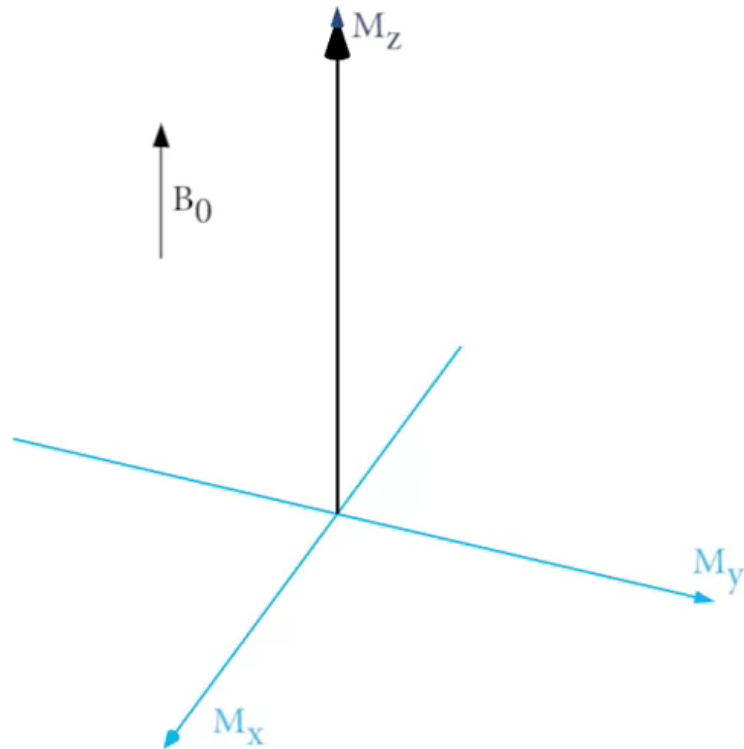
- CT = MRI

  - acute hemorrhage

- CT > MRI

  - calcification

MRI: Principles

- Excites hydrogen nuclei (protons) into releasing electromagnetic waves (in radio frequency) and then records the locations of the waves with high accuracy

**Exponential decay of magnetization towards its equilibrium value**

- Two different relaxation times
  - T1 (longitudinal relaxation time)
    - Time taken for hydrogen nuclei to realign with the external magnetic field
    - Spin-lattice relaxation time: time taken for the longitudinal magnetization to recover 63% ($1-(1/e)$) of its initial value
    - Water-based tissues in the 400-1200 ms range; fat-based tissues in the 100-150 ms range
  - T2 (transverse relaxation time)
    - Time taken for hydrogen nuclei to lose phase coherence among the nuclei
    - Spin-spin relaxation time: time taken for the transverse magnetization to irreversibly decay to 37% ($1/e$) of its initial value
    - Water-based tissues in the 40-200 ms range; fat-based tissues in the 10-100 ms range

T1 relaxation:
$$M_z = M_0 \left(1 - e^{-t/T_1}\right)$$

T2 relaxation:
$$M_{xy} = M_0 \cdot e^{-t/T_2}$$
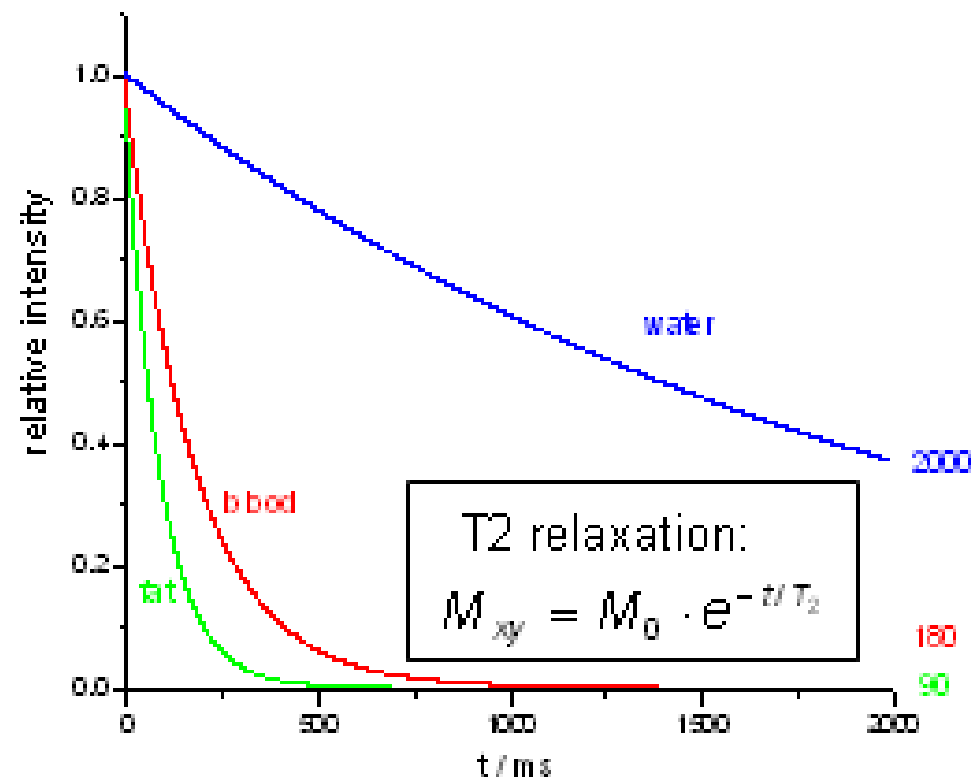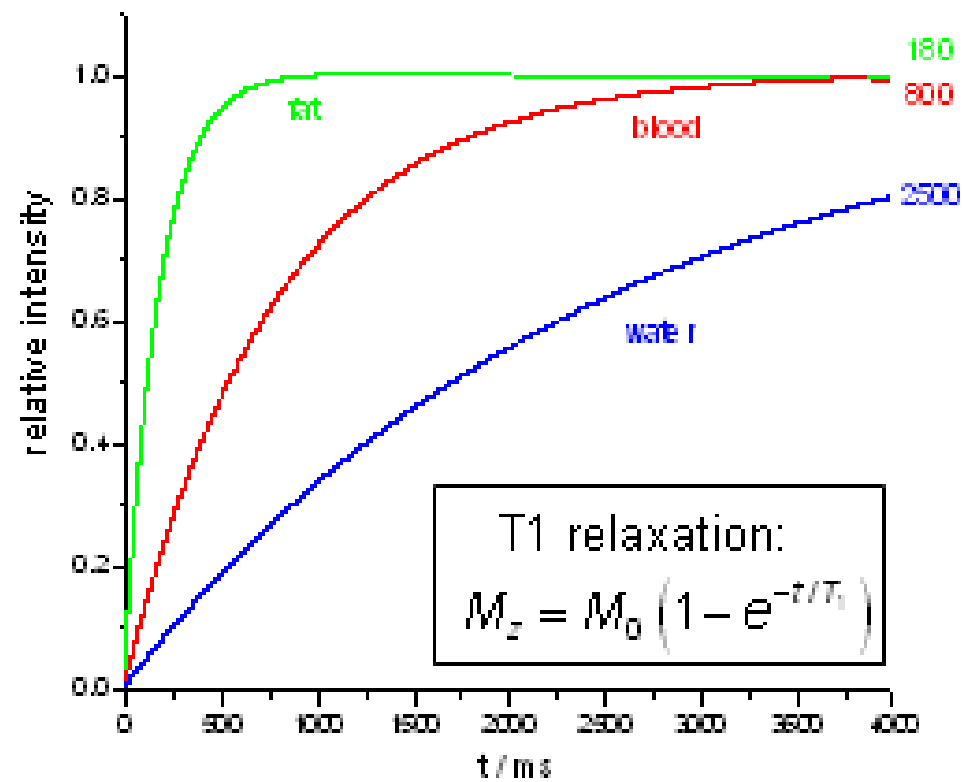
[Pollacco, 2016]

Differences in T1 and T2 relaxation times between tissues

- By varying the sequence of radio frequency electromagnetic waves (RF pulses) applied and collected
  - Repetition Time (TR): time between successive pulse sequences applied to the same slice
  - Echo Time (TE): time between the delivery of the RF pulse and the receipt of the echo signal

[https://mriquestions.com/tr-and-te.html]
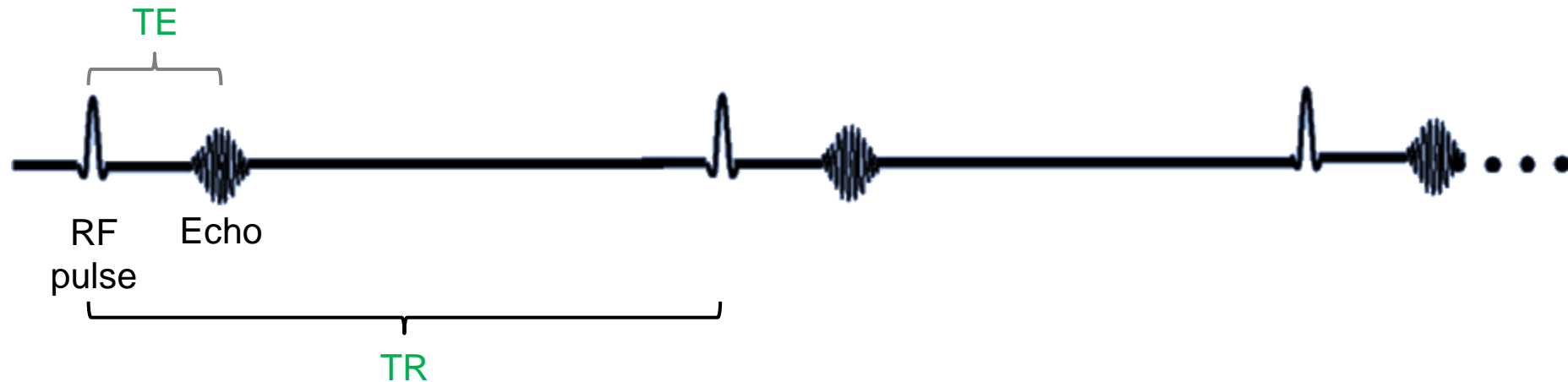
MRI Pulse Sequence

- T1-weighted
  - Contrast predominately determined by T1 differences between tissues
  - Produced by using shorter TE (decreasing the T2 effect) and shorter TR (enhancing the T1 effect by rapidly exposing hydrogen nuclei to RF pulses)
  - Tissues that return to alignment faster than other tissues are bright on a T1-weighted image

- T2-weighted
  - Contrast predominately determined by T2 differences between tissues
  - Produced by using longer TE (enhancing the T2 effect by allowing hydrogen nuclei to move away from each other) and longer TR (decreasing the T1 effect)
  - Tissues that remain in phase longer than other tissues are bright on a T2-weighted image

- Fluid Attenuated Inversion Recovery (FLAIR)
  - Heavily T2-weighted in that TE and TR are very long
  - Dampens ventricular cerebrospinal fluid signals, causing the highest signals from certain brain parenchymal abnormalities

|	TR (msec)	TE (msec)
T1-Weighted (short TR and TE)	500	14
T2-Weighted (long TR and TE)	4000	90
Flair (very long TR and TE	9000	114

[https://case.edu/med/neurology/NR/MRI Basics.htm]

Cerebrospinal fluid as dark

Cerebrospinal fluid as bright

T1-weighted
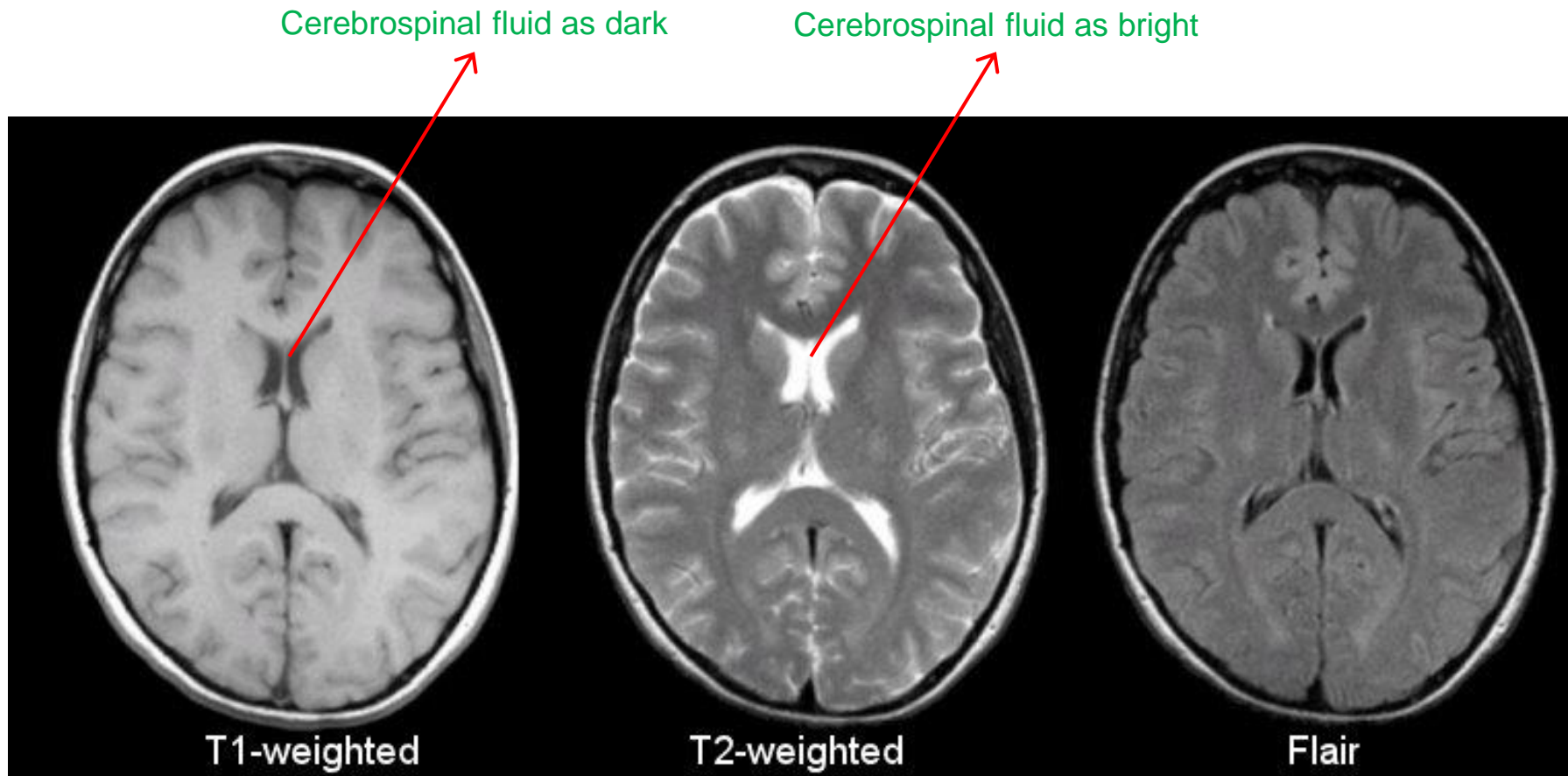
T2-weighted

Flair

[https://case.edu/med/neurology/NR/MRI Basics.htm]

Comparison between T1-weighted, T2-weighted, and FLAIR images
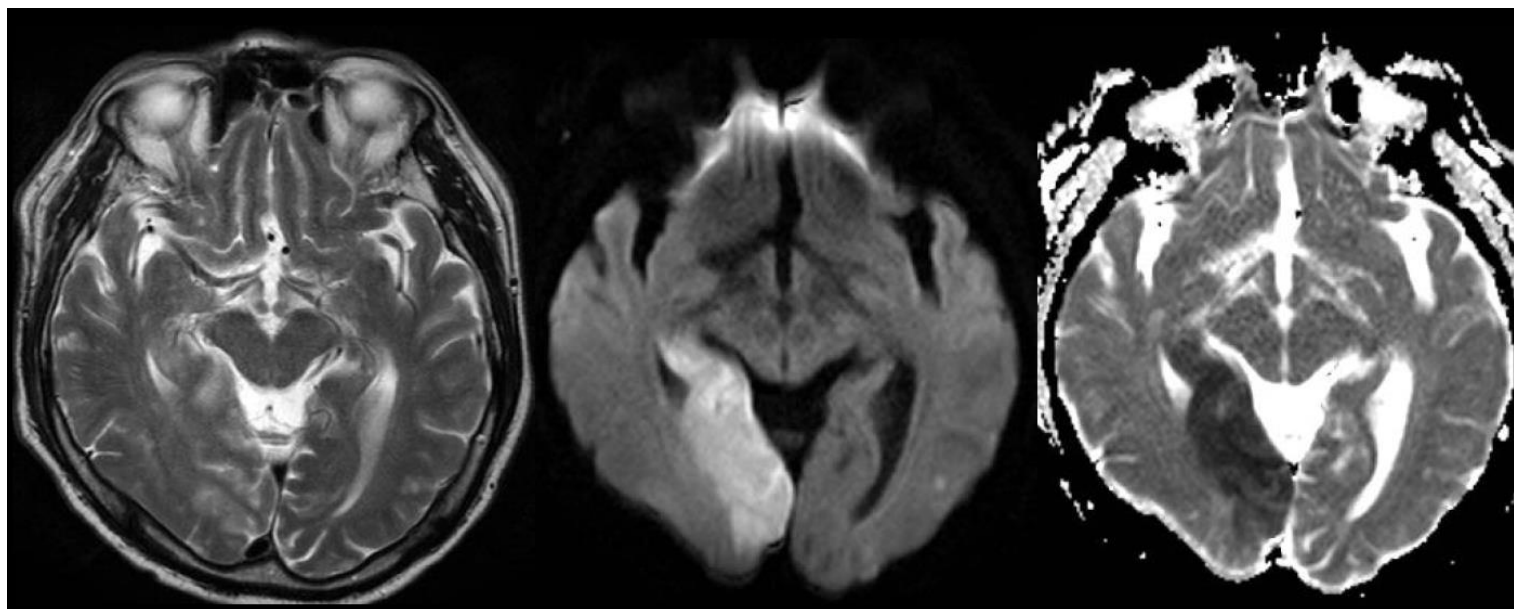
T1-weighted vs. T2-weighted
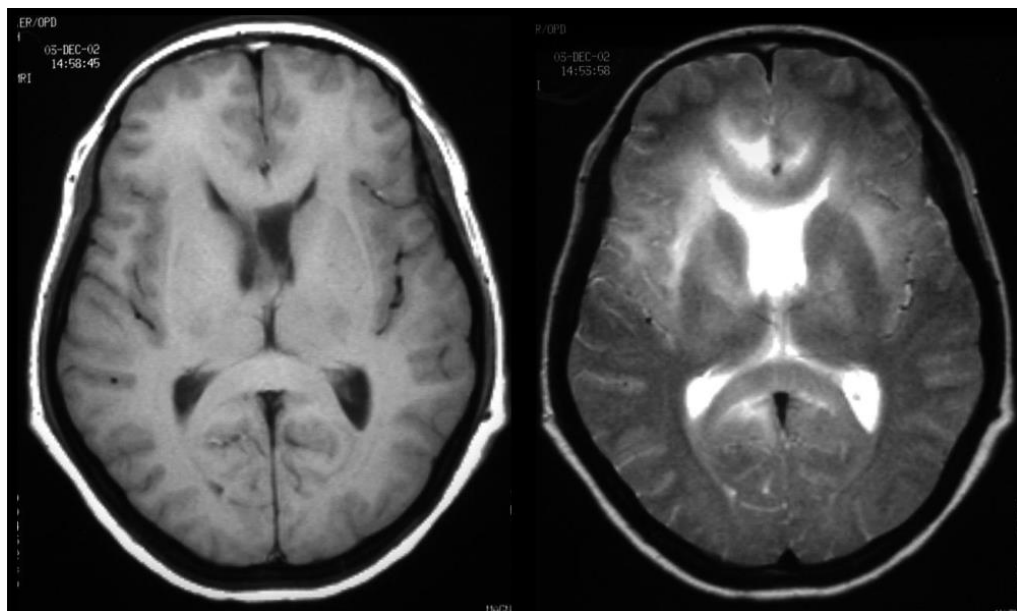
T2-weighted vs. FLAIR
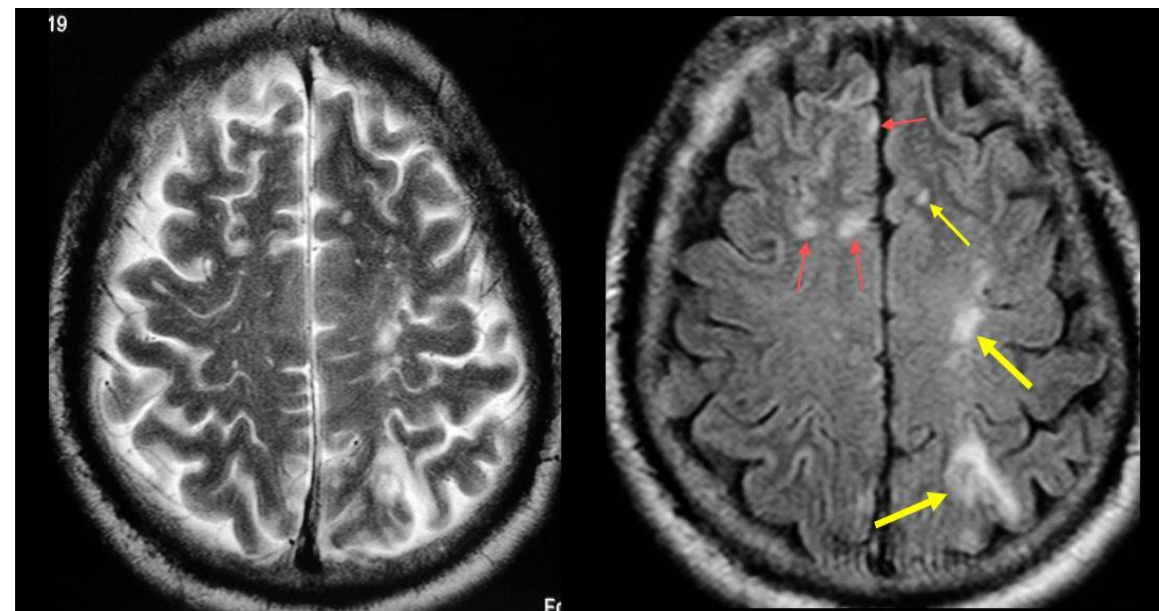
- Diffusion-weighted
  - Designed to detect the random movement (diffusion) of hydrogen nuclei
  - The restricted diffusion of hydrogen nuclei in the ischemic brain tissue results in an extremely bright signal
  - Sensitive for detecting acute stroke

T2-weighted vs. diffusion-weighted

T1-weighted Contrast of the Brain

- White matter (nerve fibres) has a very short T1 and relaxes rapidly
- Cerebrospinal fluid has a long T1 and relaxes slowly
- Grey matter (neuron congregations) has an intermediate T1 and relaxes at an intermediate rate

Producing an image
at a time when the curves are widely separated
between the tissues

- White matter contributes to lighter voxels
- Cerebrospinal fluid contributes to darker voxels
- Grey matter contributes to voxels with intermediate shades of grey
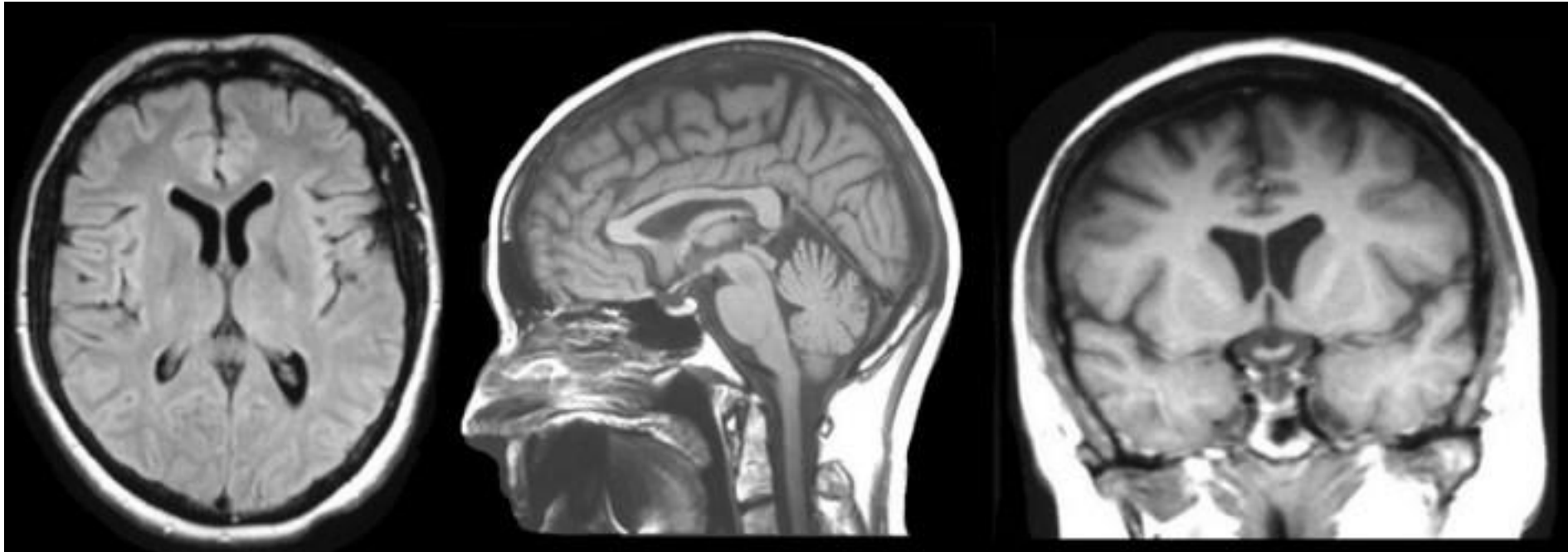
T1-weighted contrast of the brain

| Tissue	T1-Weighted	T2-Weighted	Flair
CSF	Dark	Bright	Dark
White Matter	Light	Dark Gray	Dark Gray
Cortex	Gray	Light Gray	Light Gray
Fat (within bone marrow)	Bright	Light	Light
Inflammation (infection, demyelination)	Dark	Bright	Bright

Different contrasts of the brain

Structural MRI (sMRI)

- MRI technique primarily for examining the anatomy and pathology of the brain
  - As opposed to using functional MRI to measure brain activity
- Usability of sMRI
  - Abnormality detection
  - Brain morphometry
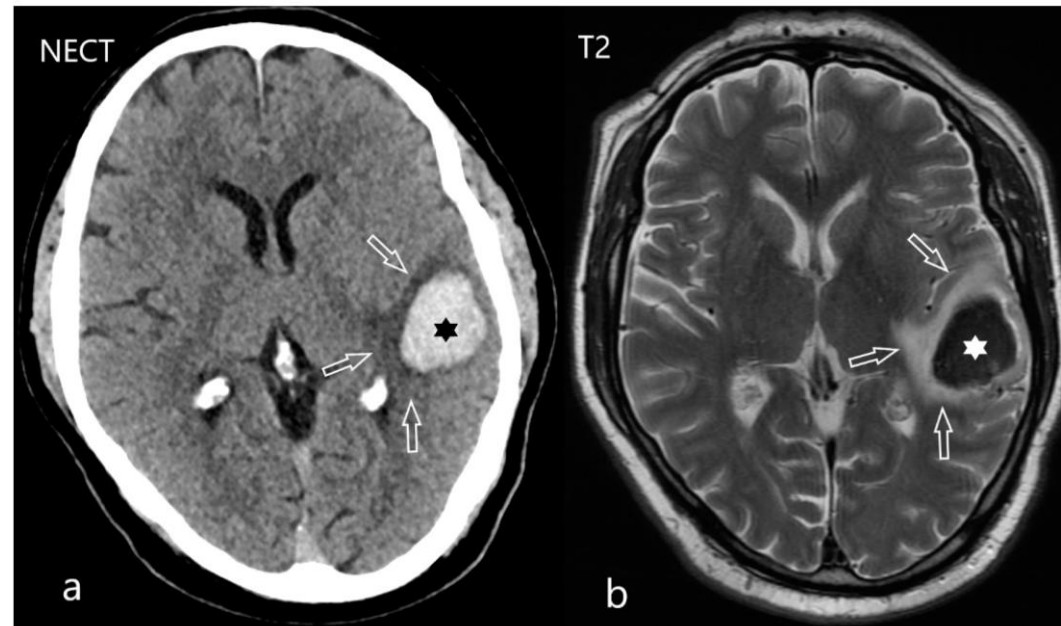 - Spatial reference of functional/diffusion-weighted MRI

Abnormality Detection with sMRI

- Brain lesion
  - Region that has been damaged by an injury or a disease
    - Brain tumour
    - Stroke
    - Epilepsy
    - Multiple sclerosis
 - Disrupts the way the brain works, causing a wide range of symptoms
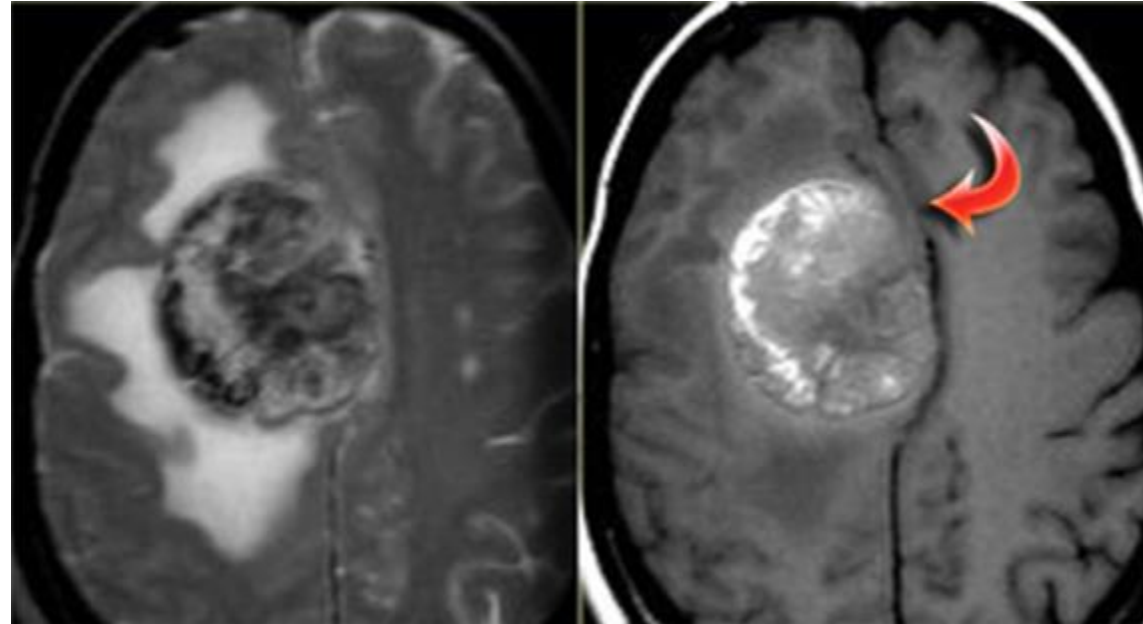
Brain tumour (melanoma metastasis) on T2-weighted and T1-weighted images

Stroke lesion (acute intracerebral hemorrhage) on CT and T2-weighted images

- White matter hyperintensity
  - Region of high intensity (increased brightness) within the cerebral white matter on a T2-weighted image
  - Reflects a lesion produced largely by demyelination and axonal loss
  - Frequently seen in older people and possibly associated with increased risk for some brain diseases
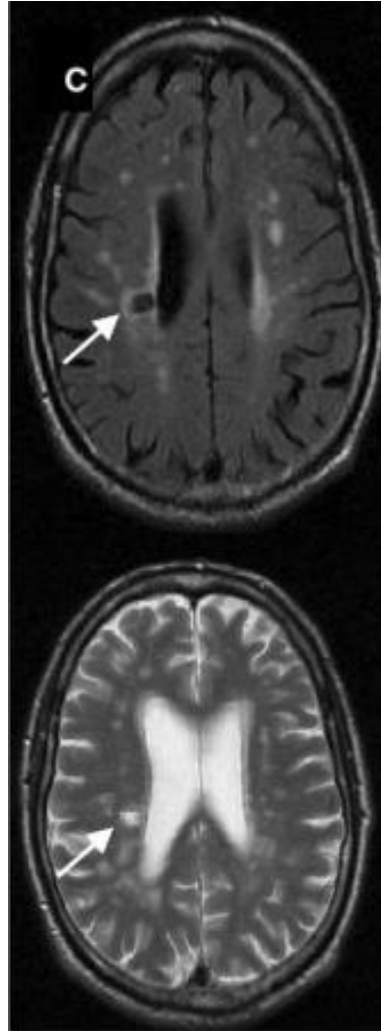
[Wardlaw et al., 2015]

White matter hyperintensity on FLAIR and T2-weighted images

- Perivascular space (Virchow–Robin space)
  - Fluid-filled space surrounding certain blood vessels
  - Typically located in the basal ganglia and white matter of the brain
  - Can become enlarged or dilated, in a close association with ageing or signaling abnormalities
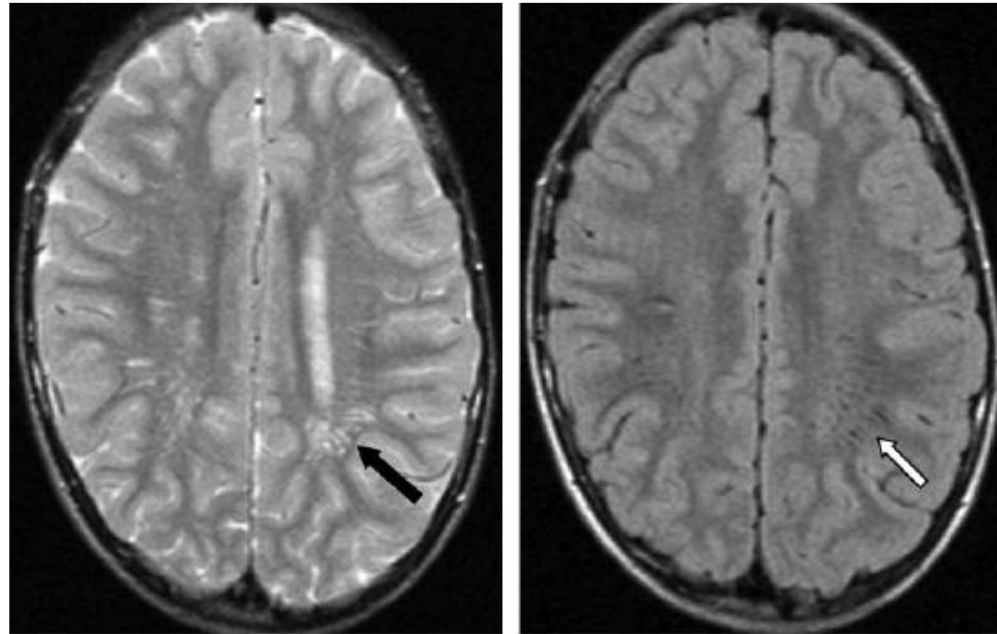
Perivascular space on T2-weighted and FLAIR images

Brain Morphometry with sMRI

- Brain morphometry
  - Measurement of brain structures
    - Density
    - Size
    - Shape
  - Based on the notion that variations in macroscopic brain anatomy are sufficiently conserved to allow for comparative analyses, yet diverse enough to reflect variations within and between individuals
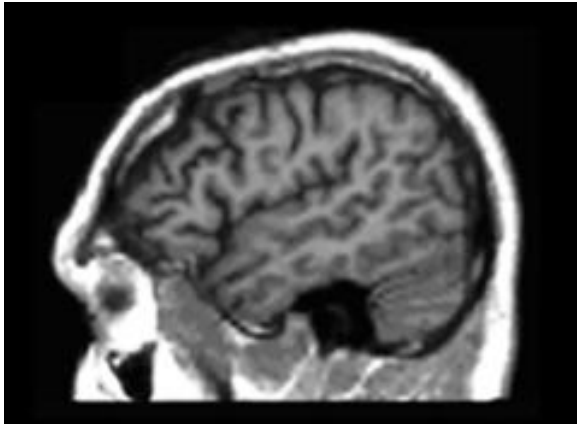
- Preprocessing before quantifying anatomical features of the brain
  - Correction for unwanted variation
    - Intensity non-uniformity
  - Segmentation
    - Classifies an image into the non-brain and brain and, furthermore, the brain into different tissues usually including grey matter, white matter, and cerebrospinal fluid
  - Normalisation
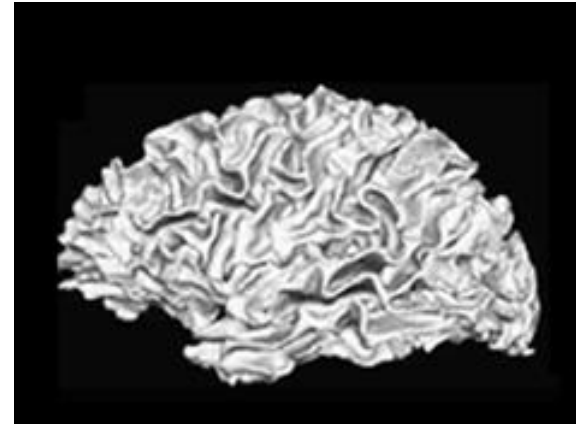   - Transforms an image from a native space to the standard space
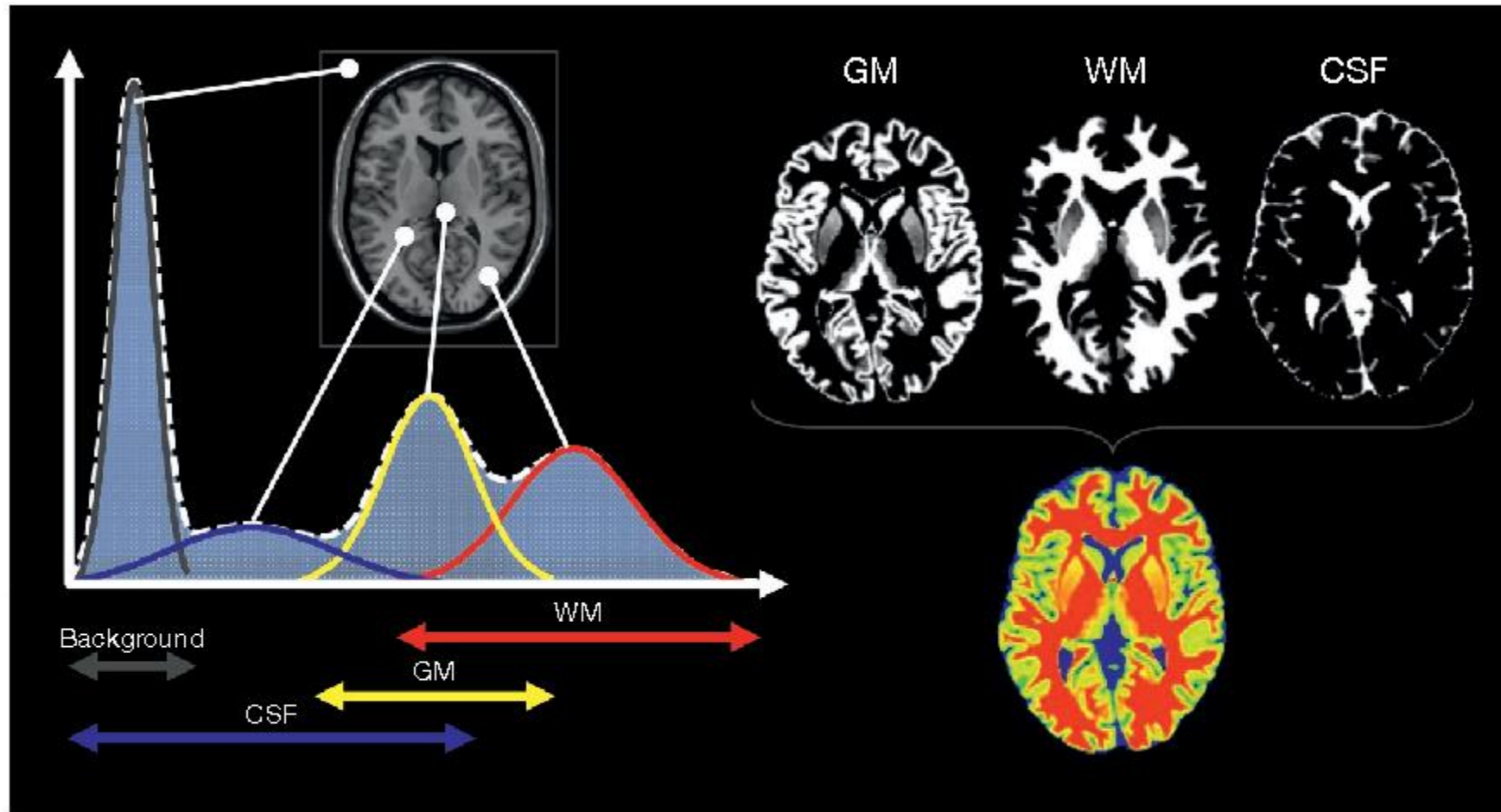
Segmentation of the brain into different tissues

- Voxel-based morphometry (VBM)
  - Local differences in density or volume
  - Given that, after the segmentation of an image, each voxel contains a measure of the probability according to which it belongs to a specific segmentation class
- Surface-based morphometry (SBM)
  - Local differences in thickness or gyrification
  - Given that, after the segmentation of an image, the boundary between different segmentation classes can be reconstructed as a surface
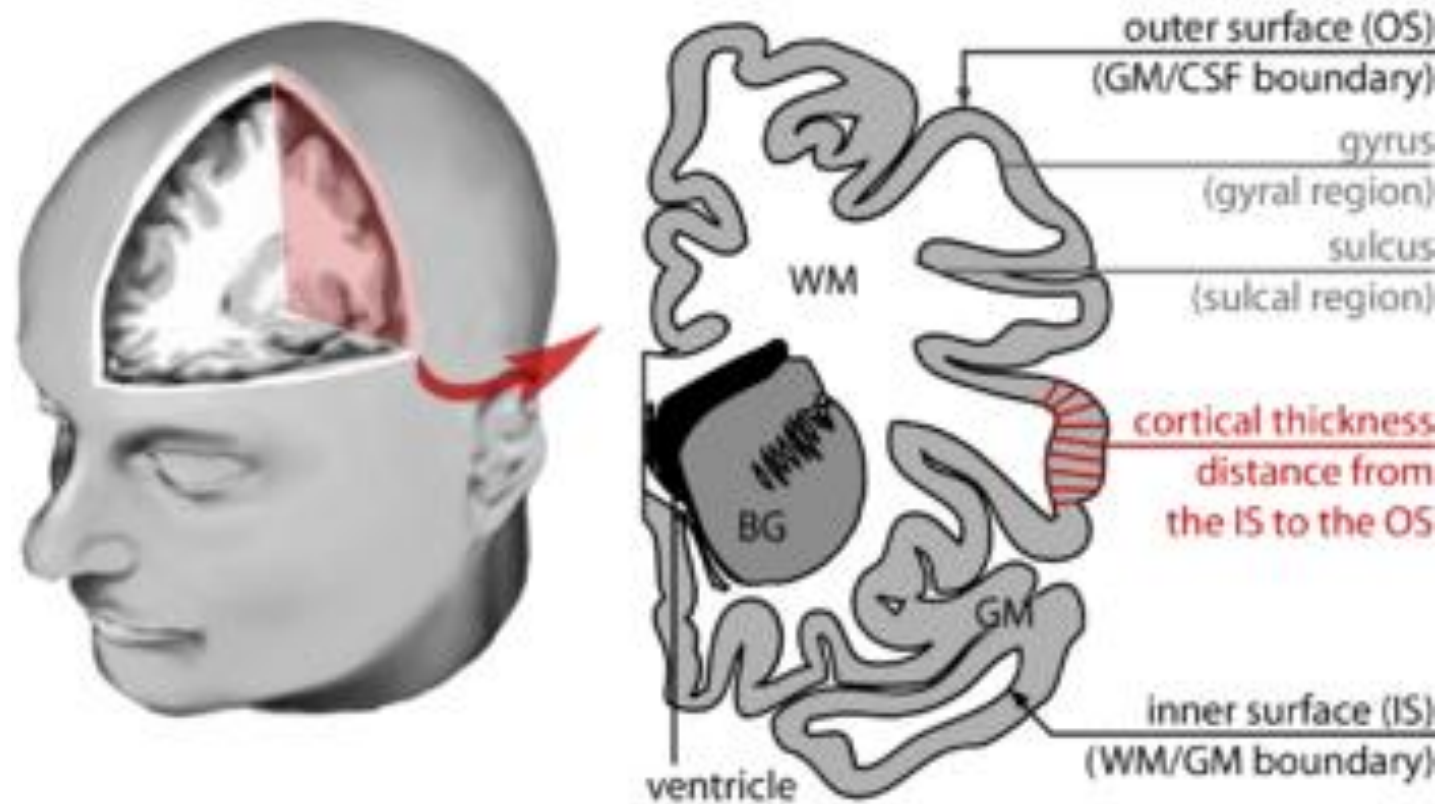
T1-weighted sMRI

Reconstructed brain surfaces

Reconstruction of brain surfaces from T1-weighted sMRI

outer surface (OS)
(GM/CSF boundary)

gyrus
(gyral region)

sulcus
(sulcal region)

WM

cortical thickness
distance from
the IS to the OS

BG

GM

inner surface (IS)
(WM/GM boundary)

ventricle

Measurement of cortical thickness based on a surface representation of the cerebral cortex

sMRI as an Individual's Spatial Reference

- Coregistration between sMRI and functional/diffusion-weighted MRI
  - Within-subject between-modality registration
  - For the anatomical localization of an individual's brain activity or diffusion properties
  - To achieve more precise normalisation of functional/diffusion-weighted images by using the same individual's structural image

Within-subject sMRI-functional MRI registration
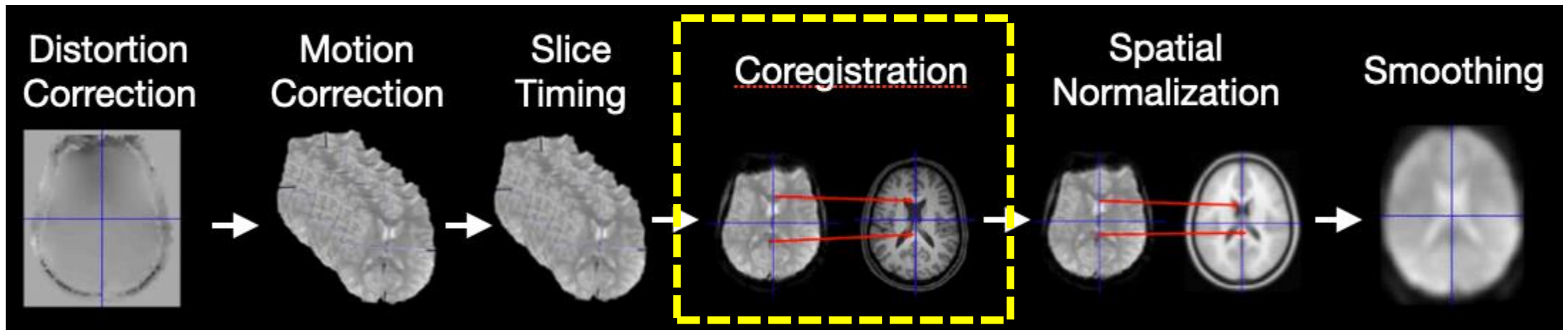
[https://dartbrains.org/content/Preprocessing.html]

Coregistration as a step of the functional MRI data prerprocessing pipeline