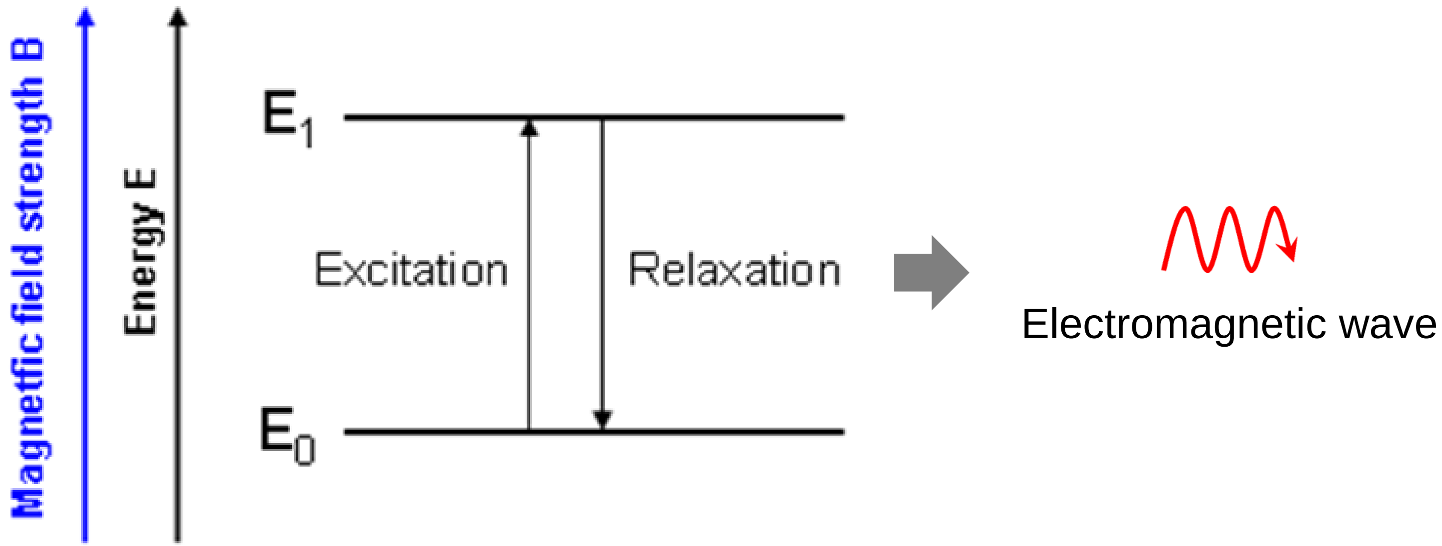
Medical/Bio Research Topics Ⅱ : Week 02 (10.09.2024)

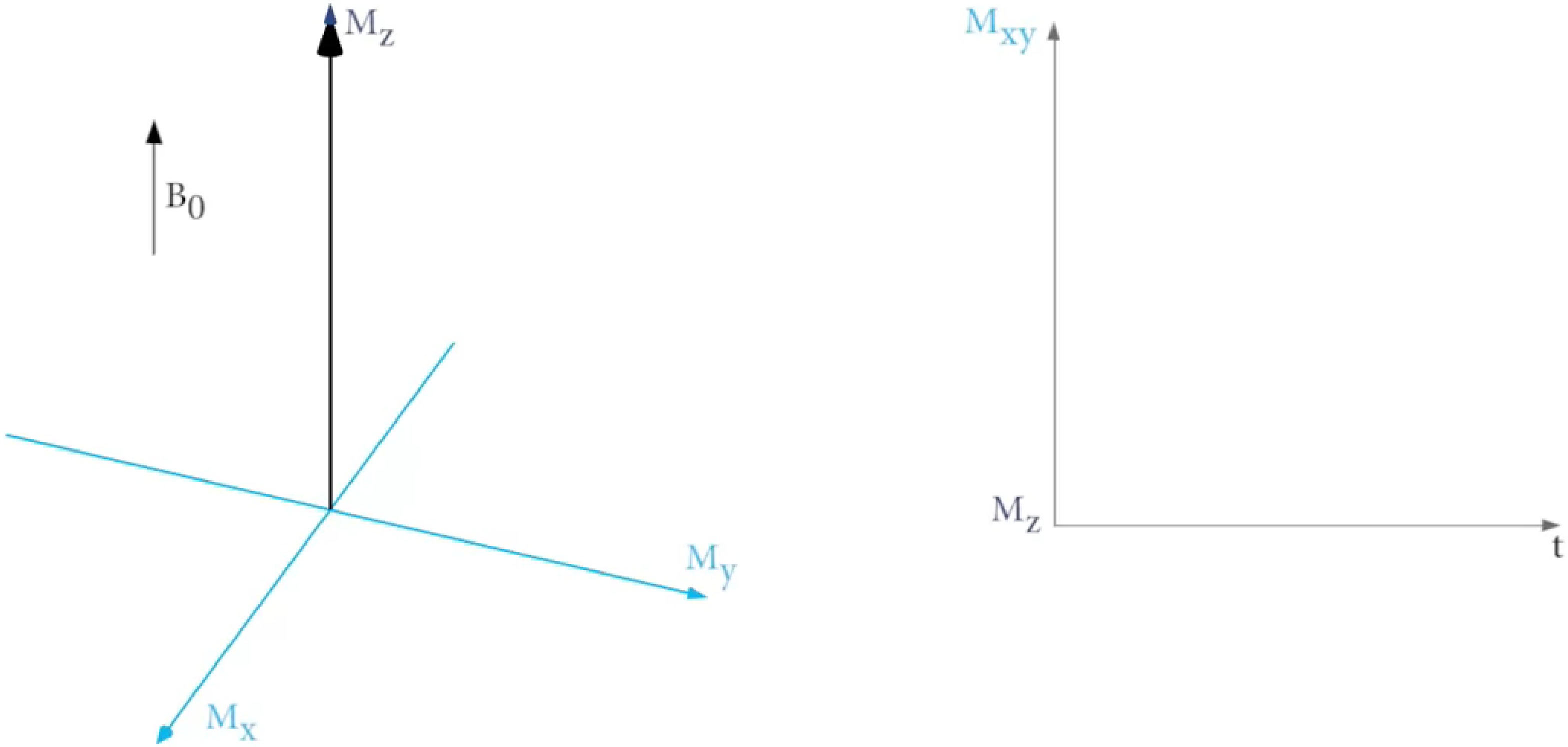
Structural MRI: Fundamental Principles and Data Processing

구조 자기공명영상: 기본 원리 및 데이터 처리 방법

MRI Principles

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

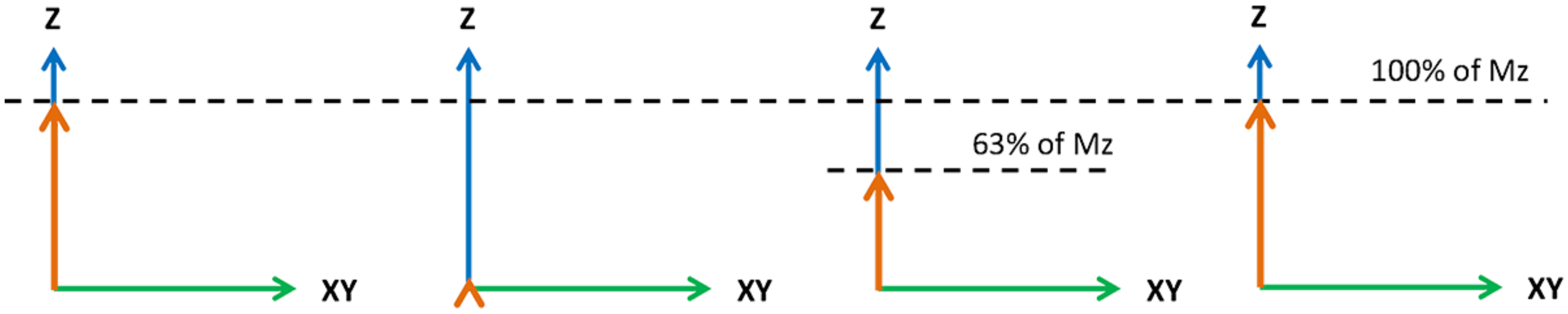




[https://en.wikipedia.org/wiki/Spin-spin_relaxation]

Exponential recovery or decay of magnetization towards its equilibrium value in relaxation

Longitudinal or spin-lattice relaxation



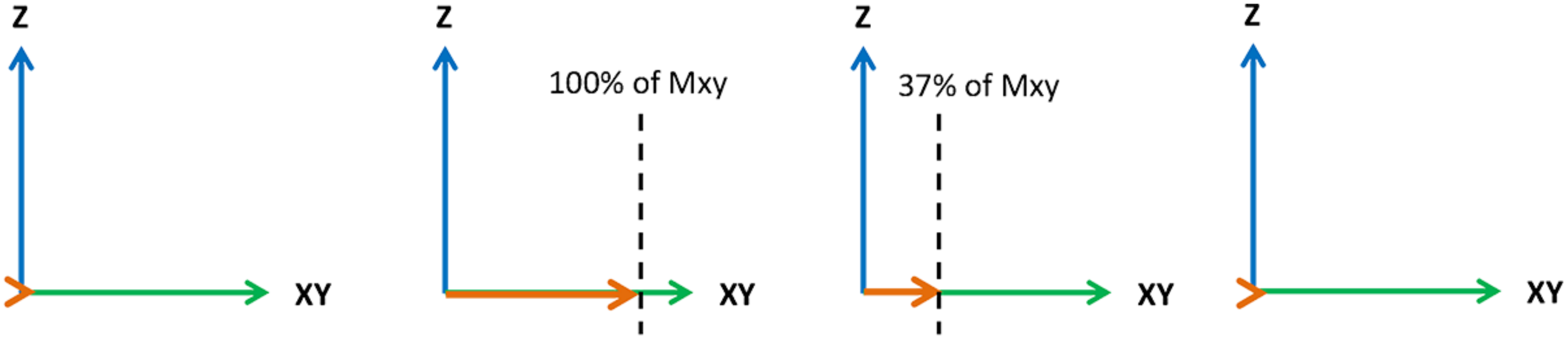
1. Before 90° pulse Mz is 100%

2. After the 90° pulse the Mz is 0

3. The Mz slowly recovers. The time it takes to recover to 63% is the time constant T1

4. The Mz continues to recover until it reaches its starting value of 100%

Transverse or spin-spin relaxation



1. Before 90° pulse Mxy is 0%

2. After the 90° pulse the Mxy is 100%

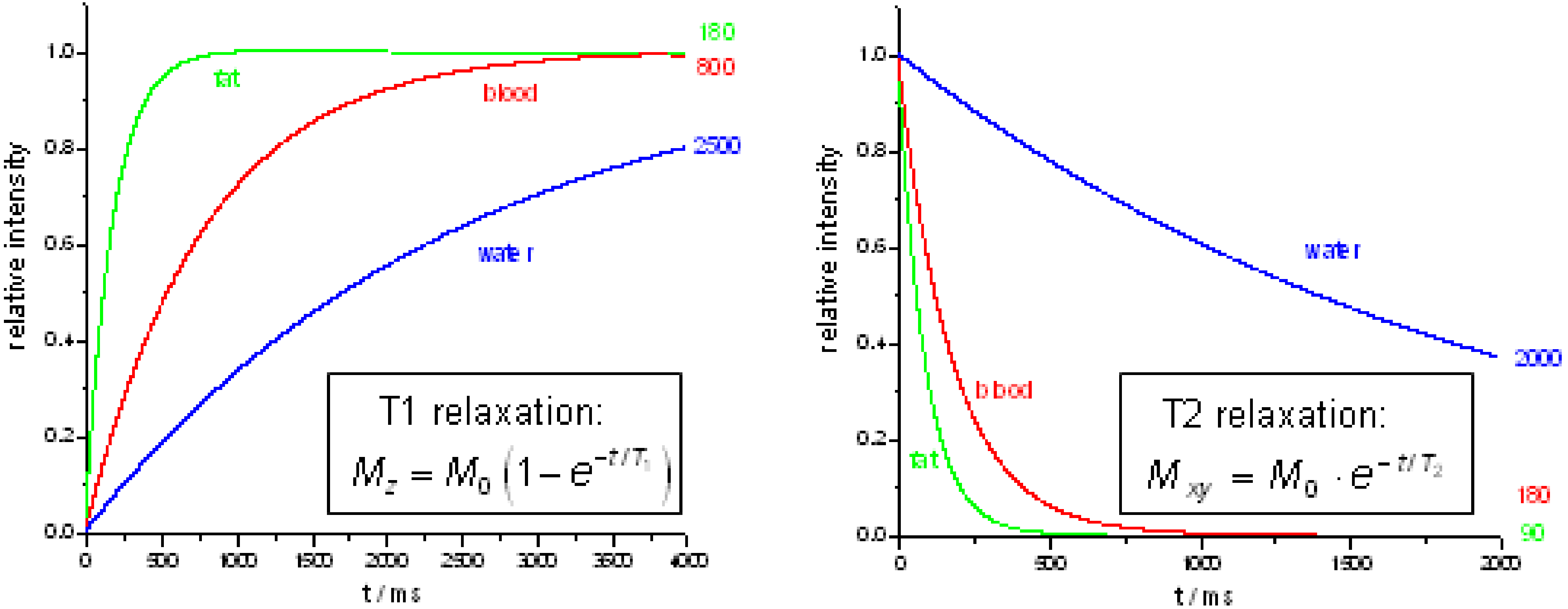
3. The Mxy slowly decays. The time it takes to decay to 37% is the time constant T2

4. The Mxy continues to decay until it reaches its starting value of 0%

[https://www.radiologycafe.com/frcr-physics-notes/mr-imaging/t1-and-t2-signal/]

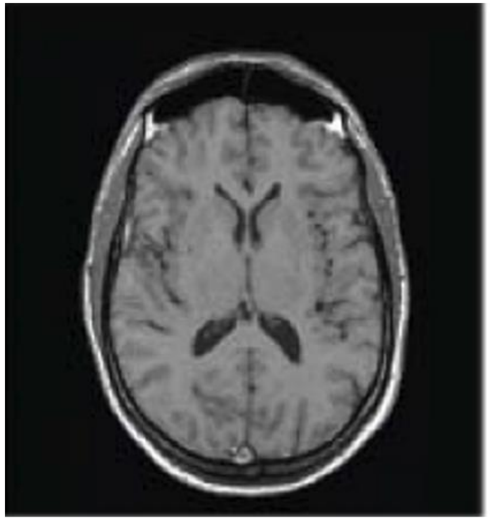
Two relaxation processes occurring at the same time but completely independently

- Two different relaxation times
  - T1 (longitudinal relaxation time or spin-lattice relaxation time)
    - Time taken for hydrogen nuclei to realign with the external magnetic field
    - 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 or spin-spin relaxation time)
    - Time taken for hydrogen nuclei to lose phase coherence among the nuclei
    - 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

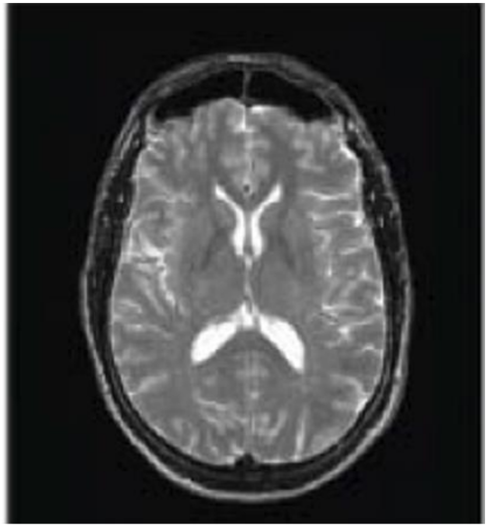


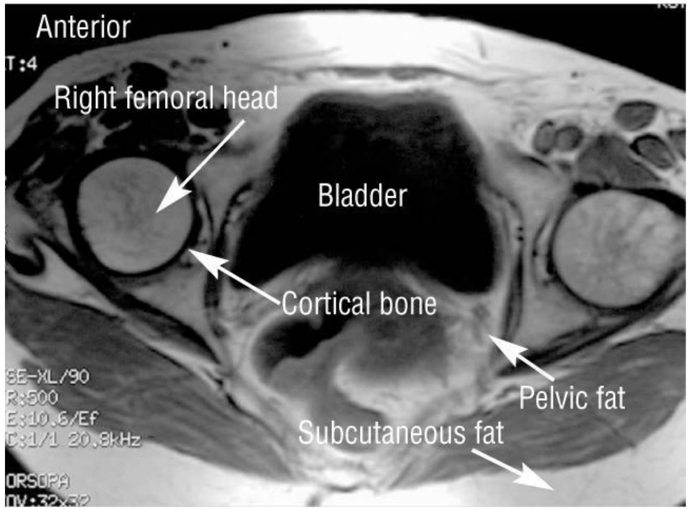
[Pollacco, 2016]

Differences in T1 and T2 relaxation times between tissues

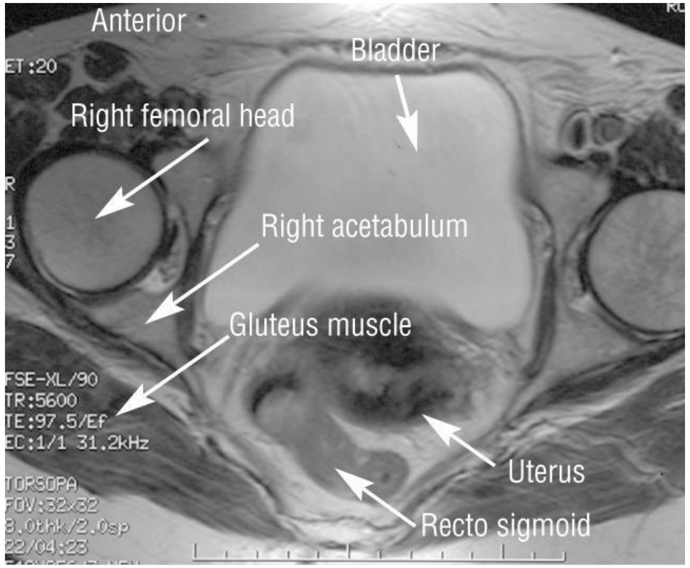


Brain





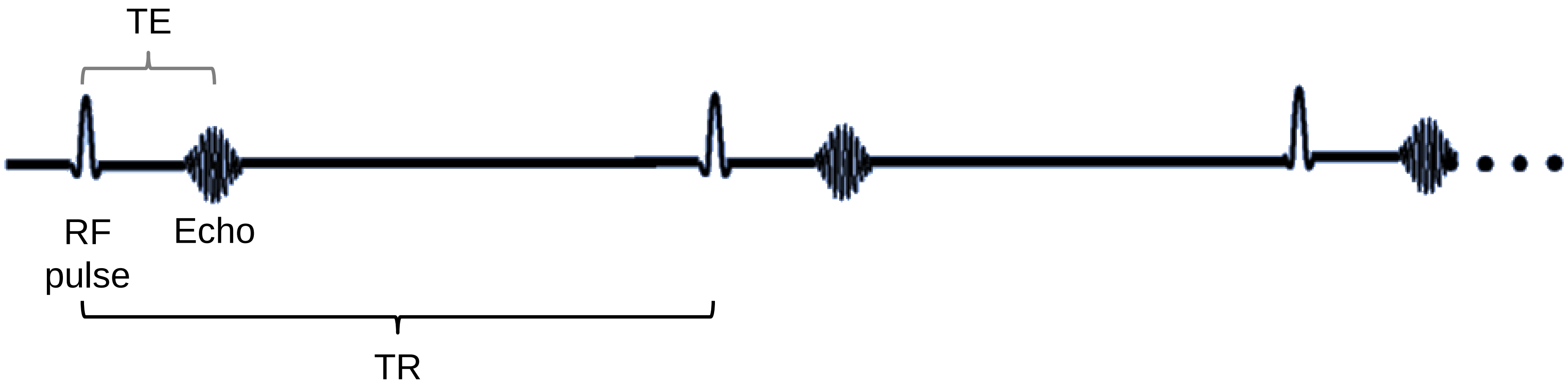
Pelvis



[https://radiologykey.com/mr-relaxation-theory-and-exchange-processes-in-the-presence-of-contrast-agents/; Berger, 2002]

T1-weighted vs. T2-weighted MRI

- 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 Contrast Mechanisms

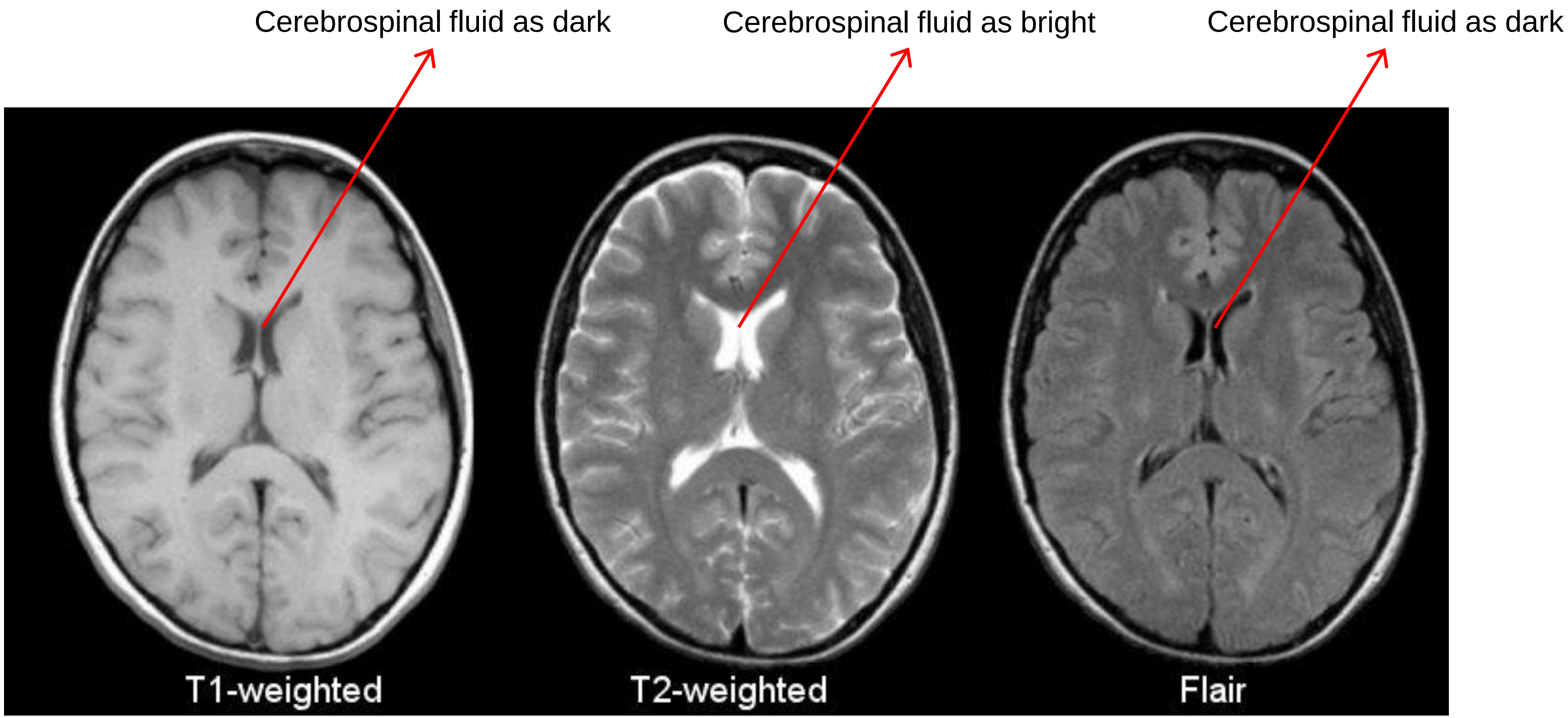
- T1-weighted
  - Contrast predominately determined by T1 differences between tissues
  - Produced by using shorter TE (decreasing the T2 effect) and shorter TR (enhancing the T1 effect by rapidly exposing hydrogen nuclei to RF pulses)
  - Tissues that return to alignment faster than other tissues are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

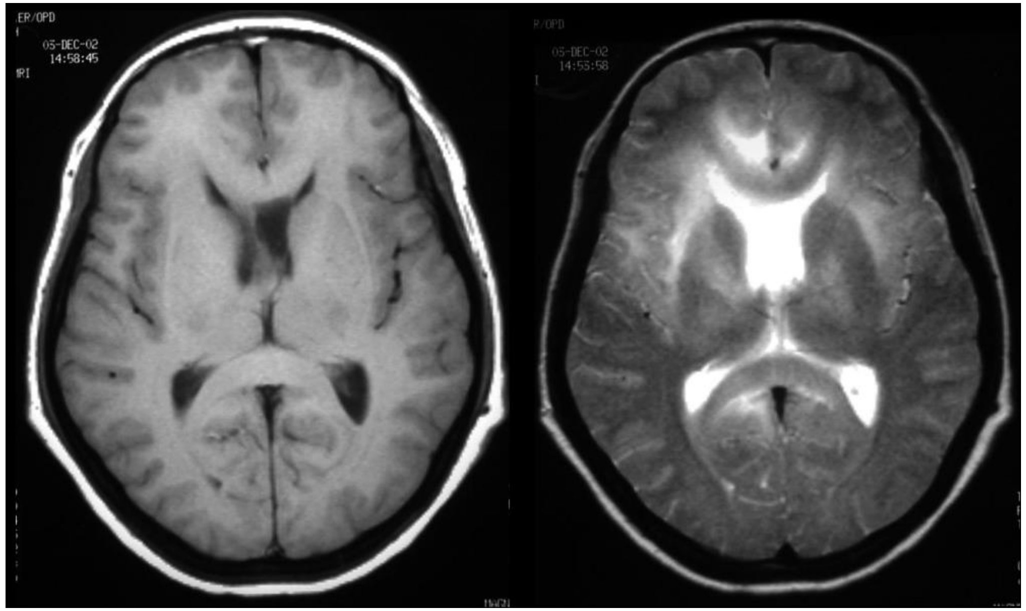
[https://case.edu/med/neurology/NR/MRI Basics.htm]



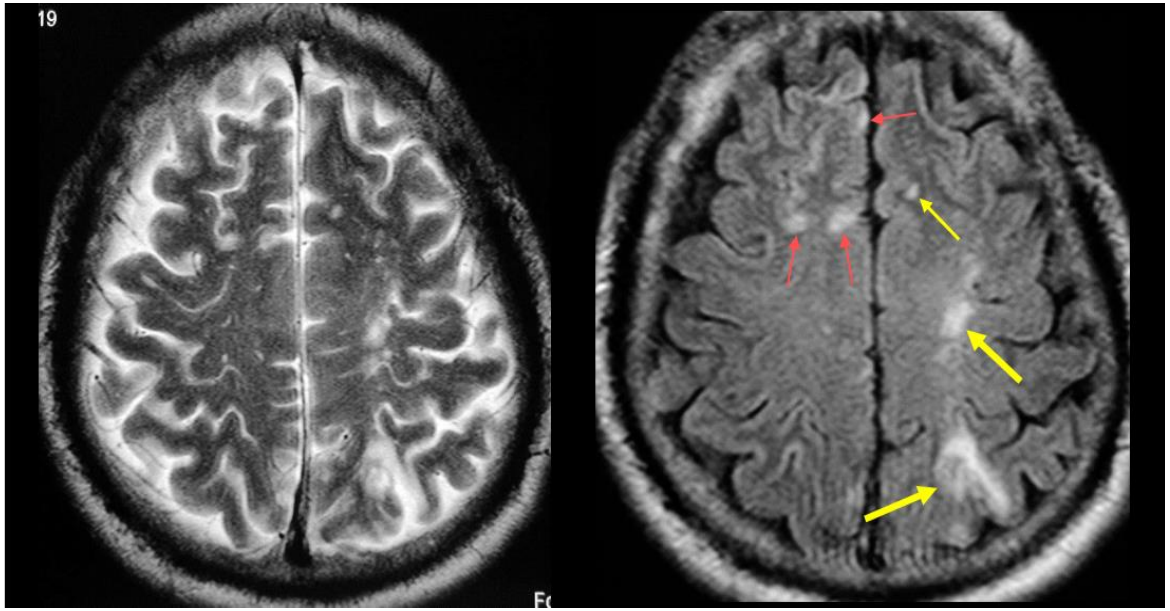
[https://case.edu/med/neurology/NR/MRI Basics.htm]

Comparison between T1-weighted, T2-weighted, and FLAIR images

T1-weighted vs. T2-weighted

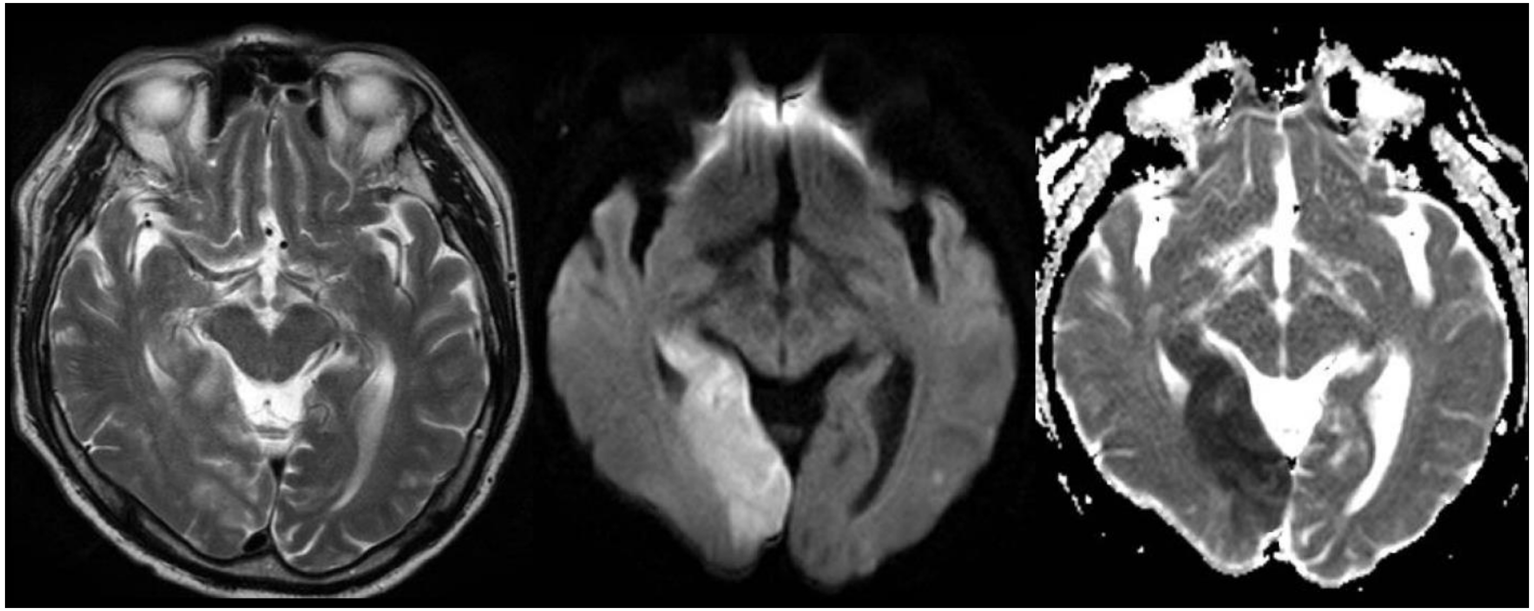


T2-weighted vs. FLAIR



- 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

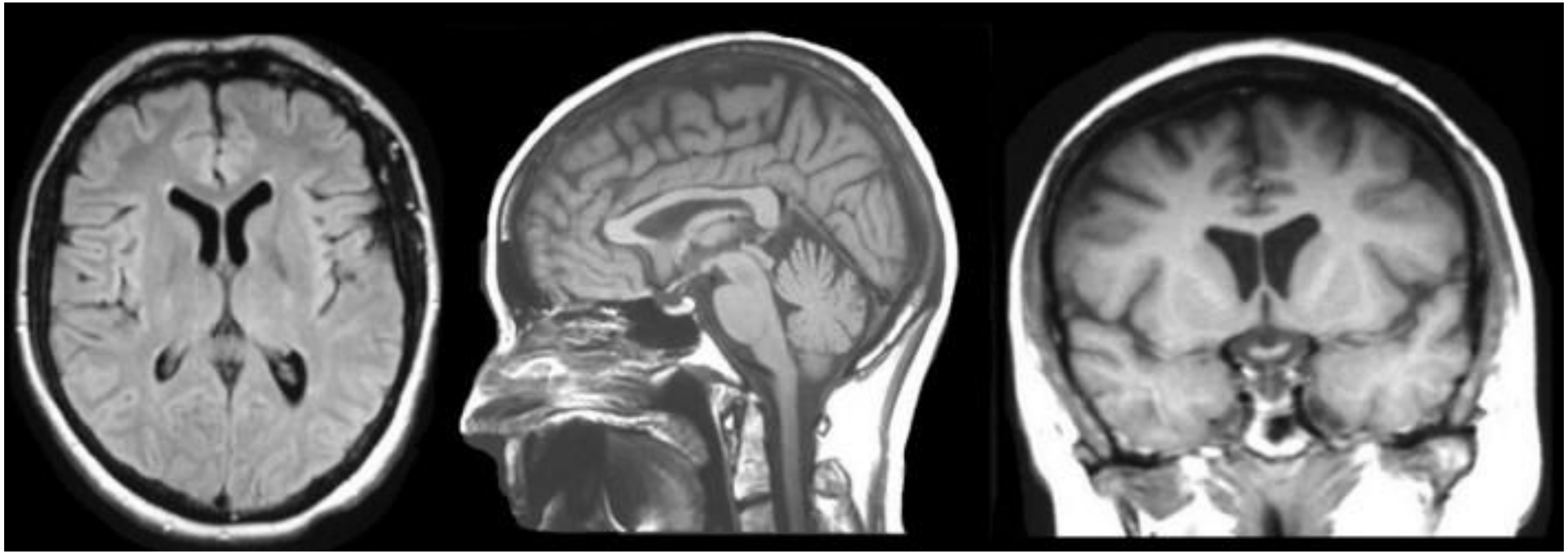


T1-weighted Contrast of the Brain

- 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



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

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

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

Different contrasts of the brain

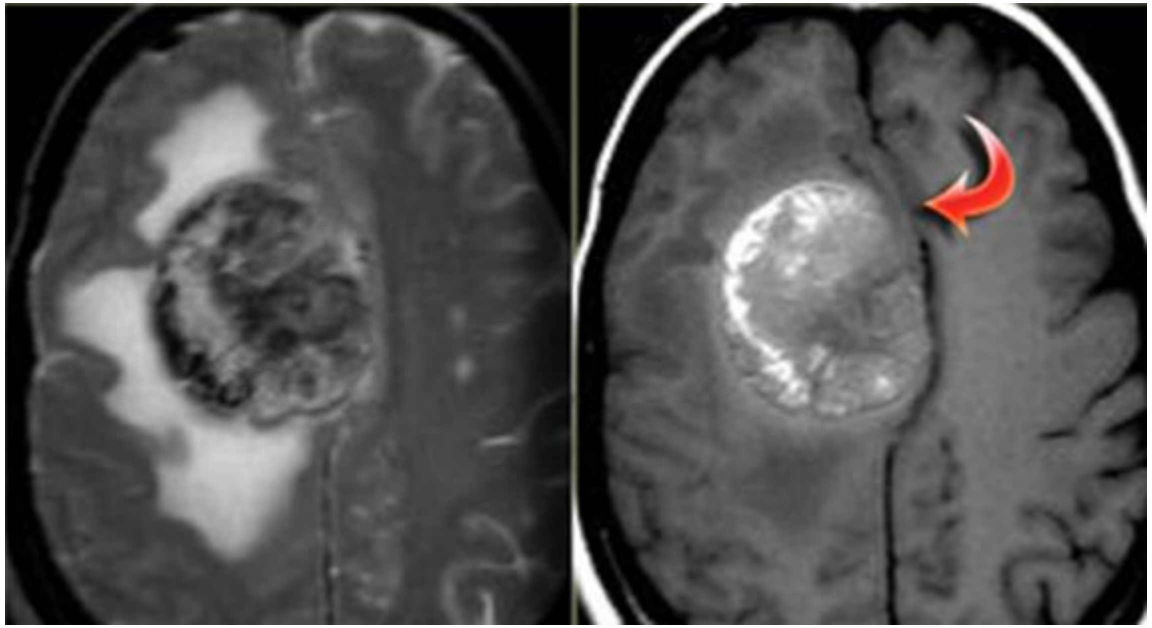
Structural MRI (sMRI)

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

Abnormality Analysis with sMRI

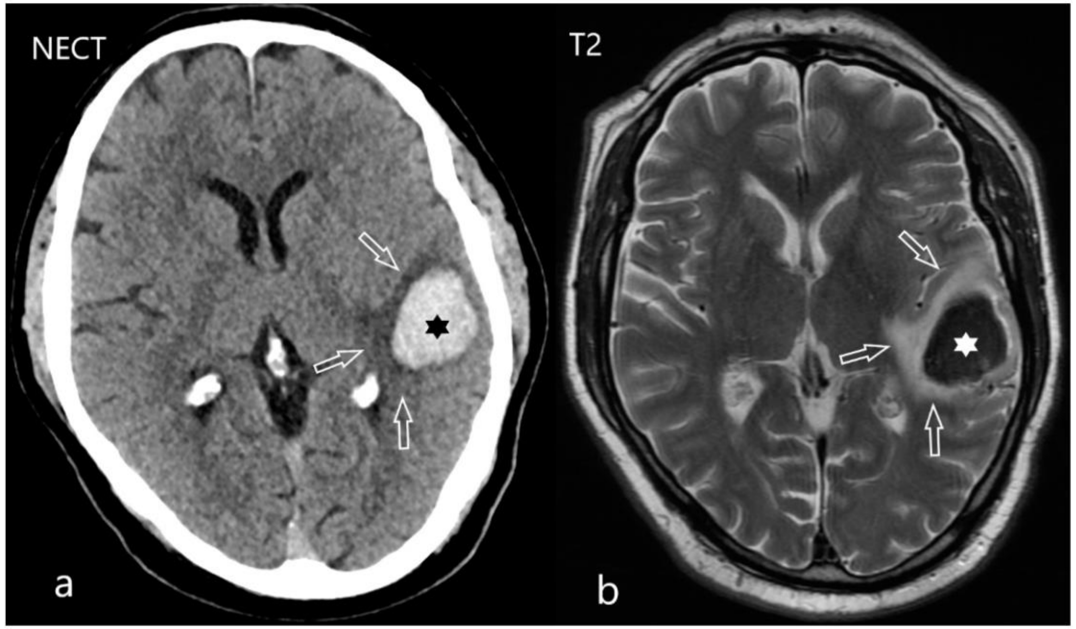
- MRI > CT
  (almost all disease)
  - infarct, tumor, inflammation, infection
  - degeneration, atrophy
  - hemorrhage, trauma
- CT = MRI
  - acute hemorrhage
- CT > MRI
  - calcification

- 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



[https://radiologyassistant.nl/neuroradiology/brain-tumor/systematic-approach]

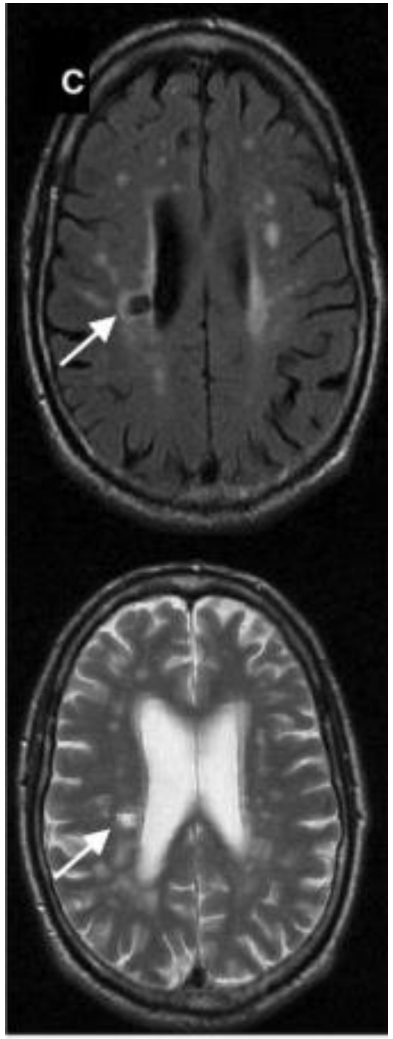
Brain tumour (melanoma metastasis) on T2-weighted and T1-weighted images



[Malikova and Weichet, 2022]

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

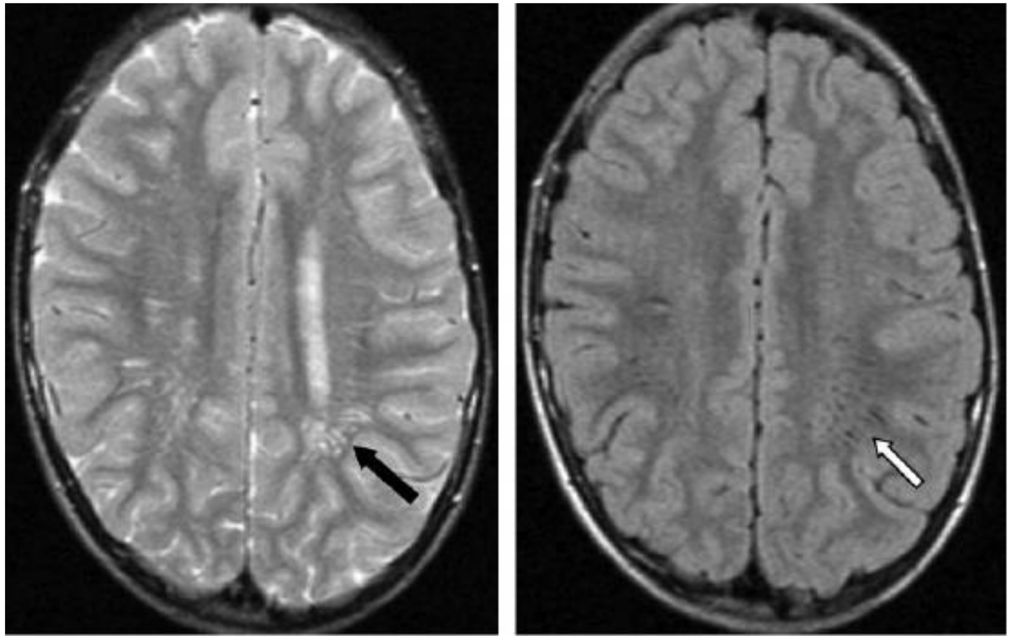
- White matter hyperintensity
  - Region of high intensity (increased brightness) within the cerebral white matter on a T2-weighted image
  - Reflects a lesion produced largely by demyelination and axonal loss
  - Frequently seen in older people and possibly associated with increased risk for some brain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



[Wardlaw et al., 2015]

White matter hyperintensity on FLAIR and T2-weighted images

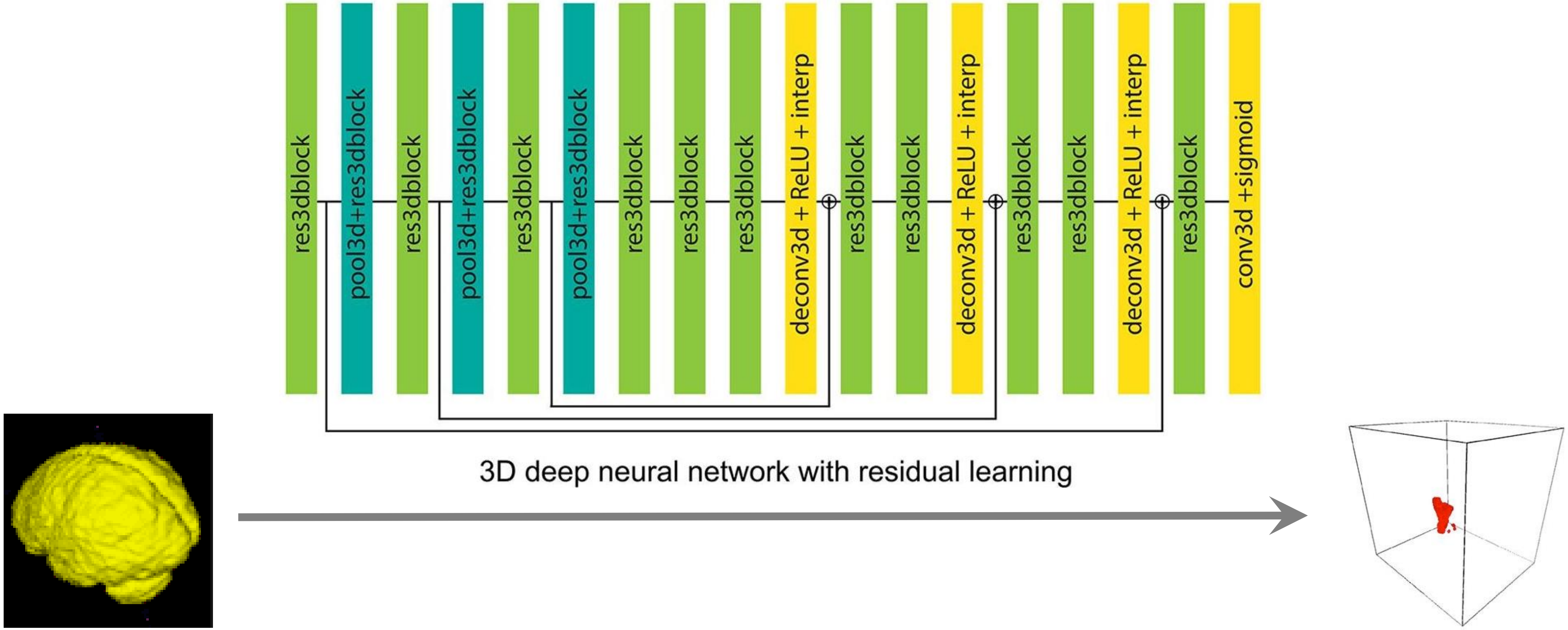
- Perivascular space (Virchow–Robin space)
  - Fluid-filled space surrounding certain blood vessels
  - Typically located in the basal ganglia and white matter of the brain
  - Can become enlarged or dilated, in a close association with ageing or signaling abnormalities



[Kwee and Kwee, 2007]

Perivascular space on T2-weighted and FLAIR images

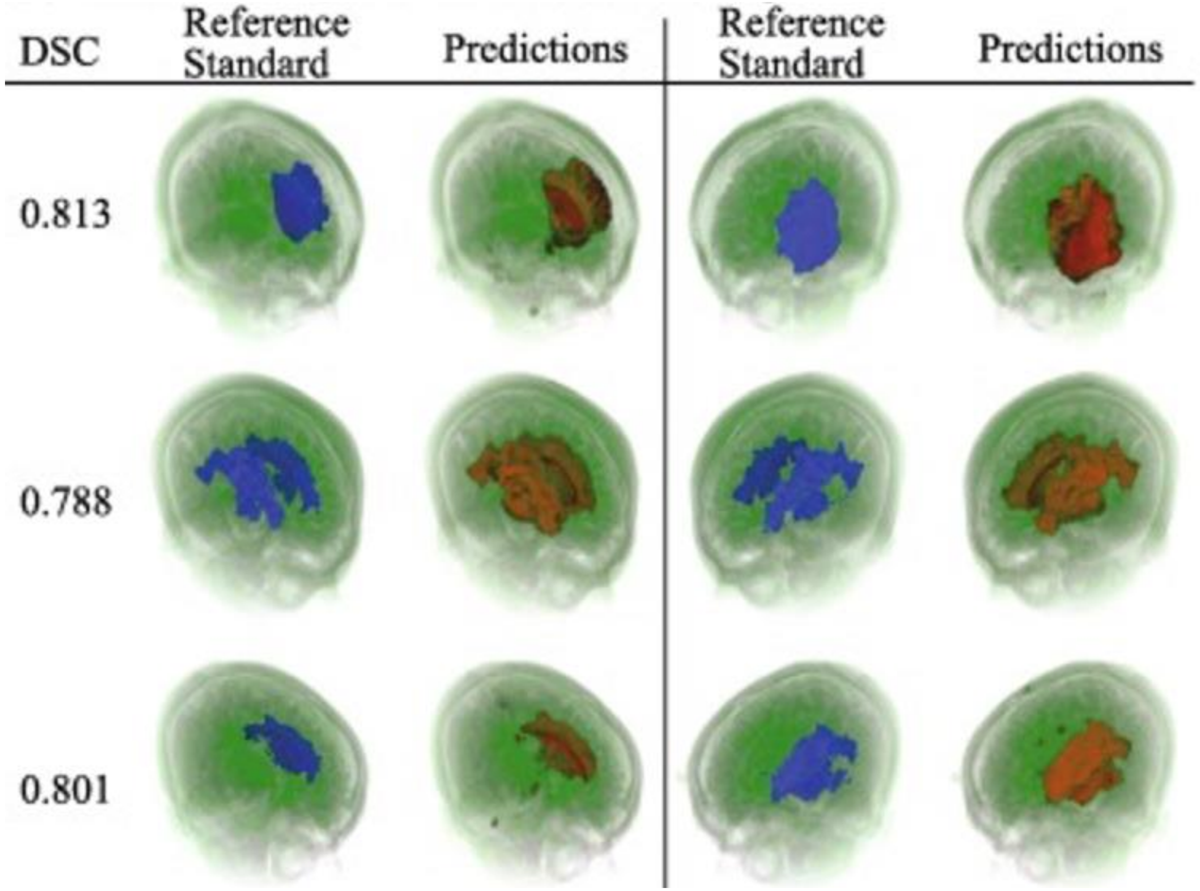
- Automatic abnormality analysis
  - Detection
    - Identifying and confirming the presence of abnormalities in an MRI scan
    - For example, detecting the presence of a stroke lesion
  - Segmentation
    - Outlining the precise boundaries of abnormalities in an MRI scan
    - For example, outlining the exact region of white matter hyperintensities
  - Grading
    - Classifying the severity or stage of detected abnormalities in an MRI scan
    - For example, assigning a grade to a brain tumour based on its characteristics such as size or aggressiveness



[Tomita et al., 2020]

Automatic segmentation of a stroke lesion

$$DSC = \frac{2|X \cap Y|}{|X| + |Y|}$$



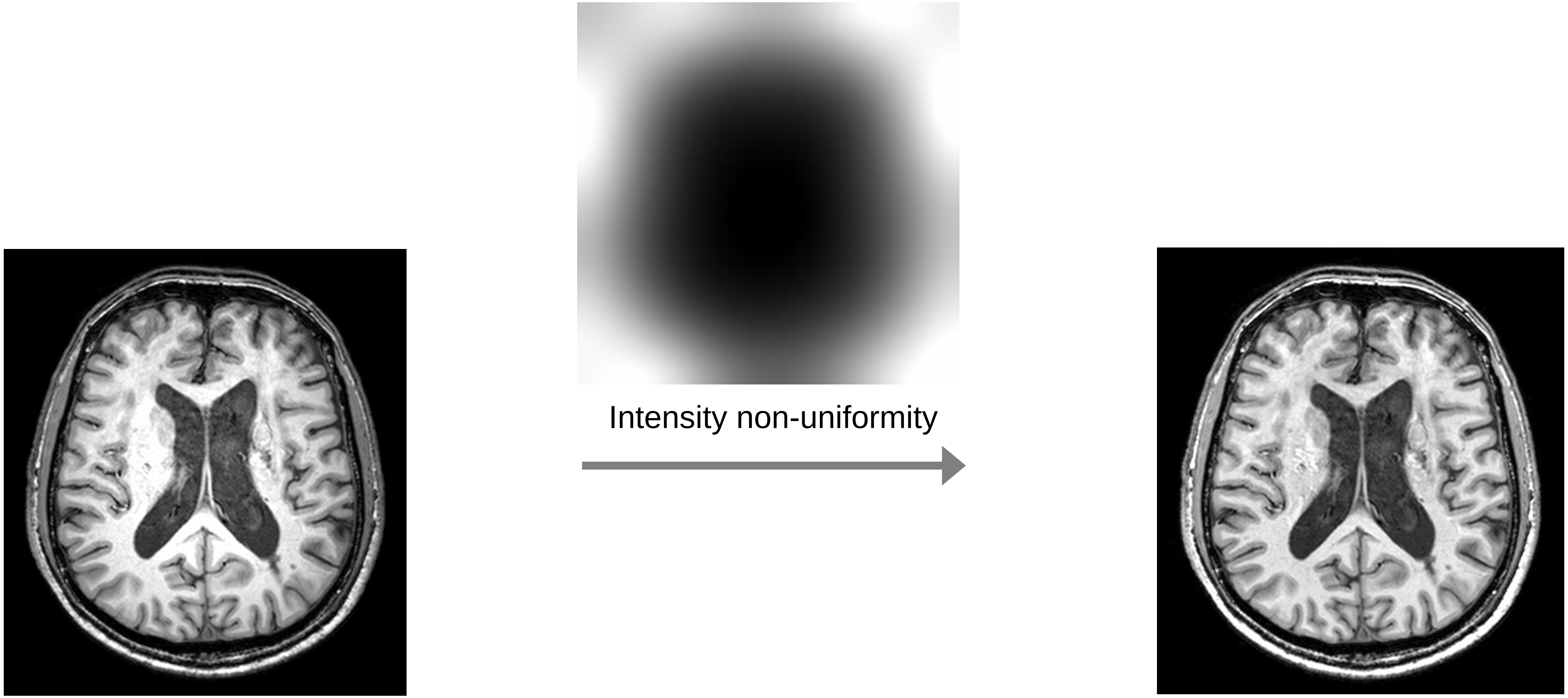
[Tomita et al., 2020]

Evaluation of the performance of stroke lesion segmentation

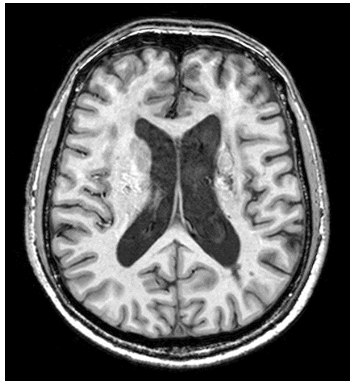
Brain Morphometry with sMRI

- Brain morphometry
  - Measurement of brain structures
    - Density or volume
    - 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 intensity non-uniformity (bias field)
    - From a broader range of sources, including imperfections in the MRI scanner's main magnetic field, inhomogeneities in the radiofrequency coil performance, and magnetic susceptibility-induced field inhomogeneities
    - Often characterized by a smooth variation in image brightness
  - Segmentation
    - Classifies an image into the non-brain and brain and, furthermore, the brain into different tissues including grey matter, white matter, and cerebrospinal fluid
  - Normalisation
    - Transforms an image from a native space to the standard space



Correction for intensity non-uniformity



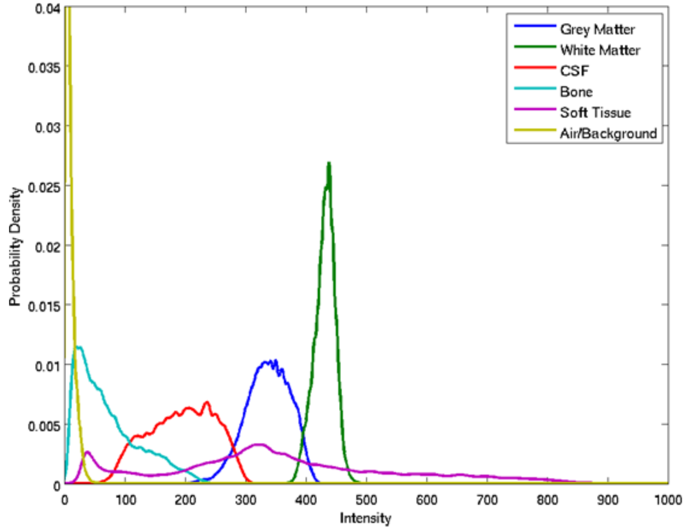
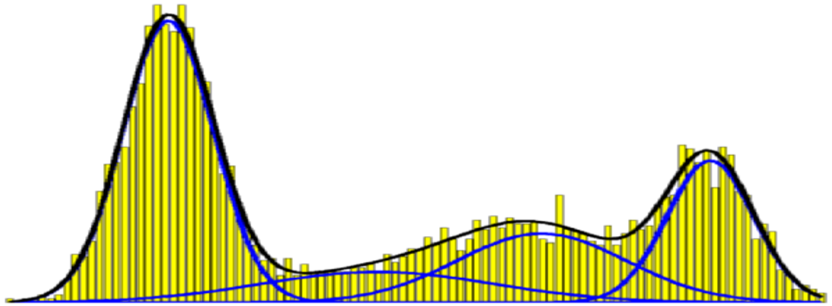


Image intensity distribution



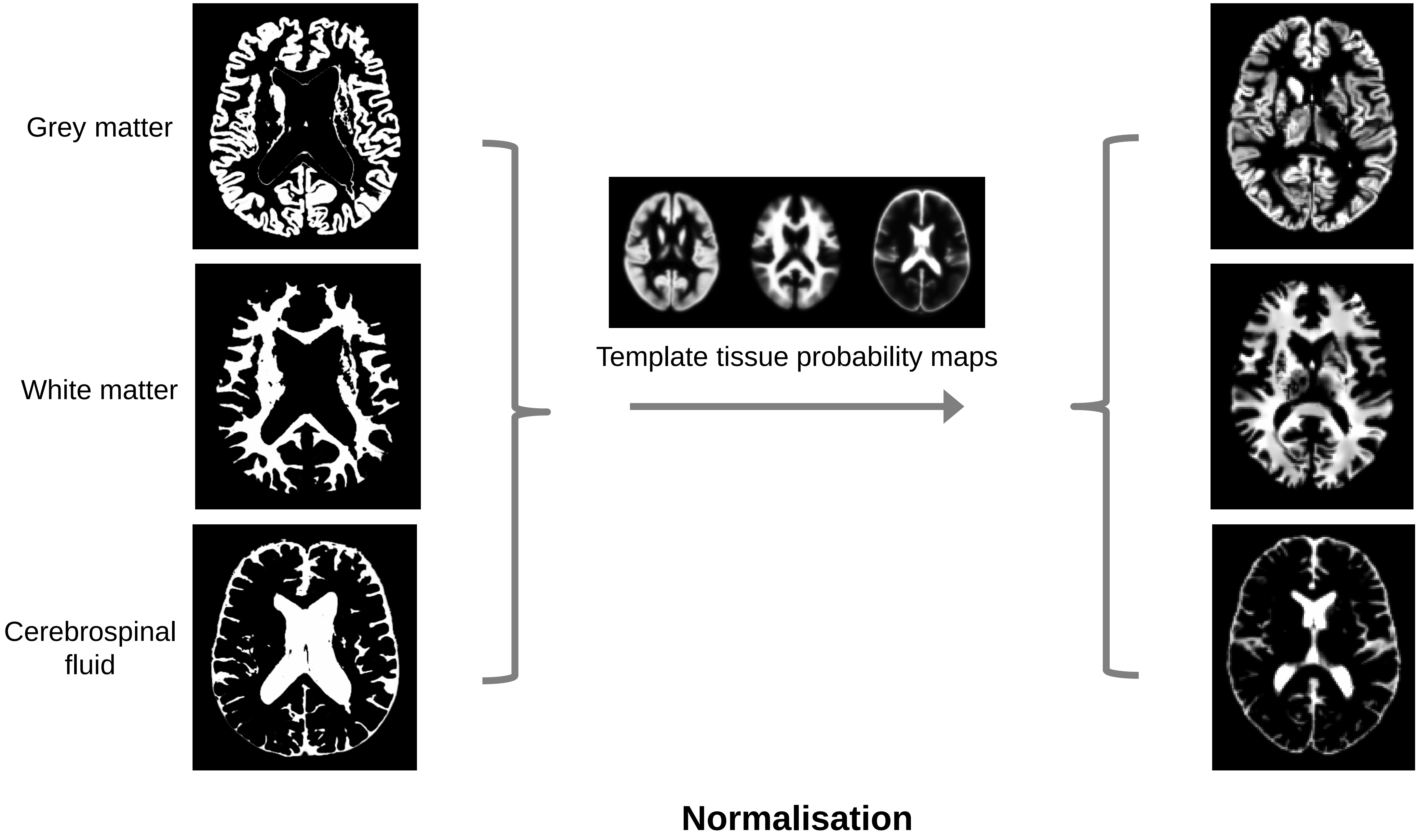
Mixture of Gaussians model

Grey matter

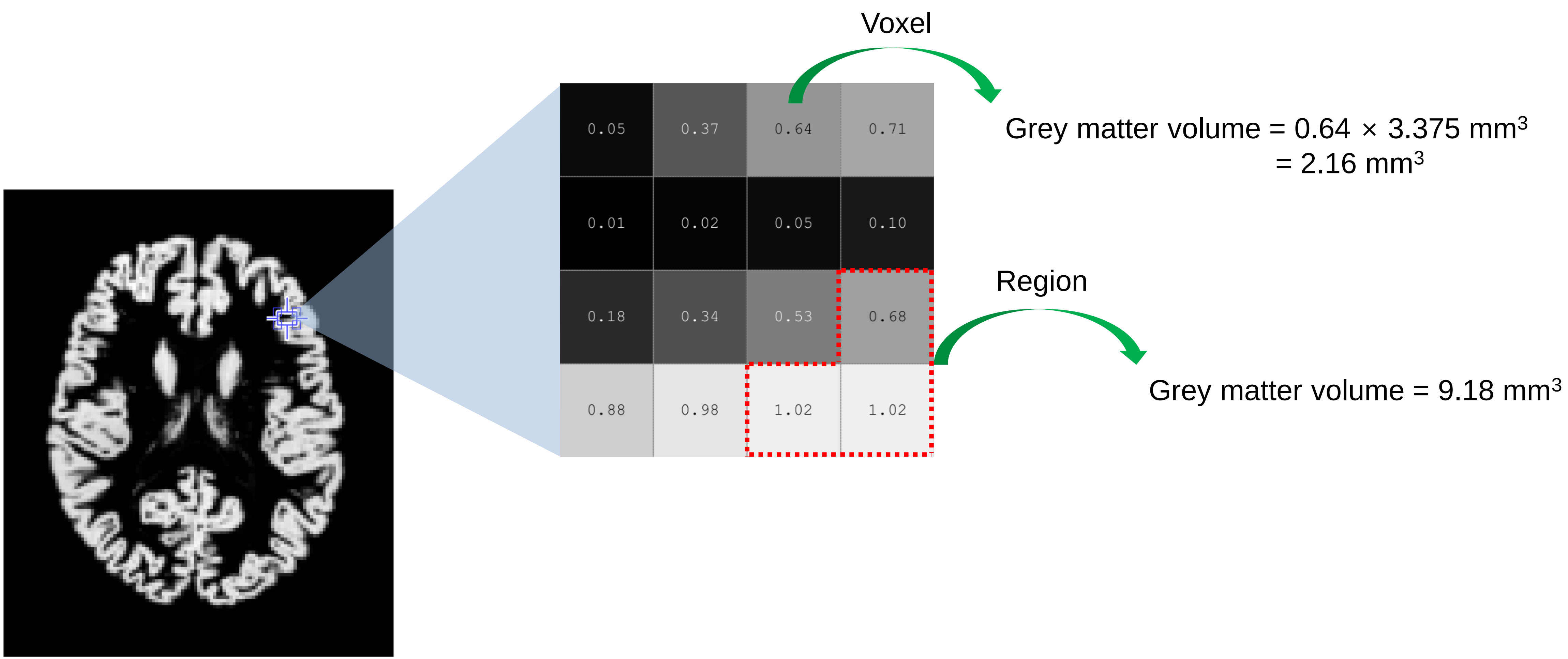
White matter

Cerebrospinal fluid

Segmentation into different tissues

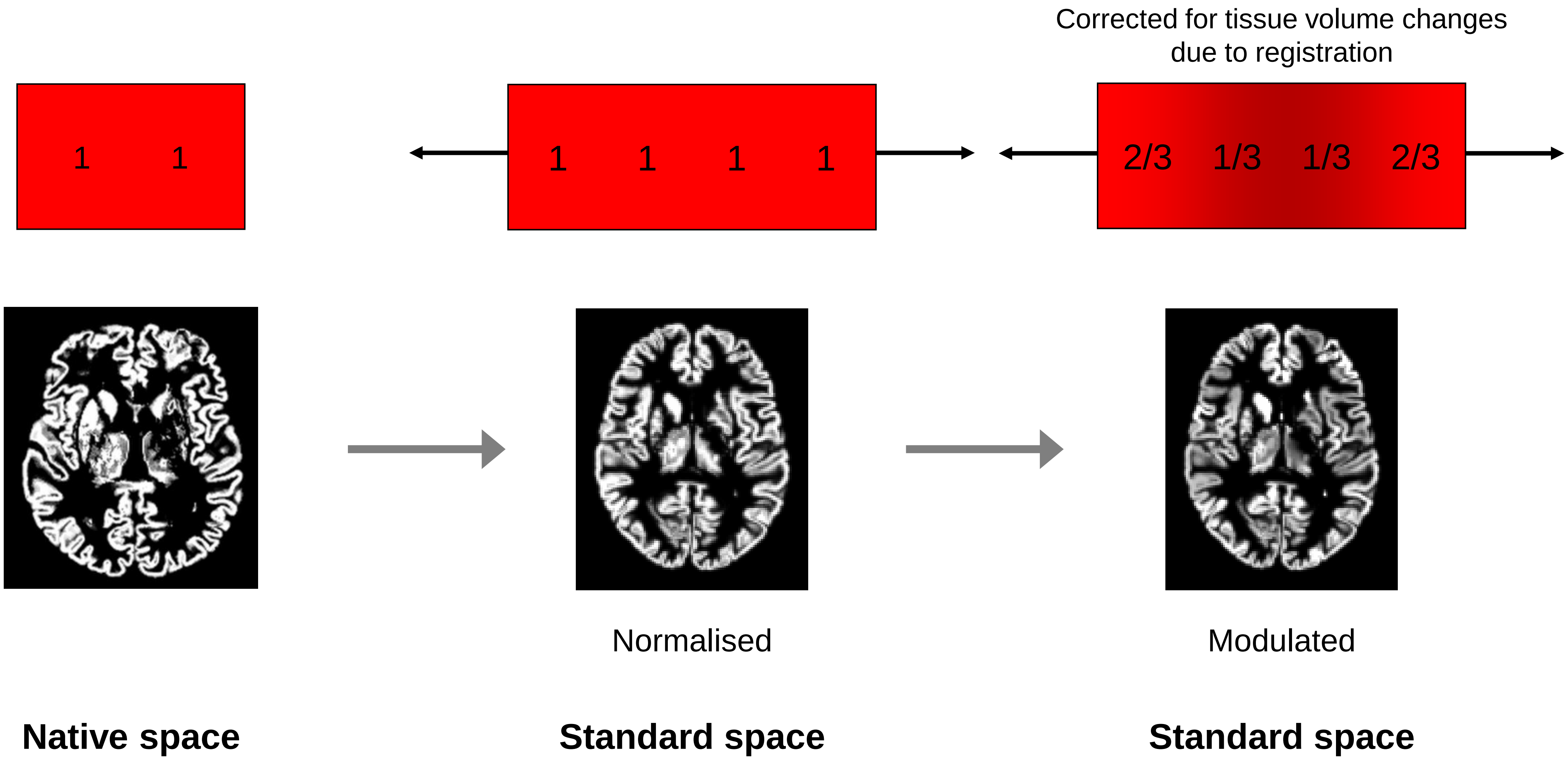

Grey matter
White matter
Cerebrospinal fluid
Template tissue probability maps
Normalisation

- 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
    - For a tissue probability map in the native space or its modulated one in the standard space

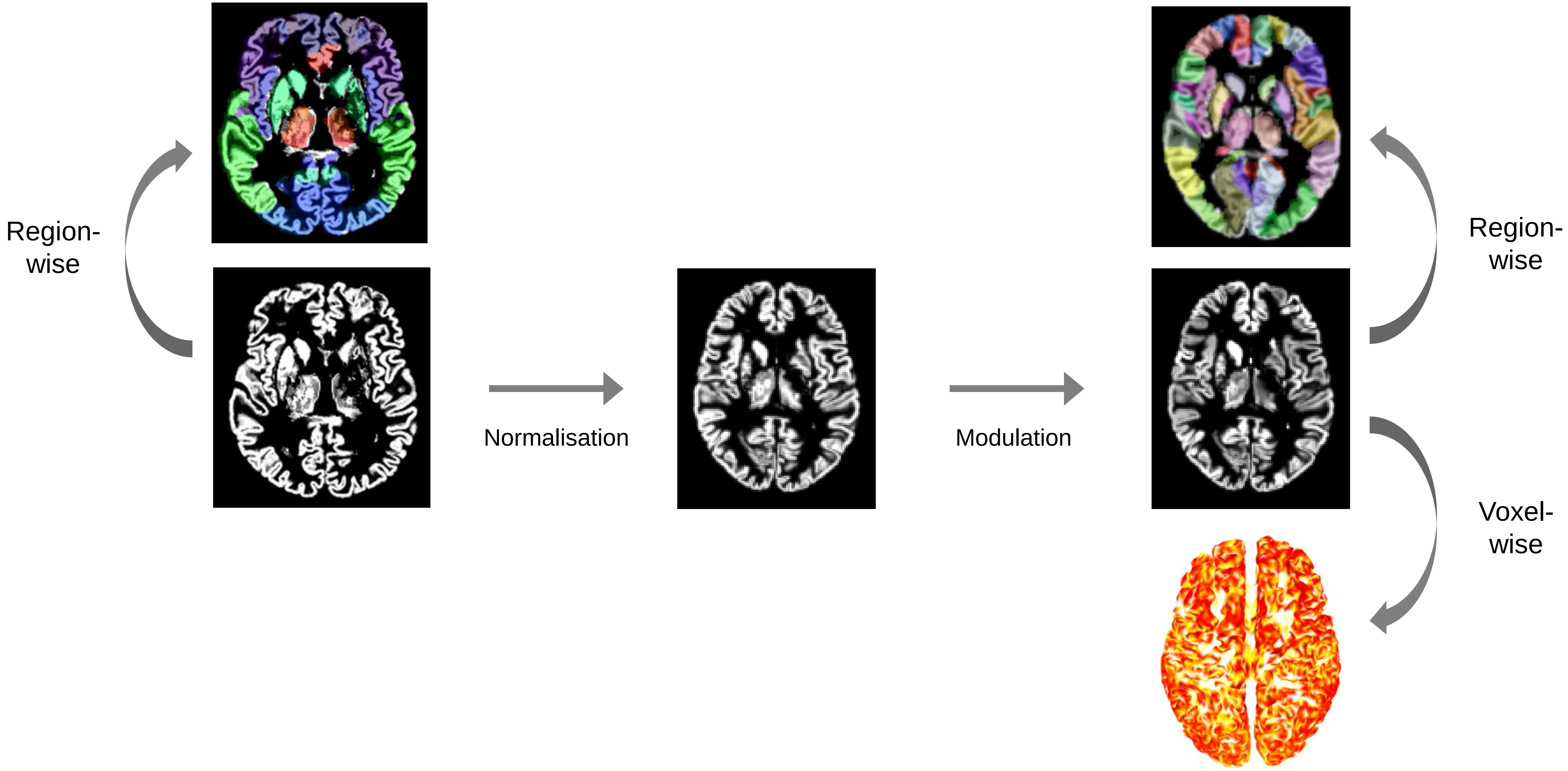


Voxel size: 1.5 mm × 1.5 mm × 1.5 mm
Voxel volume: 3.375 mm^3

Computation of grey matter volume for a voxel or a region

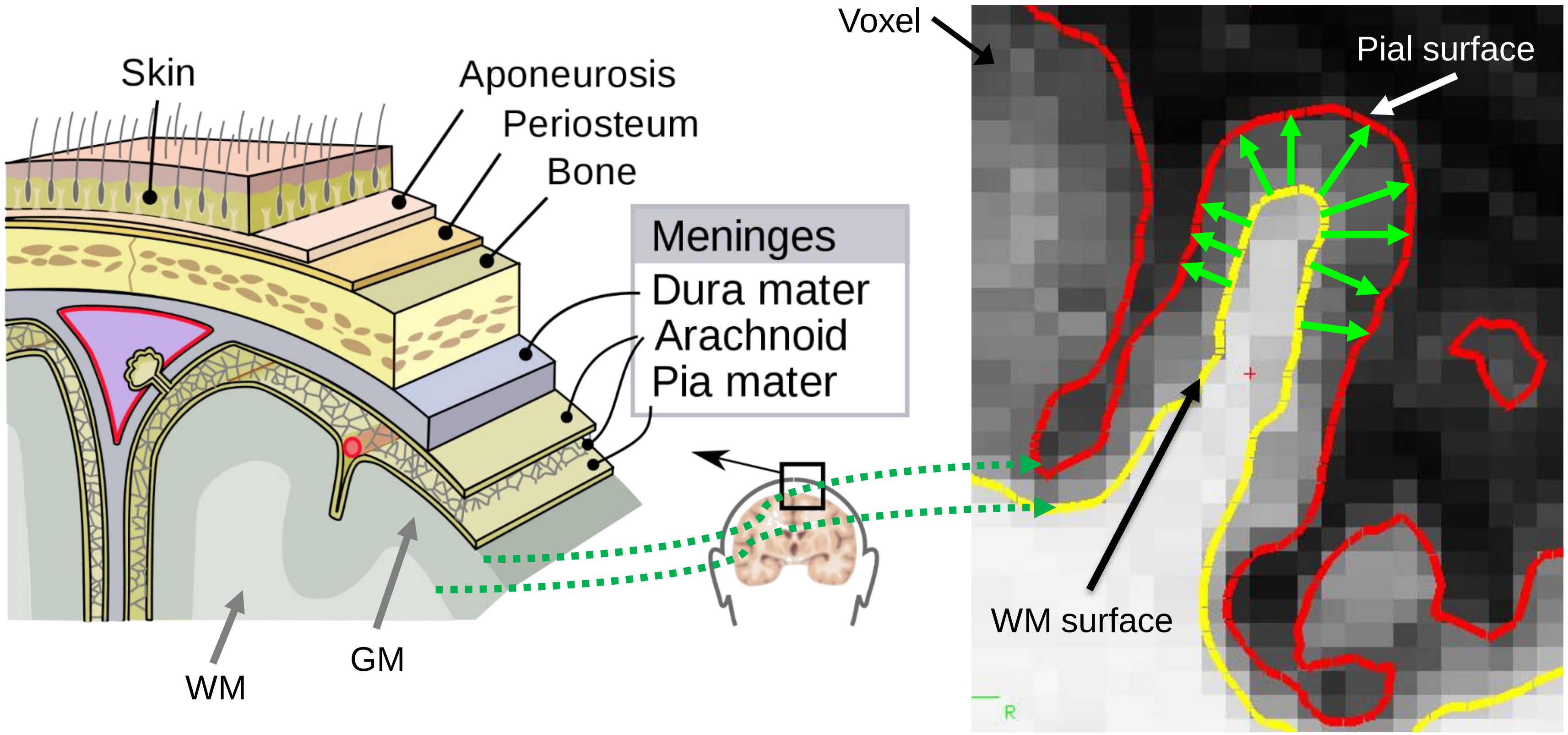


Normalisation and modulation



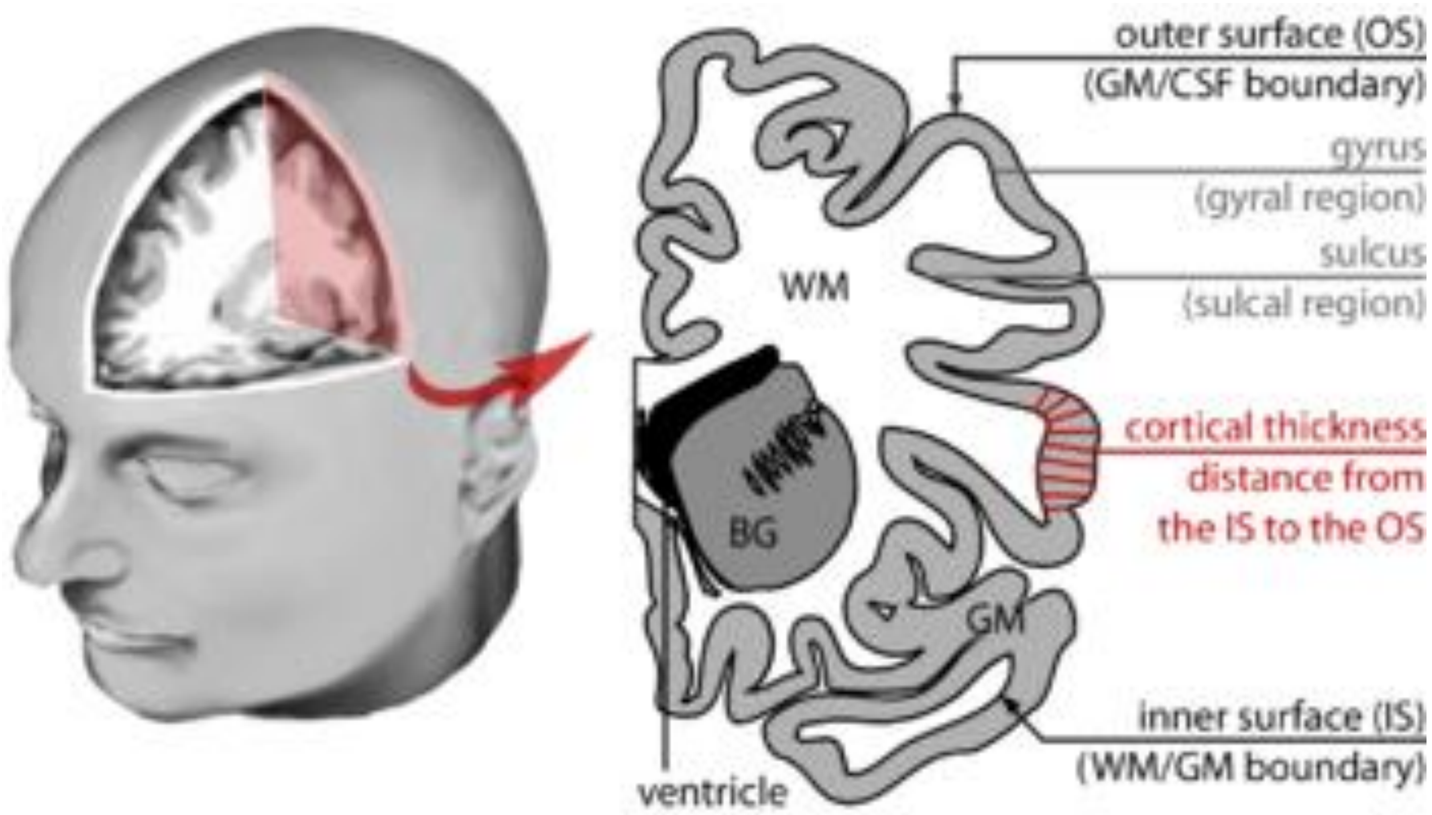
Features of grey matter volume

- 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
    - White matter surface (inner surface): inner cortical boundary between the grey matter and white matter
    - Pial surface (outer surface): outer cortical boundary between the grey matter and pia mater



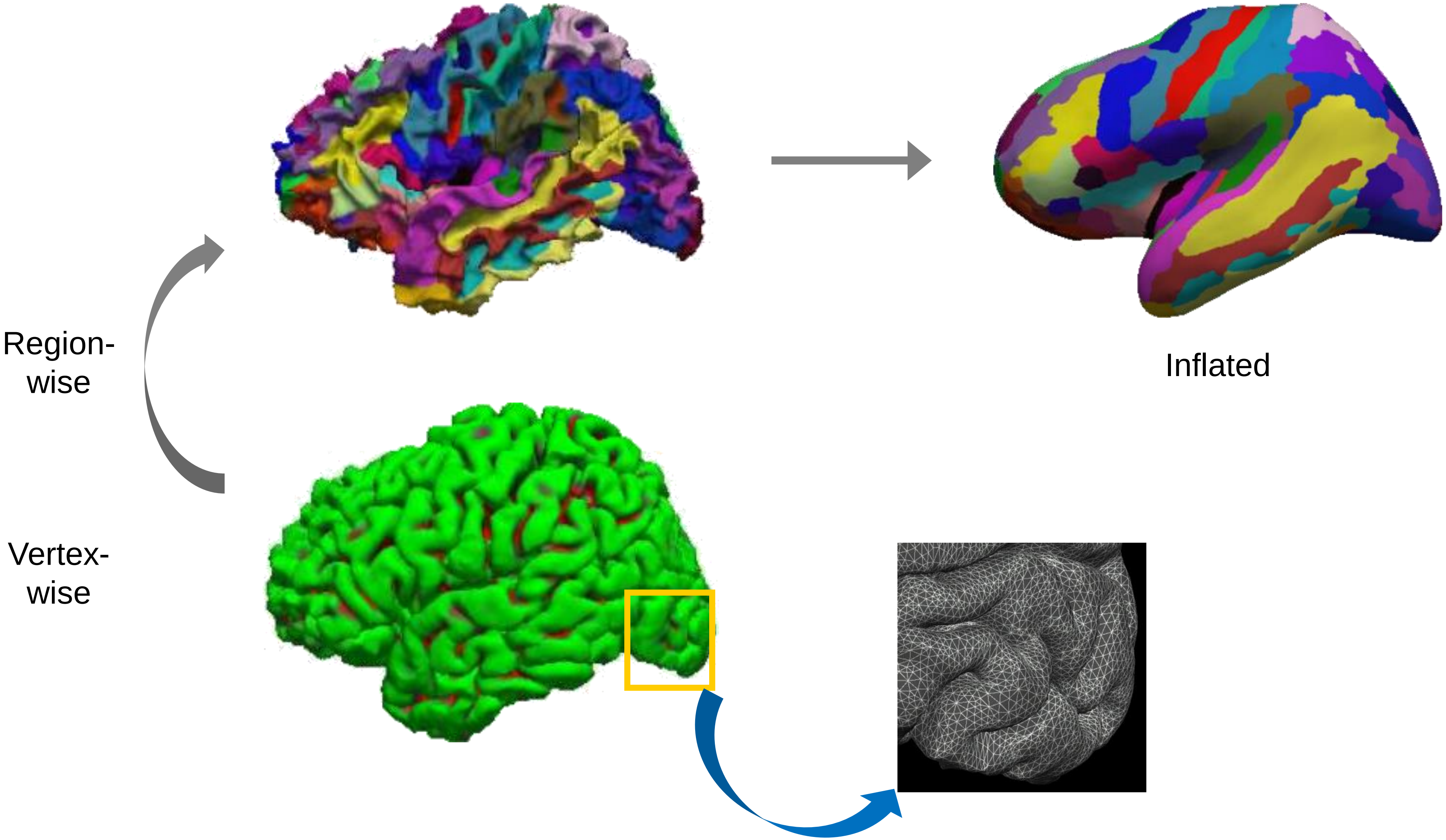
[https://www.physio-pedia.com/Meninges]

Cortical surfaces beneath cranial meninges



[https://en.citizendium.org/wiki/Brain_morphometry]

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

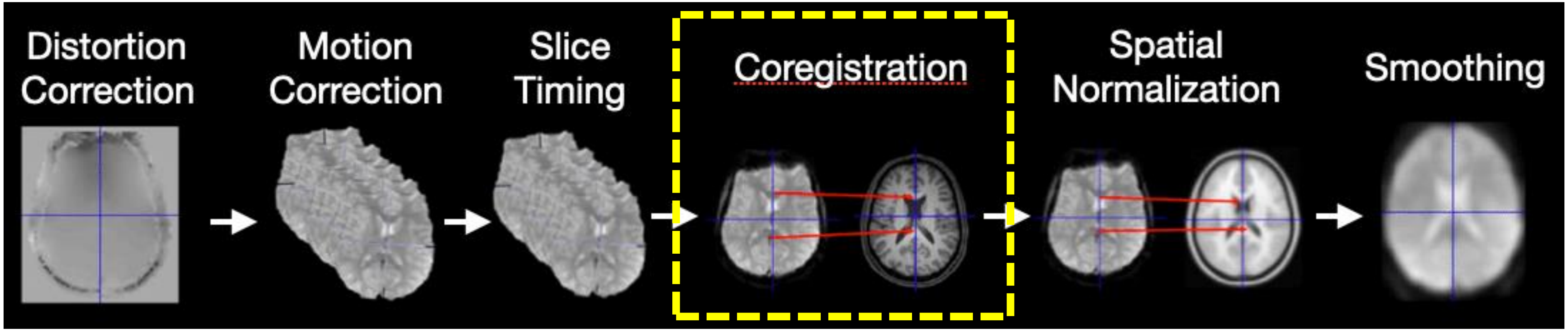


Features of cortical thickness

sMRI as an Individual's Spatial Reference

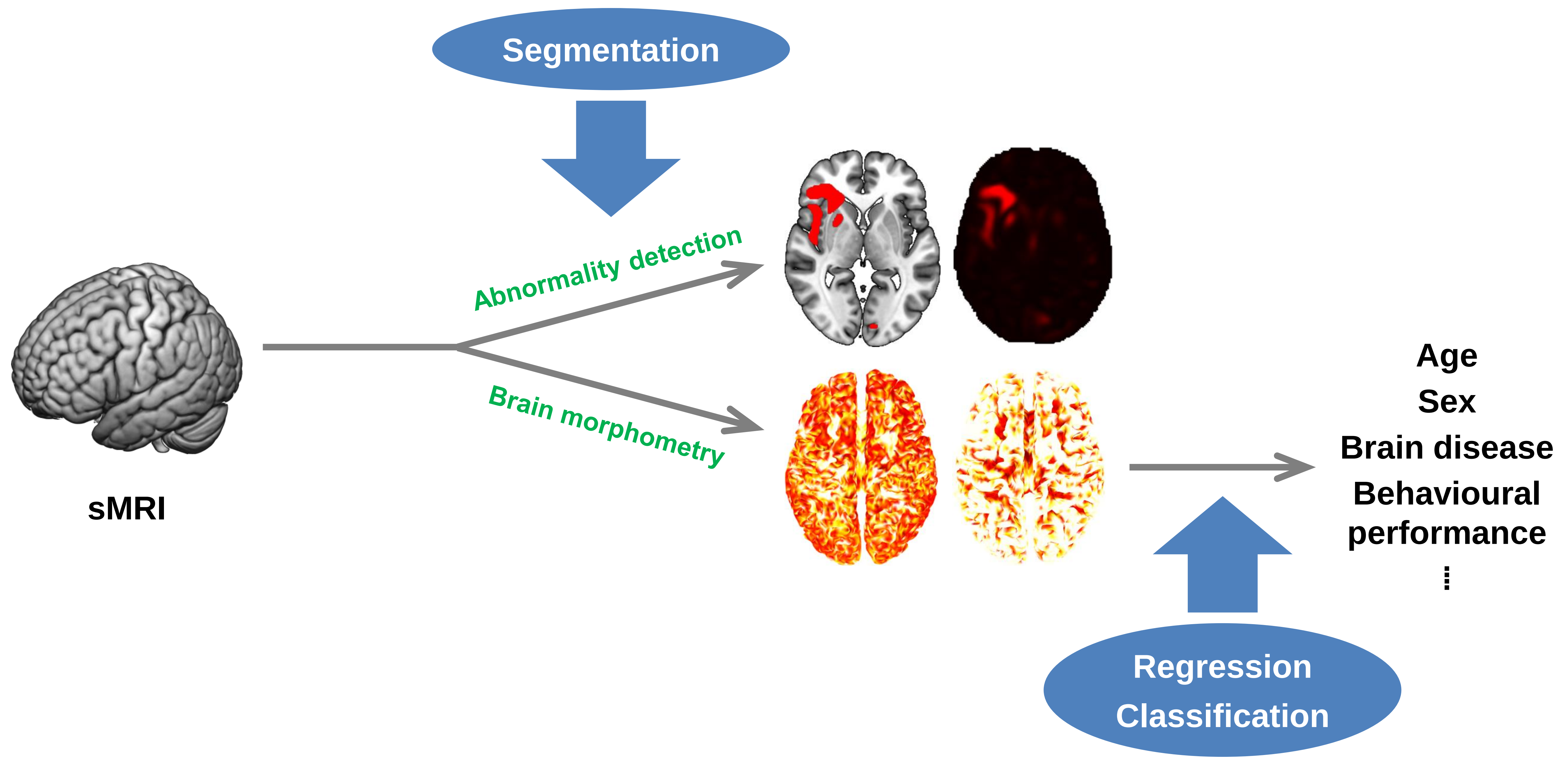
- Coregistration between sMRI and functional/diffusion-weighted MRI
  - Within-subject between-modality registration
  - For the anatomical localization of an individual's brain activity or diffusion properties
  - To achieve more precise normalisation of functional/diffusion-weighted images by using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



Segmentation
Abnormality detection
Brain morphometry
sMRI
Age
Sex
Brain disease
Behavioural
performance
⋮
Regression
Classification