KÄRNTEN
University of
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Applied Medical Image Analysis

Background for Project Task 1

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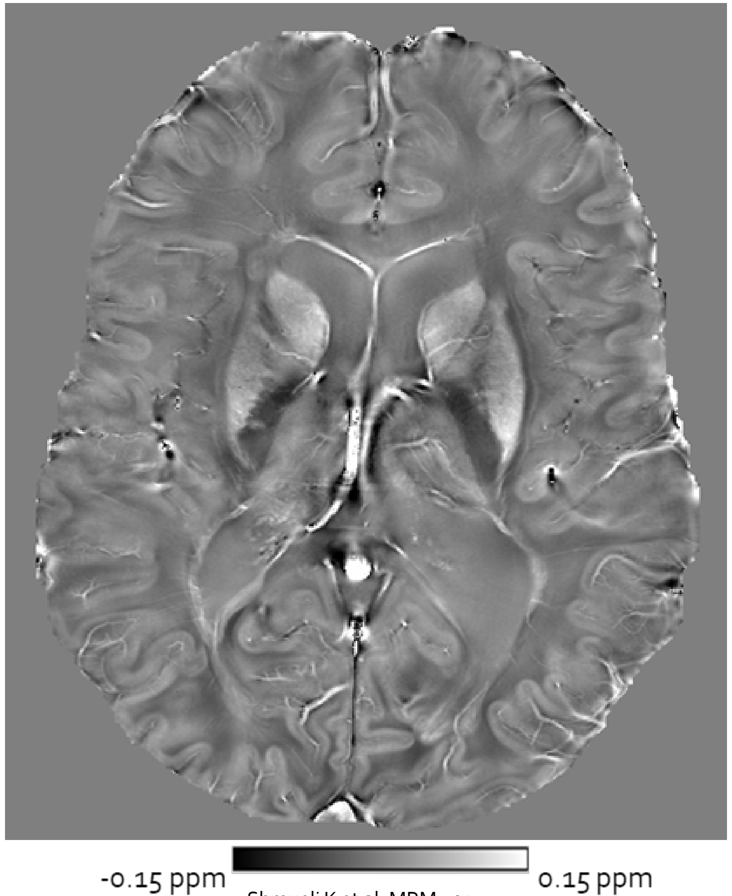
Susceptibility MR imaging

Magnetic susceptibility (χ) is a property that describes the extent to which a material is magnetized when exposed to a magnetic field. We differentiate between diamagnetic (χ<0), paramagnetic ($\chi > 0$ and $\chi < 1$) and ferromagnetic ($\chi > 1$) substances. As most biological tissues are weakly diamagnetic, tissues with large susceptibility differences show high contrast.

Material	Volume Magnetic Susceptibility (χ) in ppm
Calcium carbonate	−13
Cortical bone	−11
Oxyhemoglobin	−9.2
Water (& most tissues)	−9.0
Fat	−8.3
Gadolinium in blood	+0.03
Methemoglobin	+0.12
Oxygen (O_2)	+0.37
Gadolinium in bladder	+13

Courtesy of Allen D. Elster, MRIquestions.com



Shmueli K et al, MRM 2012

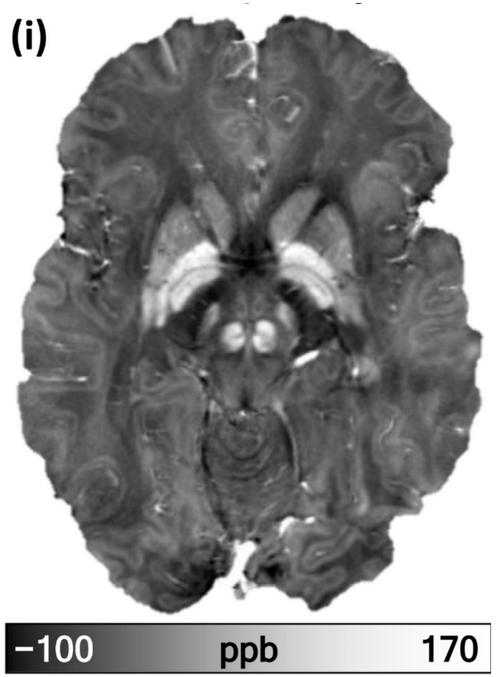
Iron

In brain, the iron concentration is the highest in deep grey matter structures and increases with age.

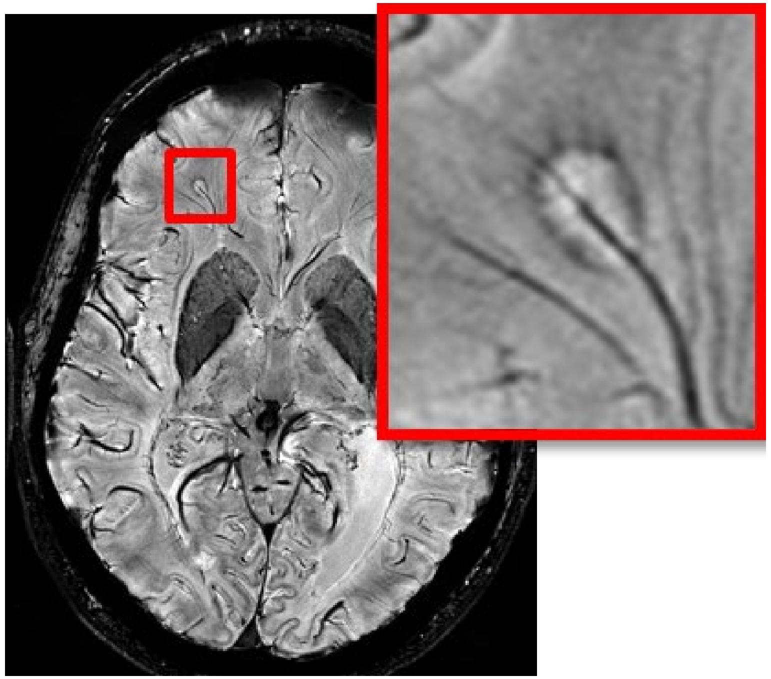
Many neurological disorders are related to increased iron deposition: e.g. Parkinson's, Alzheimer's, Multiple sclerosis, etc.

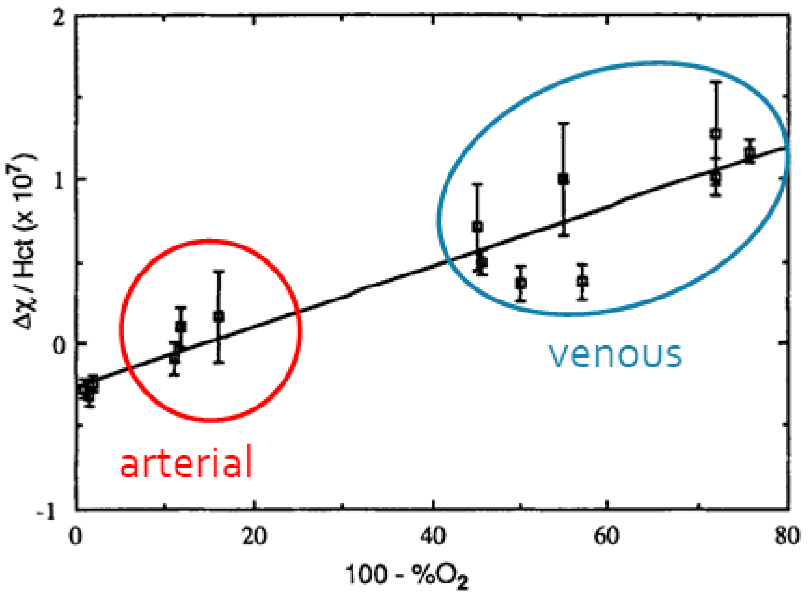
Iron levels also alter in inflammation, e.g. the iron rim of MS lesion.

Iron in haemoglobin lead the deoxy-haemoglobin (venous blood) to be paramagnetic. Binding to oxygen creates weakly diamagnetic oxy-haemoglobin (arterial blood).



Moeller et al., TINS 2019;42(6):384-401



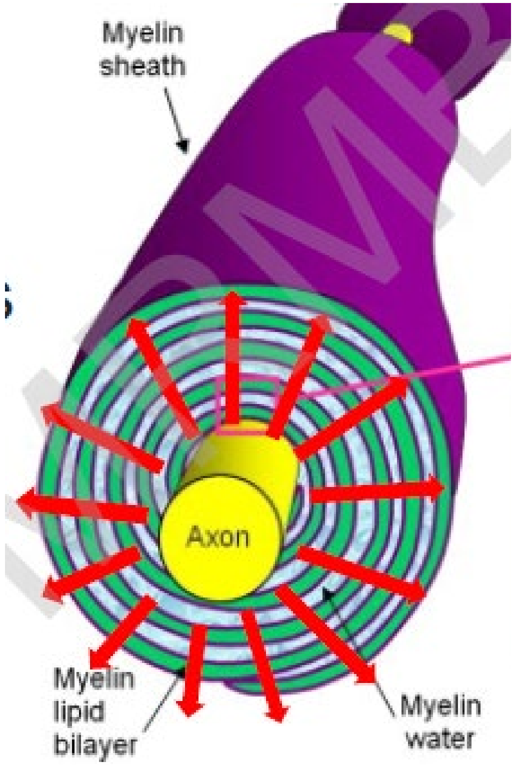


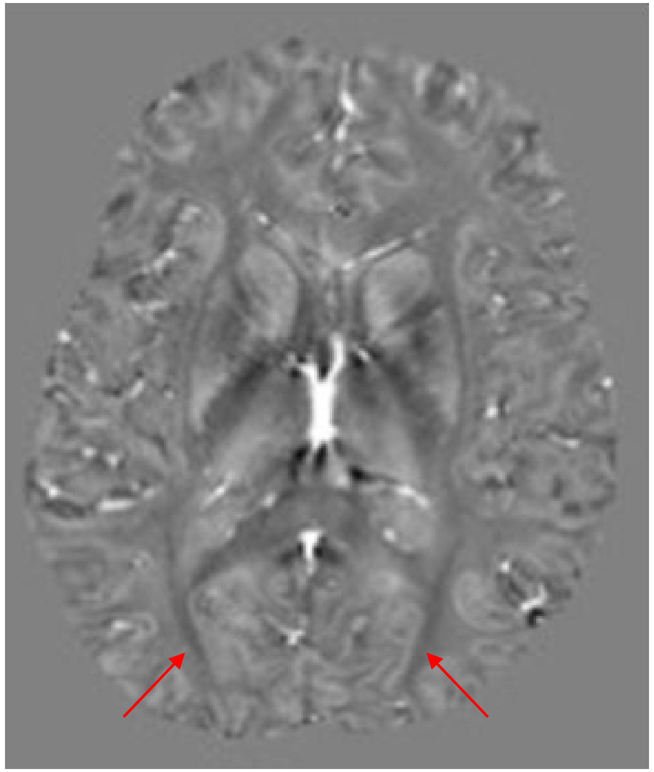
Myelin

Myelin acts as electrical insulation around axons (improves signal transmission) and is thus mainly present in white matter.

It is created mainly by diamagnetic lipids and therefore high myelin tracks appear diamagnetic.

Important histopathological hallmarks in neurological disorders.

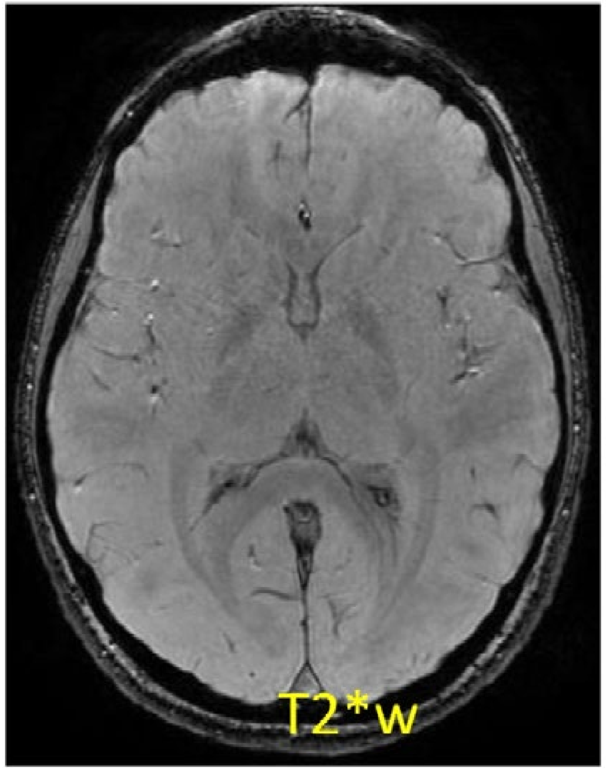




Calcium

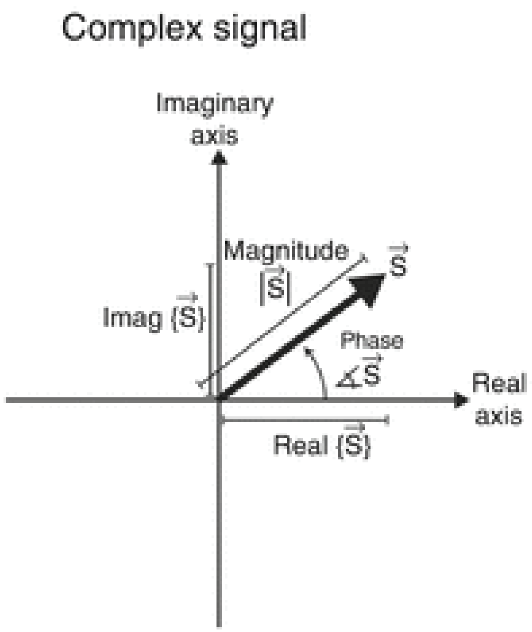
Calcifications can occur in various cases, such as vascular calcifications, brain calcifications, calcifications in tumours or kidney stones.

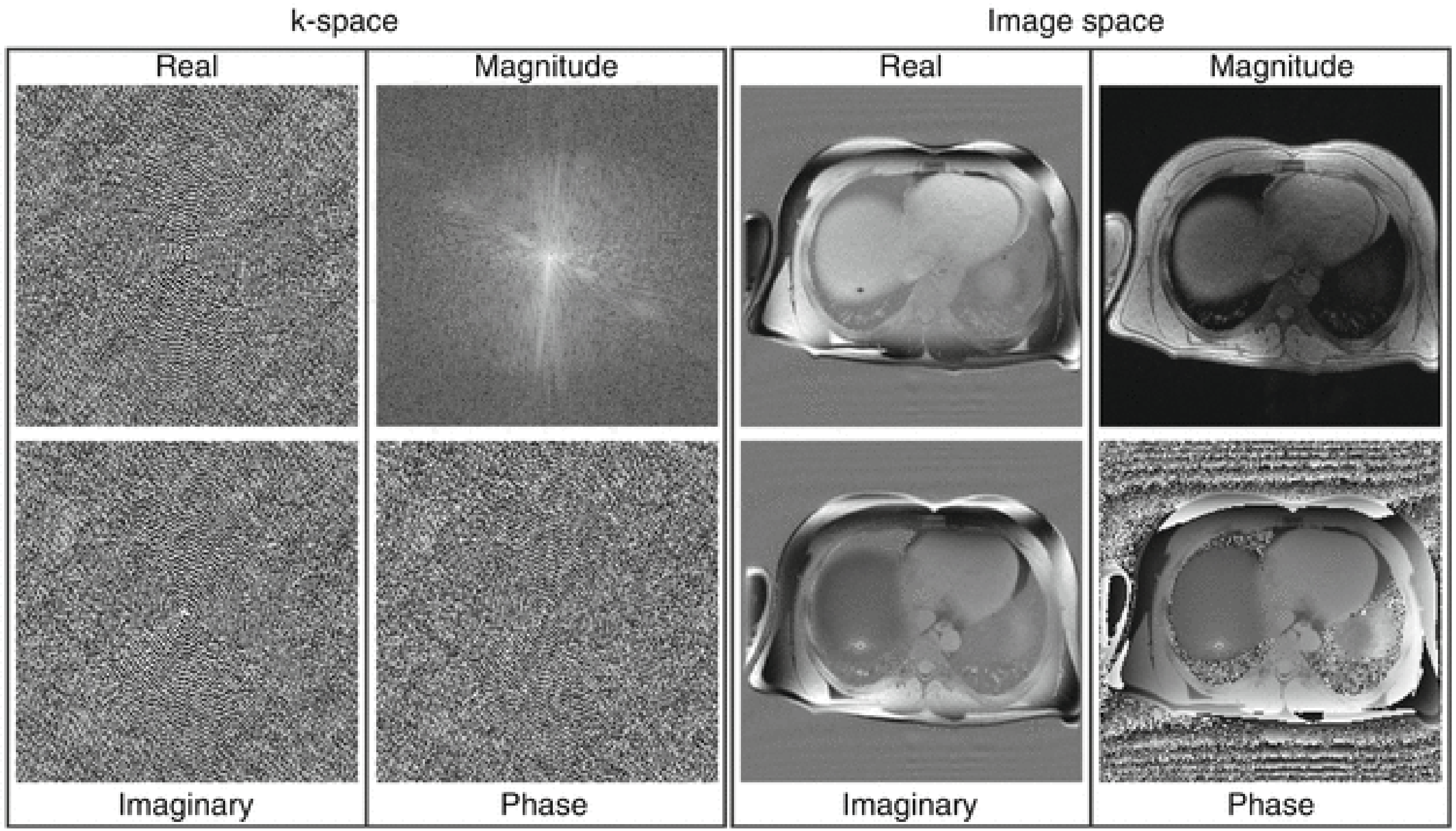
Calcium is strongly diamagnetic and based on the susceptibility can be resolved from paramagnetic iron (e.g. in haemorrhage).



Susceptibility MR imaging

The phase of the MR signal is information inherent to every MRI measurement – in every voxel, the signal has both a magnitude and a phase. Phase MR imaging provides high sensitivity to susceptibility effects and allows different contrasts to be generated.





Dipole response

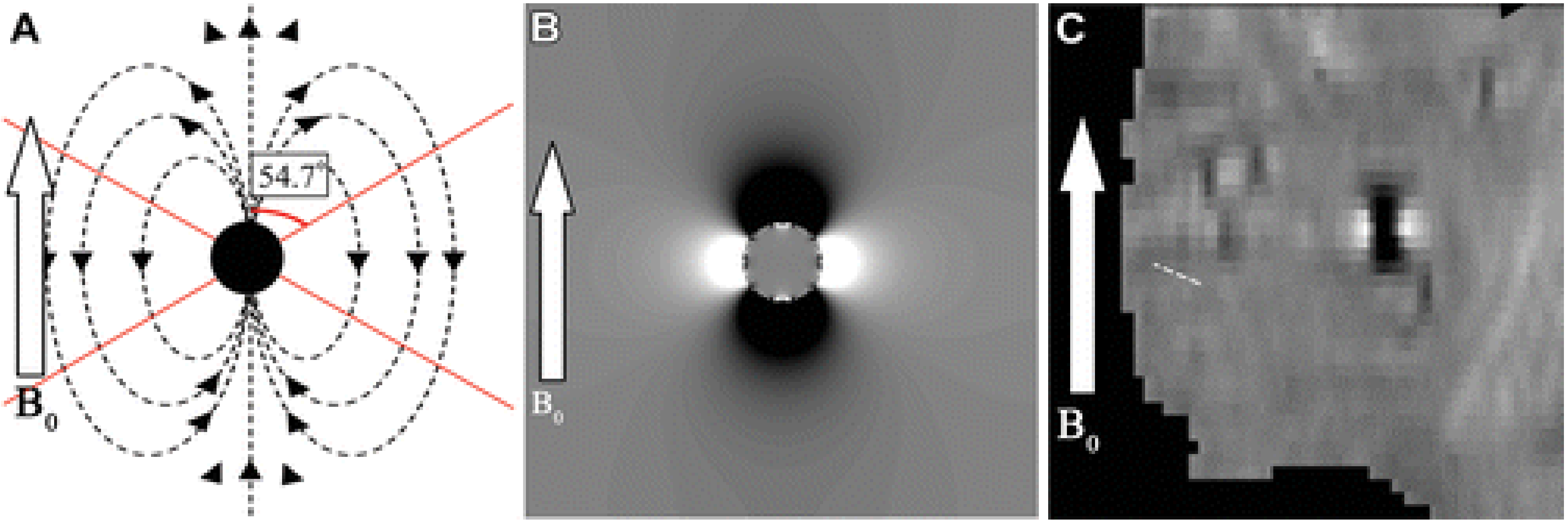
Each susceptibility source creates a weak local demagnetization field given as:

$$B_{demag} = B_0\{\chi \otimes d_z\},$$

where $B_0$is the magnetic field of the MR scanner, χ is the susceptibility and d_z is a point-dipole response function, given as:

$$d_z = \frac{3cos^2\theta - 1}{4\pi r^3}$$

The B_{demag} of all susceptibility sources superimpose on top of B_0.



The values along the magic angle (Θ=54.7°) are zero and there are lobes of positive and negative field strength.

Harada T et al., Radiographics 2022, doi:10.1148/rg.210054

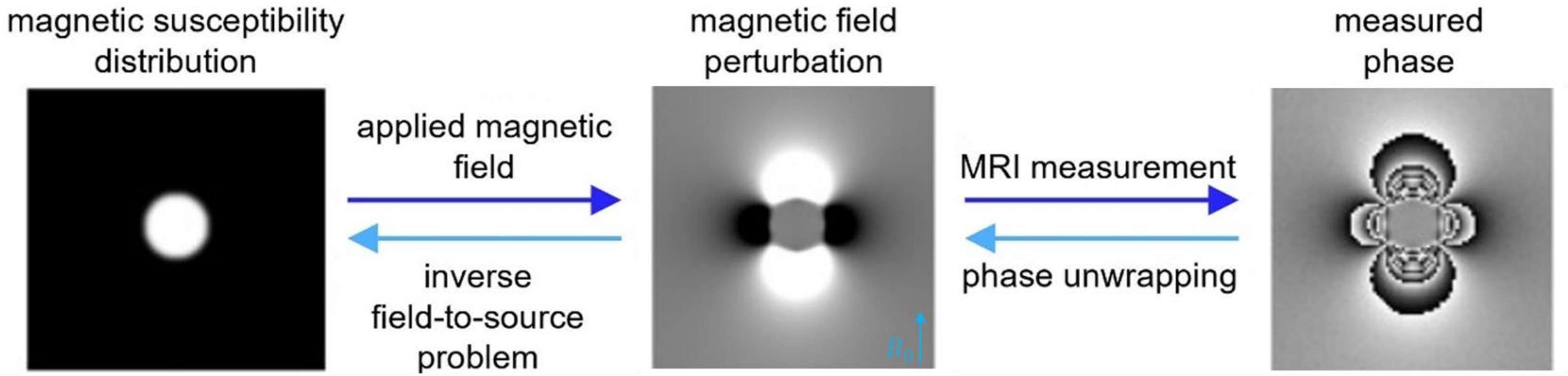
Quantitative Susceptibility Mapping (QSM)

The susceptibility distribution can be determined from the phase MRI data by a so-called dipole inversion:

$$\frac{B_{demag}(\boldsymbol{r})}{B_0} = \chi(\boldsymbol{r}) \otimes d_z(\boldsymbol{r}) \quad (in\ image\ space)$$

which represents an standard image restoration problem, in which the point-spread function can be mathematically model by the point-dipole response.

The point-dipole response is equal to zero at two conical surfaces, however, hindering the restoration by direct inverse filtering.



Schweser F et al. Z Med Phys 2016, doi:10.1016/j.zemedi.2015.10.002

Image restoration in QSM

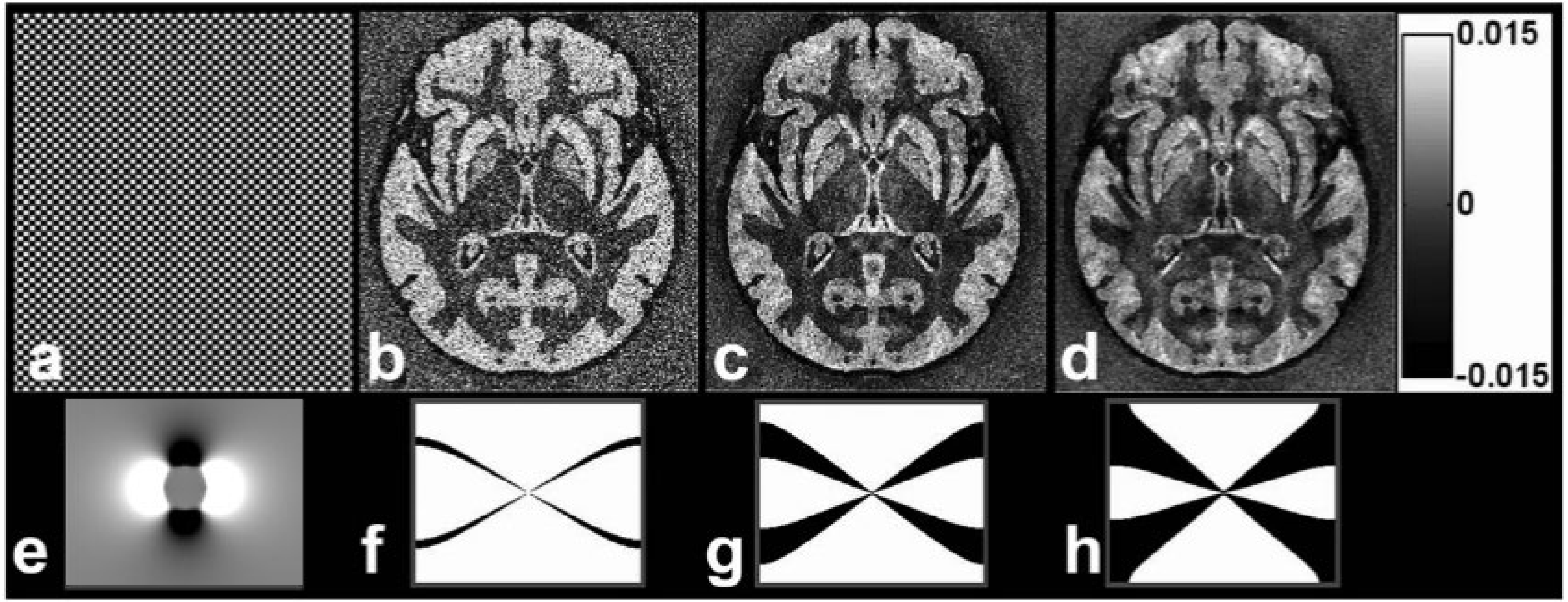


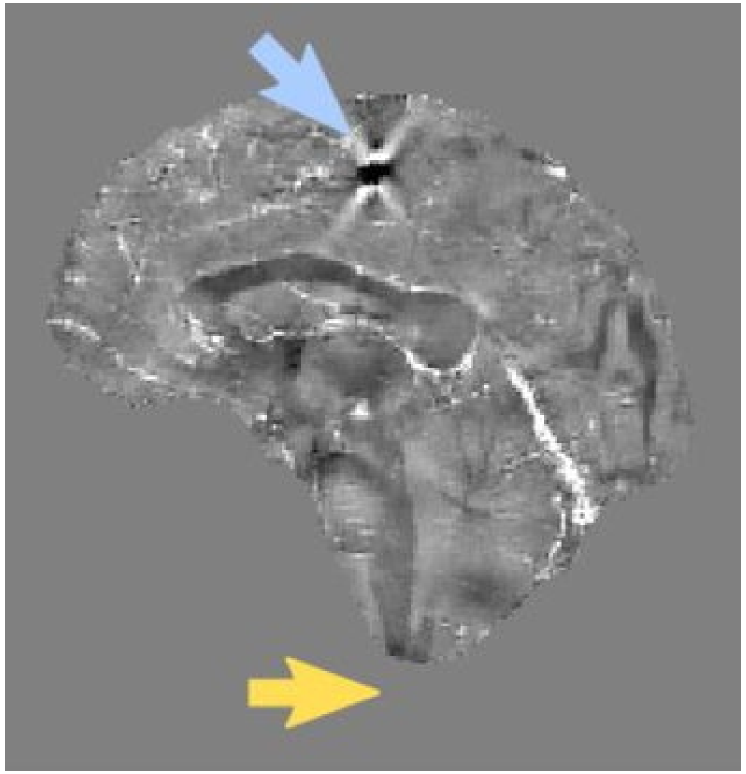
Figure 3. Demonstration of filtered deconvolution and the effect of masking in frequency space. **a–d** The deconvolution of Figure 1B with an added noise variance of 5E-5 ppm. Deconvolution was performed with different κ values namely: [0, 0.25, 0.875, 1.5]. **e–h** The masks in frequency space (sagittal view—vertical axis aligned with B_0 field). CNR values from a to d are 0.0, 1.56, 1.66, 1.36, respectively. a: Deconvolution of noisy data fails without masking in frequency space, resulting from serious noise amplification; b has a higher noise level and a lower CNR compared with c; d has the lowest noise level because of the largest κ, but a lower CNR compared with c due to low frequency artifacts resulting from masking in frequency space.

Grabner G et al, Filtered deconvolution of a simulated and an in vivo phase model of the human brain, J Magn Reson Imaging 2010, doi: 10.1002/jmri.22246

Image restoration in QSM

The measured tissue field deviates from perfect dipole patterns, particularly in regions with low SNR. This leads to deconvolution errors, manifesting as streaking and shadowing artifacts.

Masking out such a low SNR regions and the regions in the proximity of large susceptibility gradients such as air- and bone-tissue interfaces can help to reduce such artefacts.

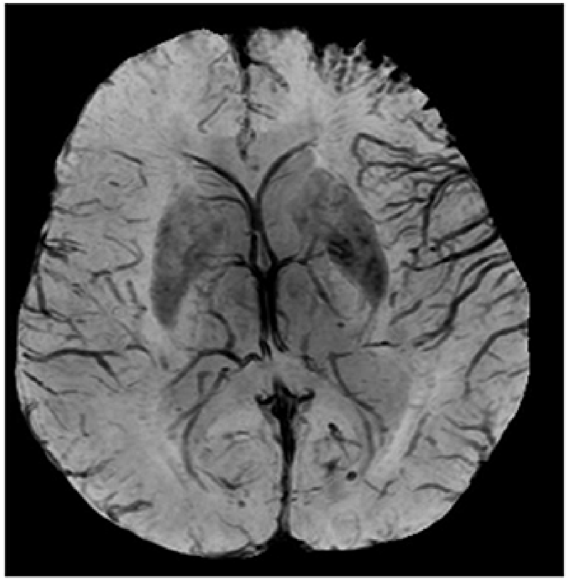


Bilgic et al, arXiv 2023, doi:10.48550/arXiv.2307.02306

Susceptibility-weighted imaging (SWI)

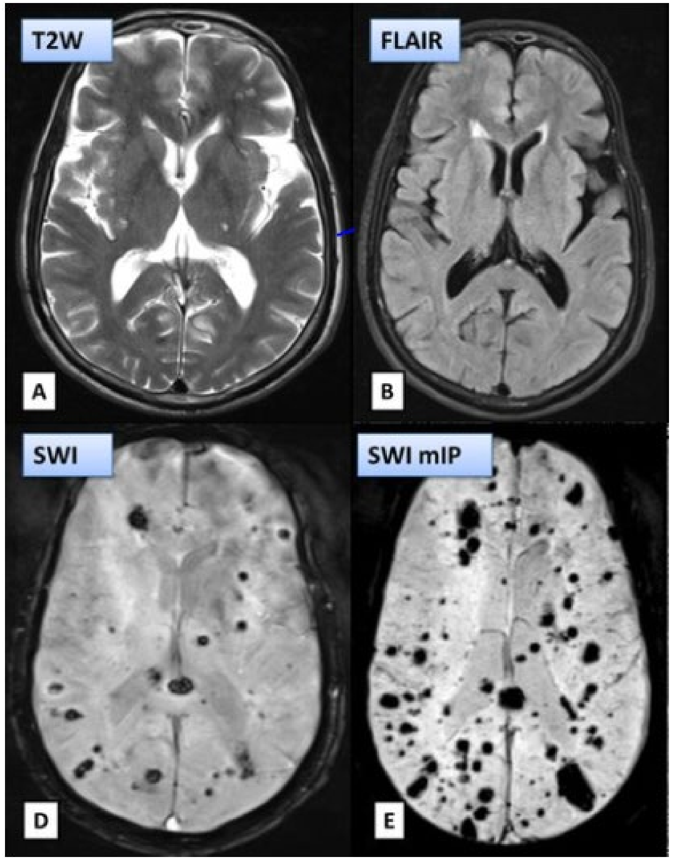
SWI combines magnitude and phase images of GRE acquisition to enhance image contrast by tissues susceptibility differences. It has a wide range of clinical applications – detection of venous anomalies, haemorrhages, stroke, multiple sclerosis, traumatic brain injuries, mineral depositions, etc.

Cerebral ischemia



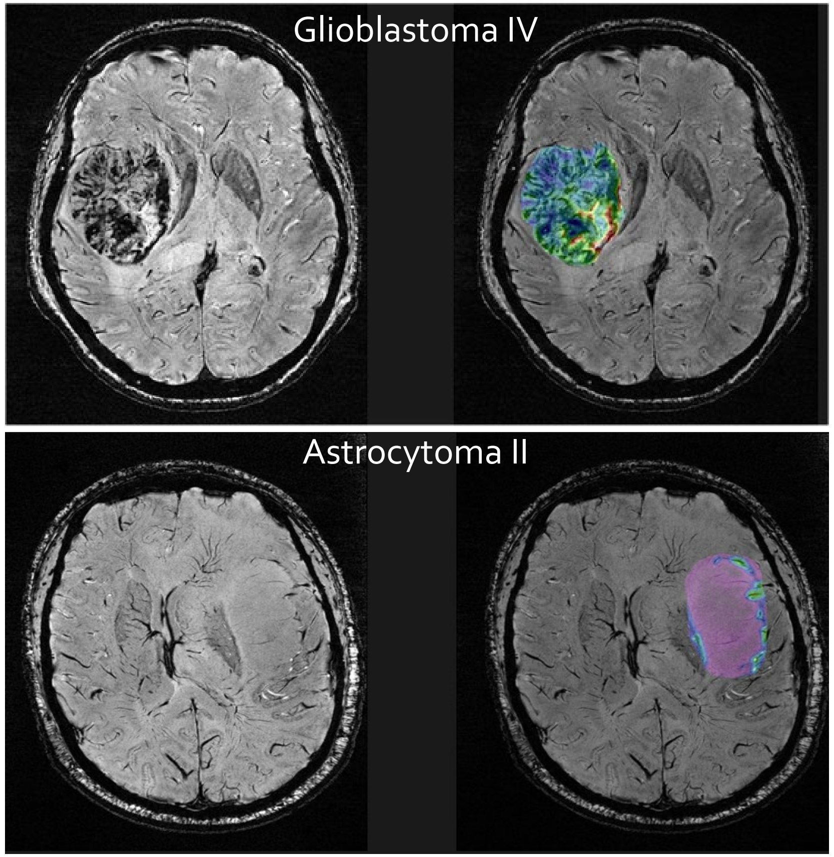
Xu et al., Front Neurol 2021, doi:10.3389/fneur.2021.660529

Bleedings



Hanumaiah, ECR 2016, doi:10.1594/ecr2016/C-1773

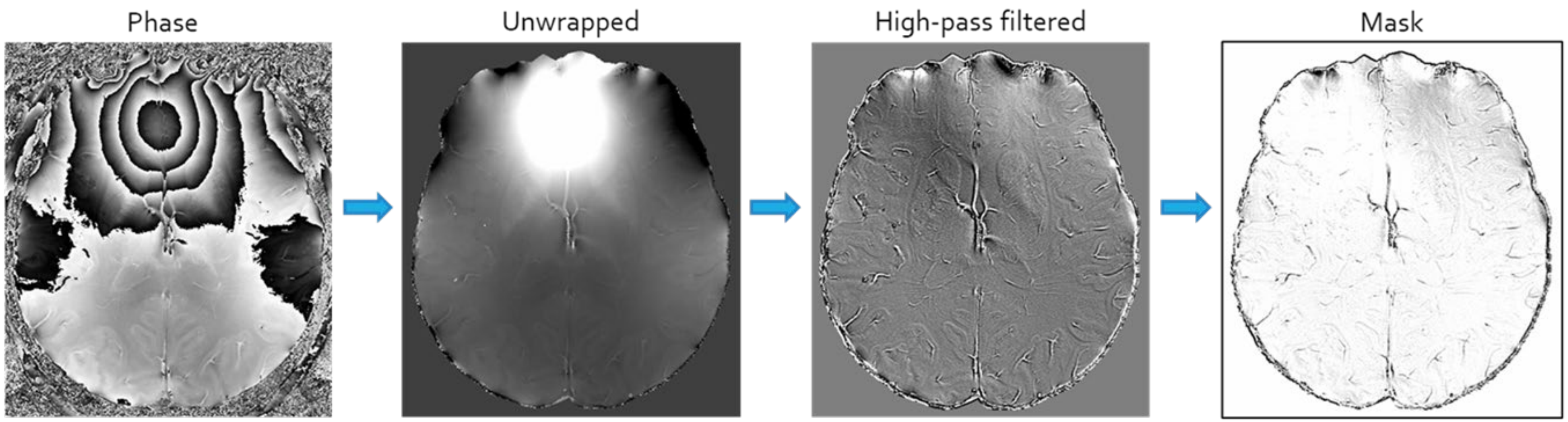
Tumour grading by local variability in SWI

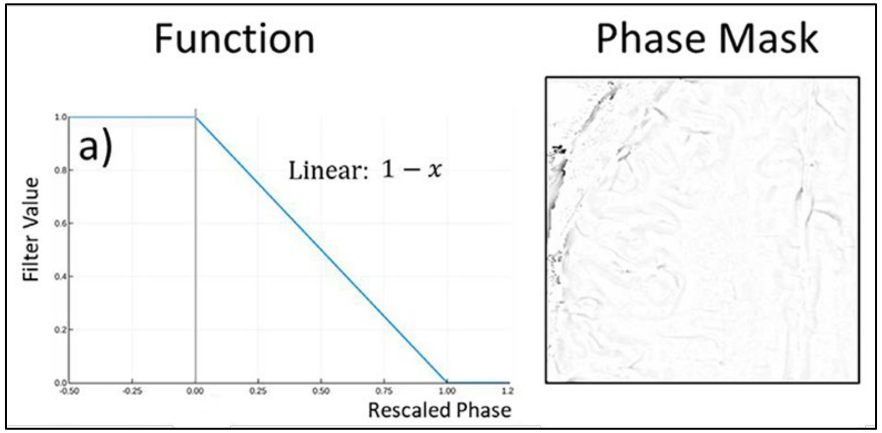


Grabner et al., Neuroradiology 2013, doi:10.1055/s-0033-1344310

Susceptibility-weighted imaging (SWI)

The phase data need to be first unwrapped. Then, they are high-pass filtered to remove low-frequency variations due to static magnetic field inhomogeneities and converted to a phase mask, scaled between 0 and 1.

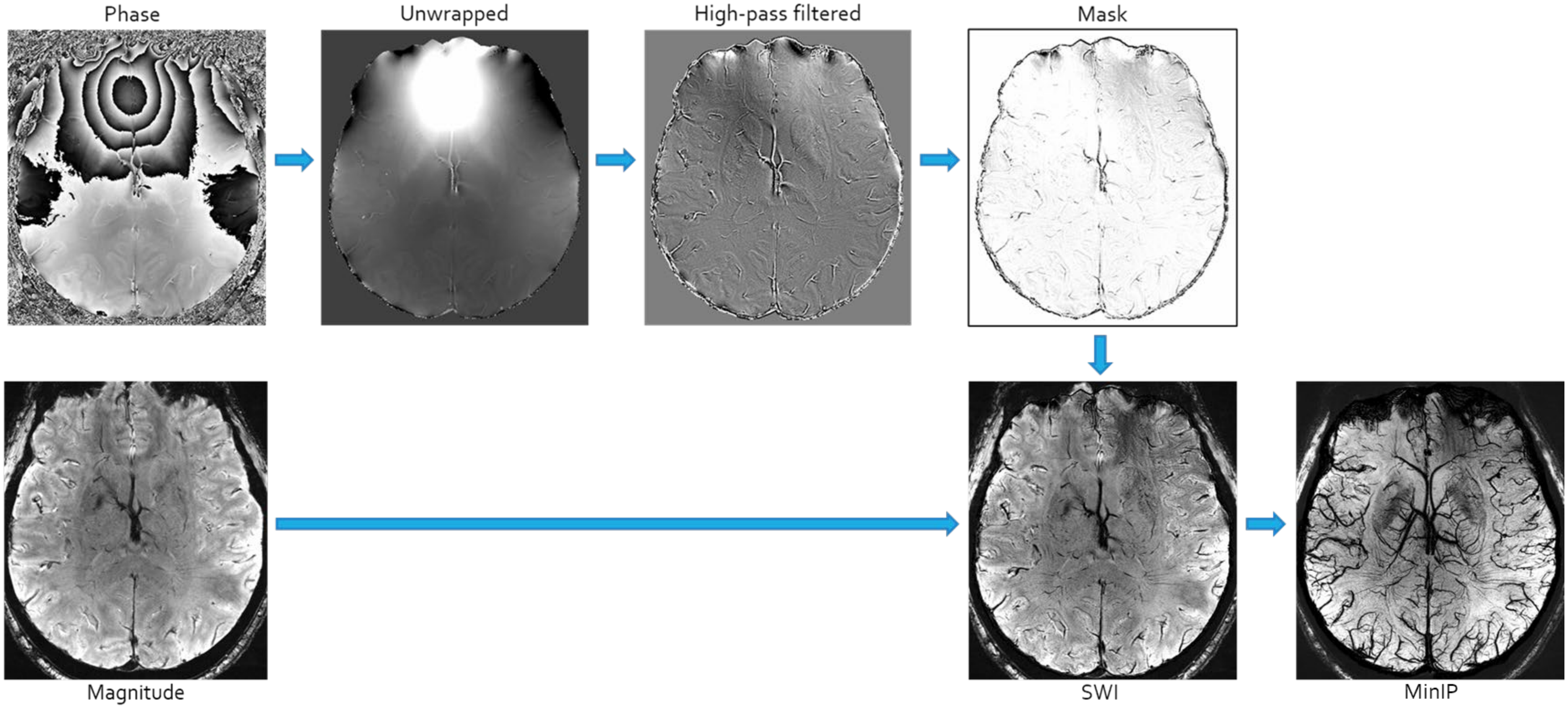




Eckstein et al., Neuroimage 2021. doi:10.1016/j.neuroimage.2021.118175

Susceptibility-weighted imaging (SWI)

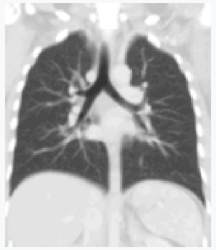
The magnitude image is then several times multiplied by the phase mask to enhance the contrast between tissues of different susceptibilities. SWIs are often displayed by minimum intensity projection over several slices.



Min intensity projection (MinIP)

Is a data visualization method that from several slices (or whole 3D volume) generates a 2D image, by projecting the voxels with the lowest value along the given projection. It enables detection of the darkest structures in a given volume.

Examples of different algorithms of thickening multiplanar reconstructions[112]

Type of projection	Schematic illustration	Examples (10 mm slabs)	Description	Uses
Average intensity projection (AIP)			The average attenuation of each voxel is displayed. The image will get smoother as slice thickness increases. It will look more and more similar to conventional projectional radiography as slice thickness increases.	Useful for identifying the internal structures of a solid organ or the walls of hollow structures, such as intestines.
Maximum intensity projection (MIP)			The voxel with the highest attenuation is displayed. Therefore, high-attenuating structures such as blood vessels filled with contrast media are enhanced.	Useful for angiographic studies and identification of pulmonary nodules.
Minimum intensity projection (MinIP)			The voxel with the lowest attenuation is displayed. Therefore, low-attenuating structures such as air spaces are enhanced.	Useful for assessing the lung parenchyma.

https://en.wikipedia.org/wiki/CT_scan#cite_note-112

Project description

Aim of this first project task is to exploit the gained knowledge on image filtering, restoration, and segmentation. The task is to generate Susceptibility-Weighted Images (SWI) and Quantitative Susceptibility Maps (QSM) from MRI images and to do a quantitate evaluation of the susceptibility values in the defined regions of interest.

Two datasets are provided

1) in-vivo dataset for SWI
   - 7T MRI images of a healthy volunteer
   - magnitude image, unwrapped phase image, and brain mask are provided
2) simulated dataset for QSM
   - generated by using the code and in-silico head phantom by: *Marquez J et al., Magn Reson Med 2021, doi:10.34973/m20r-jt17*
   - magnitude image, demagnetization field image and ground truth susceptibility maps are provided
   - helper function to generate the point-dipole response (i.e. the point-spread function)

A script **RUN.m**, which executes, computes all results, and plots them without user interaction.

Deadline: May 27th, 3 pm.