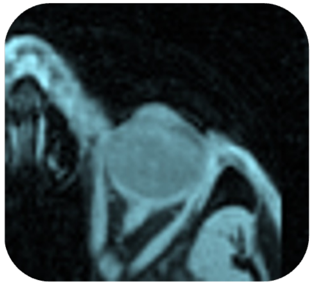
MR-EYE: MAGNETIC RESONANCE IMAGING OF THE HUMAN EYE

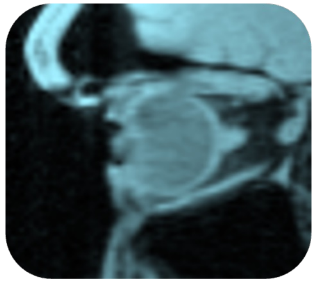


Yiwei Jia, PhD student

School of Engineering, HES-SO Valais-Wallis

The Sense Innovation and Research Institute, Lausanne and Sion

Graduate school of cellular and biomedical science, University of Bern, Bern



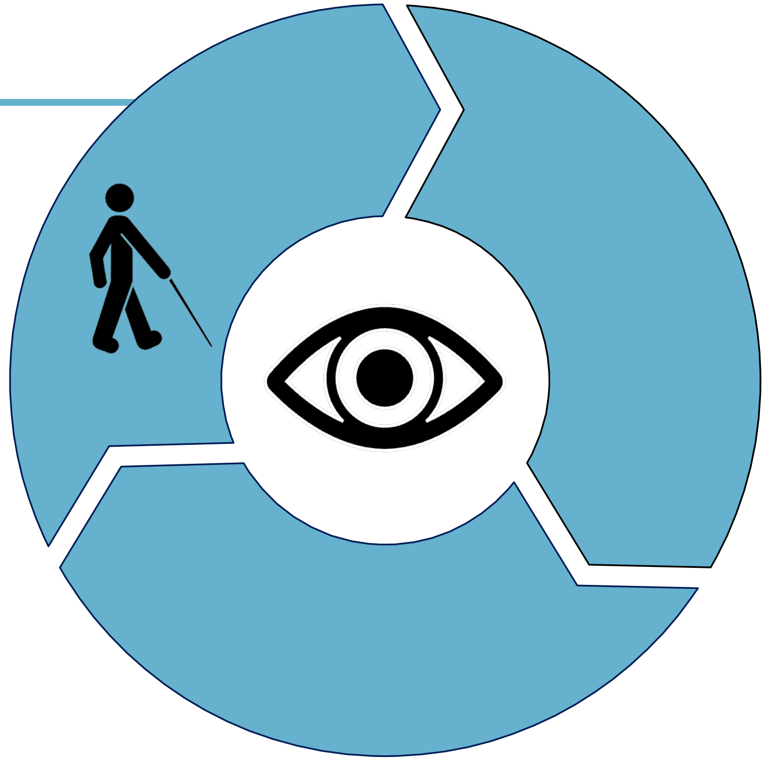
23.09.2025

Séminaire MathPhys

WHY DO WE NEED MRI OF THE EYE… AND ITS LINK TO THE BRAIN

Vision impairment

- **2.2 Billion** people have vision impairment
- **400 Million** is the world prevalence of strabismus
- Vision loss is associated with **increased suicidal risk**



Benedetta Franceschiello, talk in TIC seminar

WHY DO WE NEED MRI OF THE EYE… AND ITS LINK TO THE BRAIN

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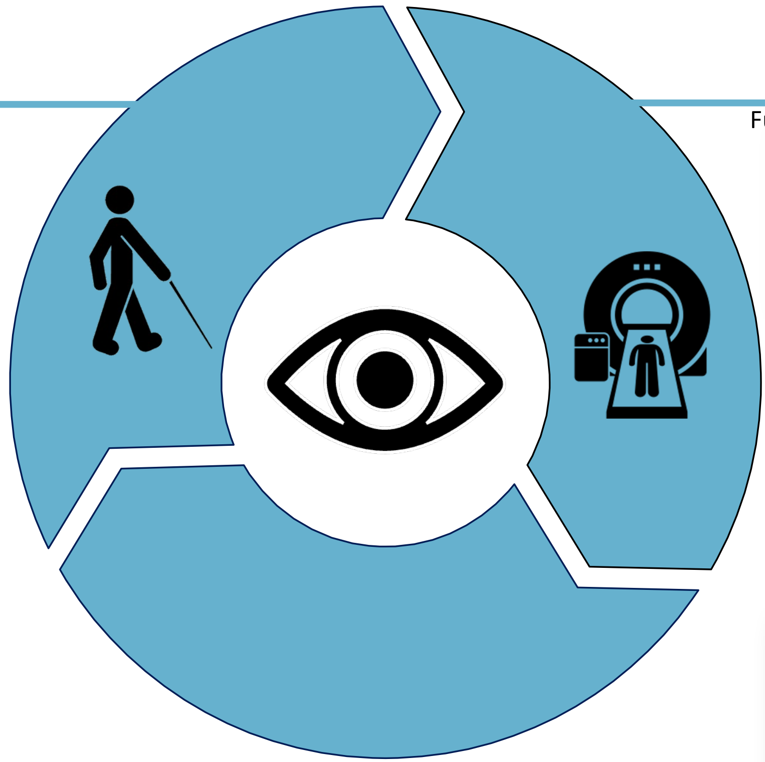

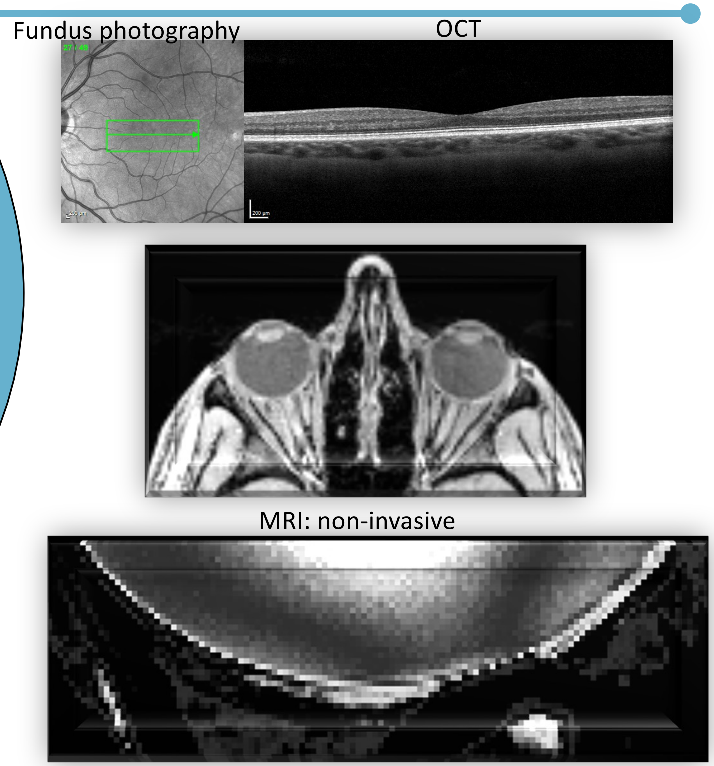

Images of Rebecca K. Glarin et al. 2021; Prof. P. Maeder, Dr. A. Pica, M. Bach Cuadra; Niendorf et al. 2021.

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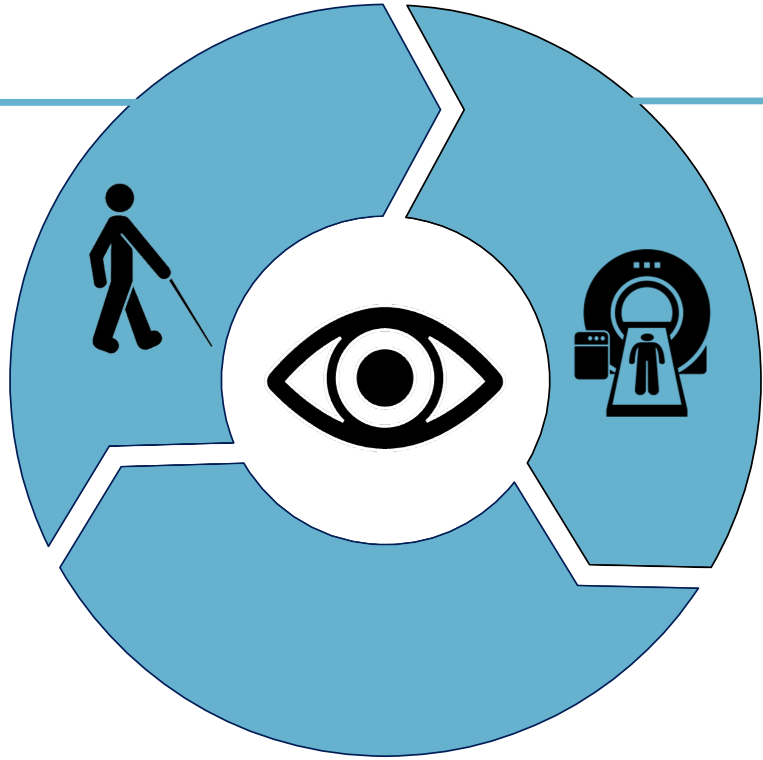

Ocular oncology and treatment

Orbital inflammation

Surgical planning

Patient-specific modeling

Images of Rebecca K. Glarin et al. 2021; Prof. P. Maeder, Dr. A. Pica, M. Bach Cuadra; Niendorf et al. 2021.

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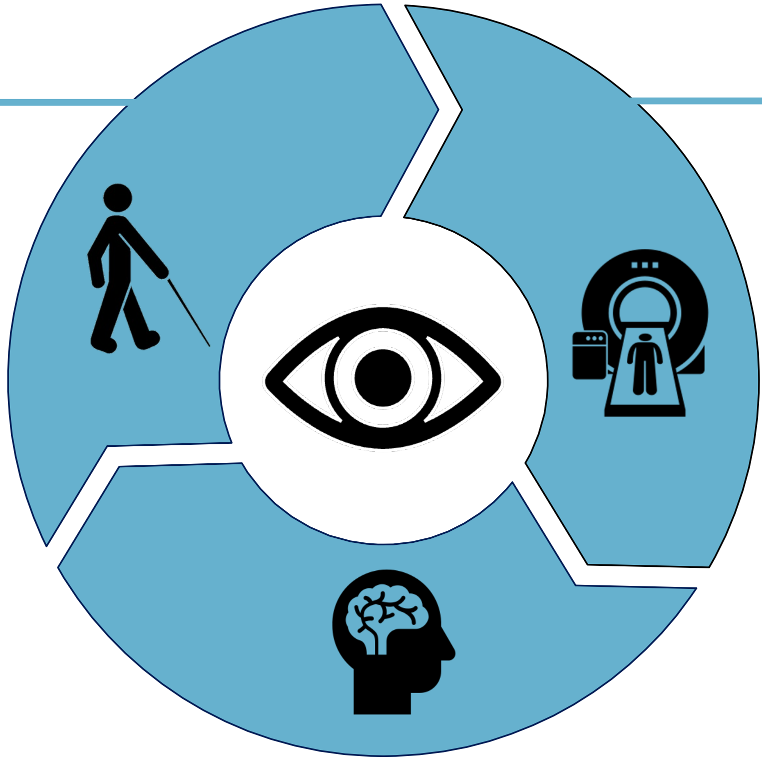


Eye ←→ Brain
Koronyo (2023), Retinal features signature AD
Anderson (2013), Eye Movements in neurodegeneration
"The eyes are our windows onto the brain"

Ocular oncology and treatment

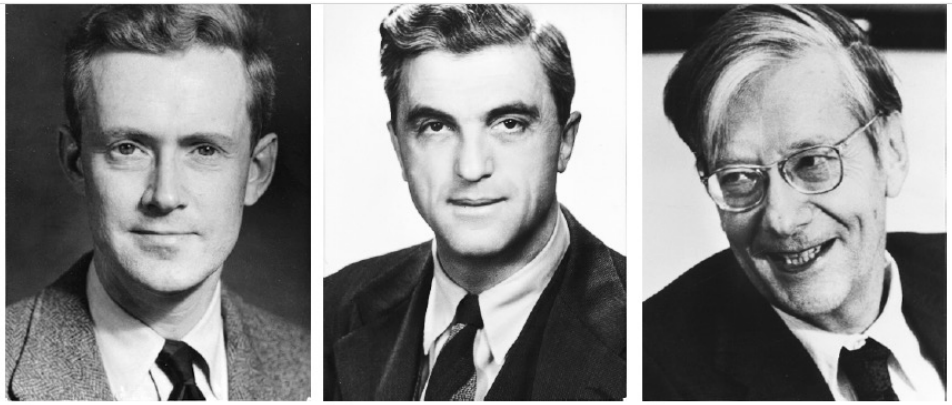
Surgery planning

Orbital Pathologies and disorders

Patient specific modelling

WHERE DOES THE MRI SIGNAL COME FROM, AND WHY DO DIFFERENT TISSUES LOOK THE WAY THEY DO ON AN IMAGE?

FOUNDATIONS OF NMR



(a) Edward Purcell (b) Felix Bloch (c) Nicolaas Bloembergen

1946 – 1948 Foundations of Nuclear Magnetic Resonance (NMR)

- 1946 – Purcell and Bloch detect the **nuclear-induction signal**.
- 1949 – Bloembergen, Purcell and Pound publish the **BPP relaxation theory** of NMR relaxation, a foundation for later contrast mechanisms: T1 recovery and T2 decay (contrast).

McRobbie, D. W., Moore, E. A., Graves, M. J., & Prince, M. R. (2017). *MRI from picture to proton* (3rd ed.). Cambridge University Press.

WHAT IS MRI: TURNING A SIGNAL INTO AN IMAGE

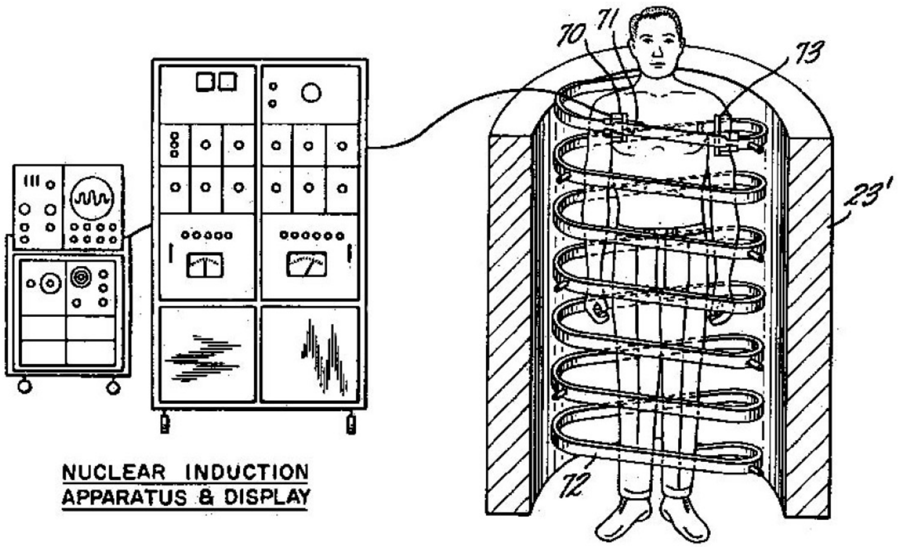


Figure 1.2 Raymond Damadian's "Apparatus and method for detecting cancer in tissue". US patent 3789832 filed 17 March 1972, issued 5 February 1974. Image from the US Patent and Trademark Office.

Turning a Signal into an Image

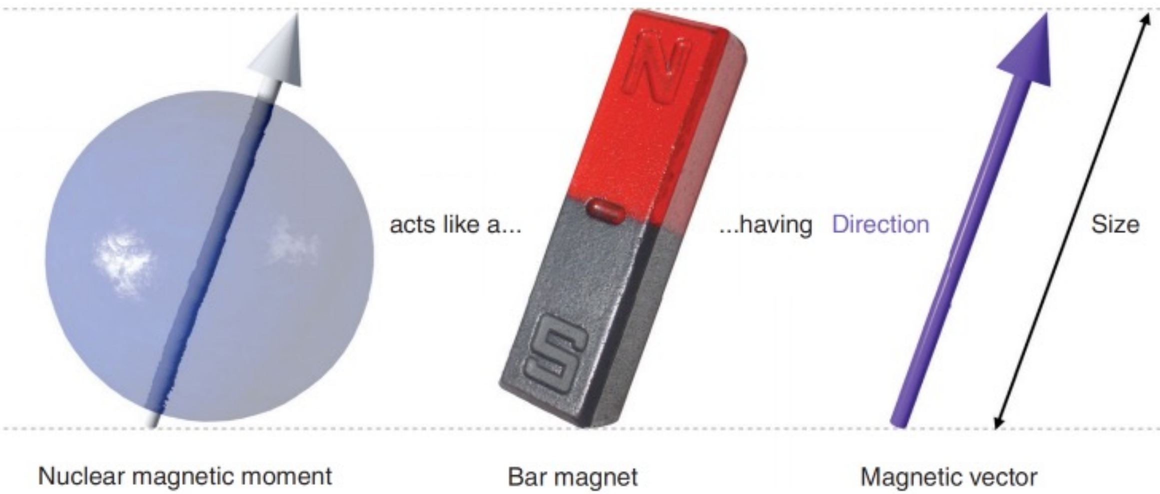
1971 – Damadian:

- Tumor samples have longer excitation than healthy tissue
- Detected by NMR.
- The first prototype scanner.

McRobbie, D. W., Moore, E. A., Graves, M. J., & Prince, M. R. (2017). *MRI from picture to proton* (3rd ed.). Cambridge University Press.

WHAT IS MRI: NMR

- The **protons** in the body can be thought of as small bar magnets.
- **Water and fat** make up the largest source of protons in the body.
- Commonly imaged nuclei are ^{1}H, ^{13}C, ^{15}N, ^{19}F, ^{23}Na, and ^{31}P.



C. Westbrook and J. Talbot, *MRI in Practice*, 5th ed. Hoboken, NJ: Wiley-Blackwell, 2018.

WHAT IS MRI: NMR

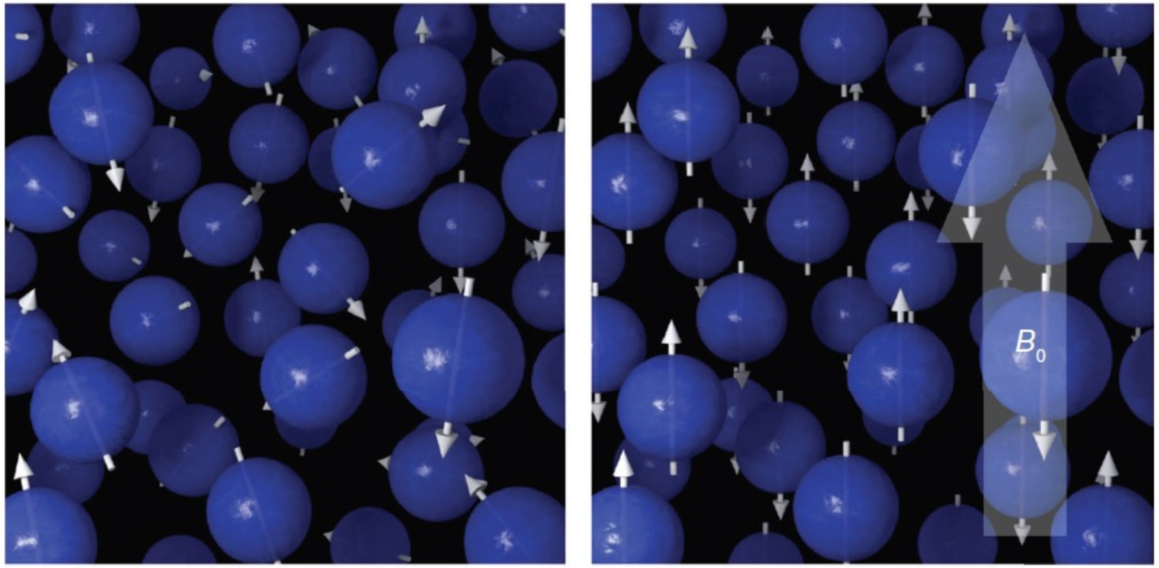
Normally the direction of these protons is completely **random**. → **no net magnetization**

Protons in a Magnetic Field (B0)

- they tend to align with that external field.

At the atomic scale:

- some protons **align with** the applied field
- others align **against** it.
- There is always a **small excess** of protons aligned with the field. → **net magnetization**



Random alignment
No external field

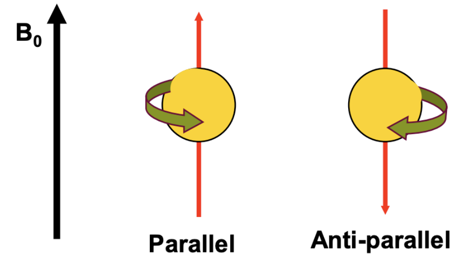
Alignment
External magnetic field

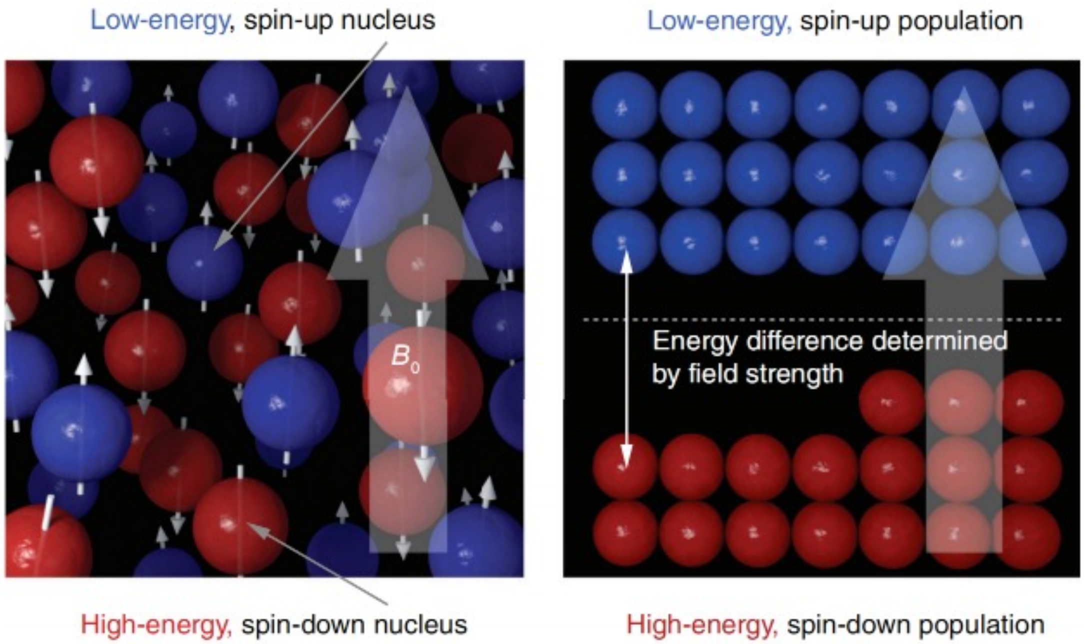
C. Westbrook and J. Talbot, *MRI in Practice*, 5th ed. Hoboken, NJ: Wiley-Blackwell, 2018.

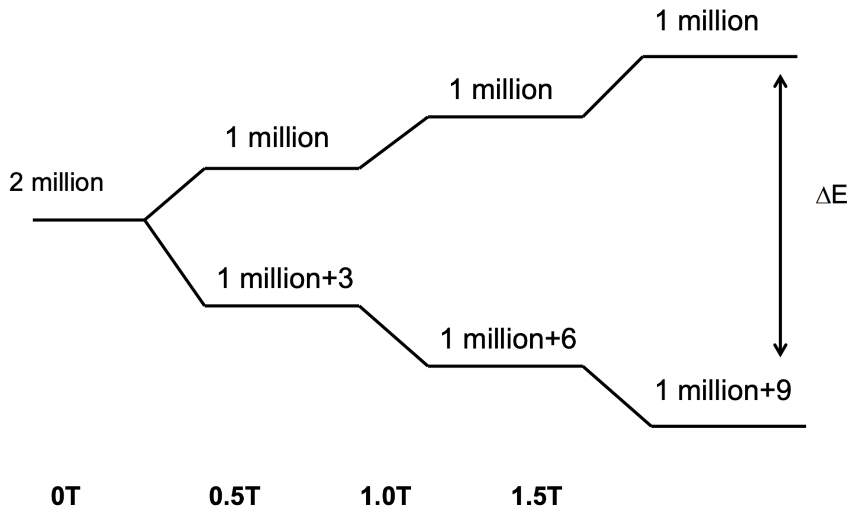
WHAT IS MRI: NMR

Quantum Alignment of Protons (thermal equilibrium)

- Proton may occupy **two energy states**:
  - parallel (lower energy) and anti-parallel (higher energy)
- $\Delta E \sim B0$
- Stronger field → stronger signal



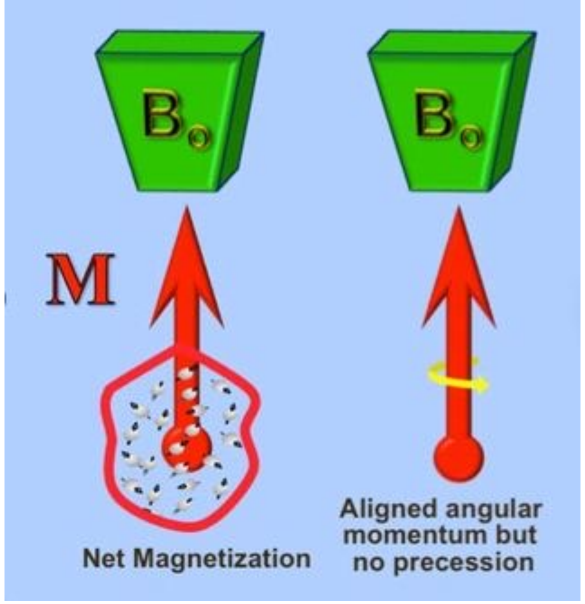




C. Westbrook and J. Talbot, *MRI in Practice*, 5th ed. Hoboken, NJ: Wiley-Blackwell, 2018.

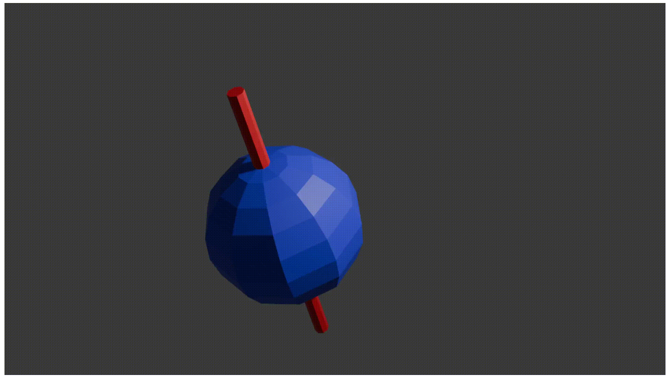
WHAT IS MRI: NET MAGNETIZATION

- Net magnetization M_0 is exactly along B_0
- No transverse component → no MR signals



https://mriquestions.com/does-m-also-precess.html

WHAT IS MRI: LARMOR FEQUENCY



After external injection of energy (an RF pulse)

Single proton (A hydrogen nucleus)
- Tip the magnet off z-axis → transverse component.
- **Precession:** rotates (precesses) around the field direction
  - At the **Larmor frequency** ω_0.
- **Larmor equation**:
  $\omega_0 = \gamma B_0$.
- Gamma γ: gyromagnetic ratio (radians · s^{-1} · T^{-1}), a constant unique to each type of nucleus.
- For hydrogen γ=42.56MHz/T

1.5 T $42.58 \times 1.5 = 63.9$MHz

3 T $42.58 \times 3.0 = 127.7$MHz

7 T $42.58 \times 7.0 = 298.1$MHz

https://fabienbryans.com/educational/the-principles-of-mri/#why-protons

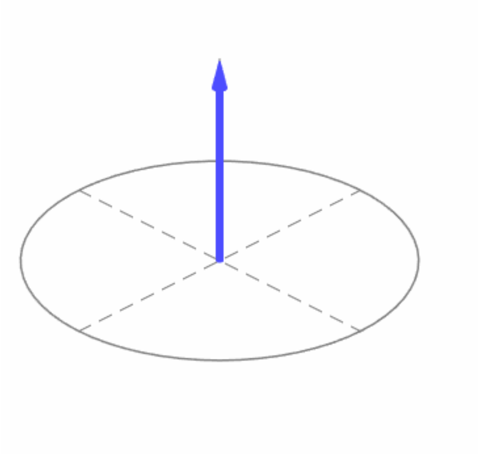
WHAT IS MRI: PROCESSION OF M_0

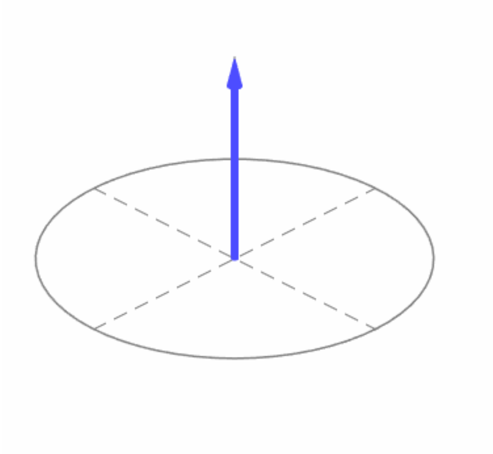
After external injection of energy (an RF pulse)

- The net vector **M** now has a transverse part (x–y plane).
- **M** rotates around $\mathbf{B_0}$ at the **same Larmor frequency** as each proton.

Signal detection

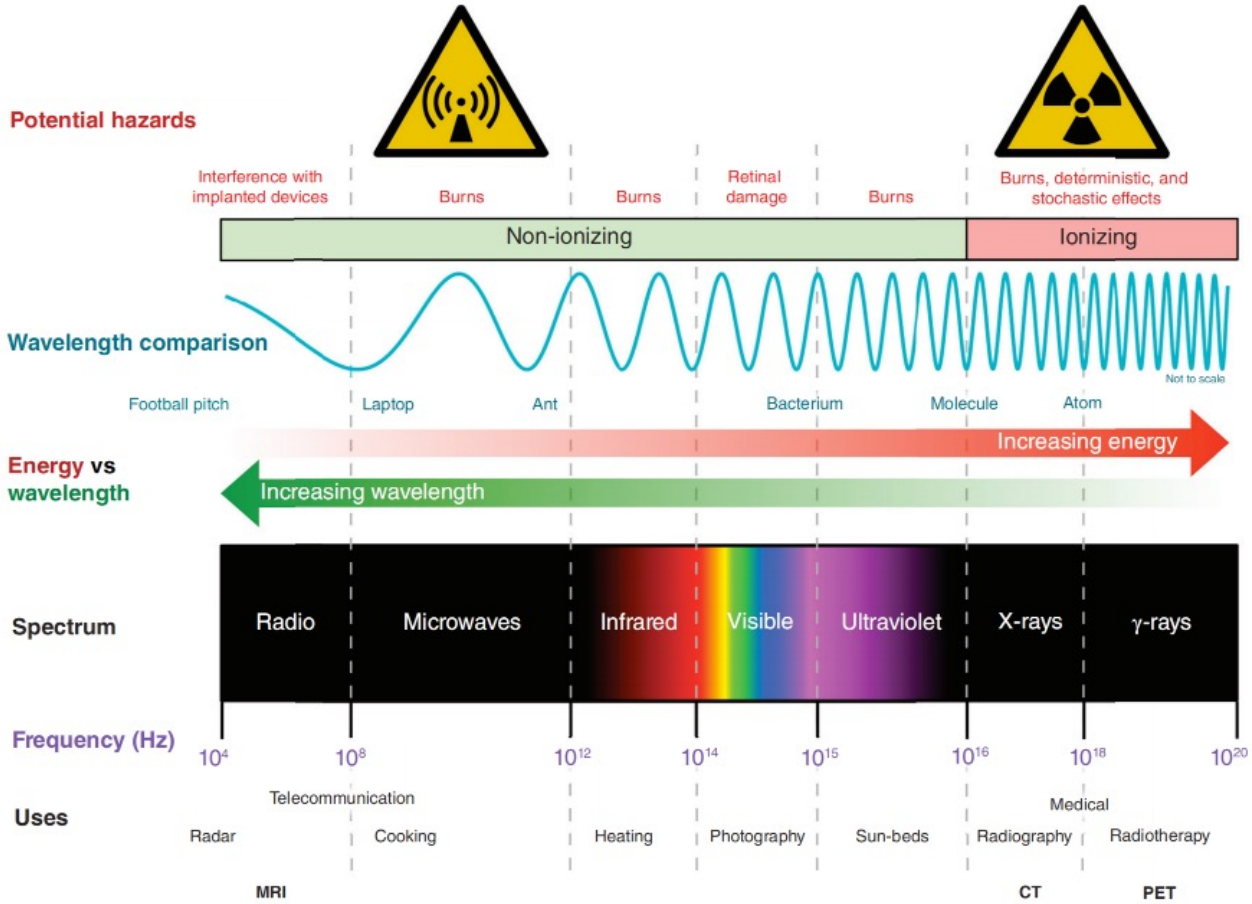
- The rotating transverse magnetization cuts magnetic-flux lines in the receive coil.
- This changing flux induces a voltage → the MR signal.





WHAT IS MRI: POTENTIAL HAZARDS

These frequencies fall into the **radiofrequency (RF)** band of the electromagnetic spectrum



"Make the participants well
Not well done."
Brian Dale
MRI sequence course
2025 January

C. Westbrook and J. Talbot, *MRI in Practice*, 5th ed. Hoboken, NJ: Wiley-Blackwell, 2018.

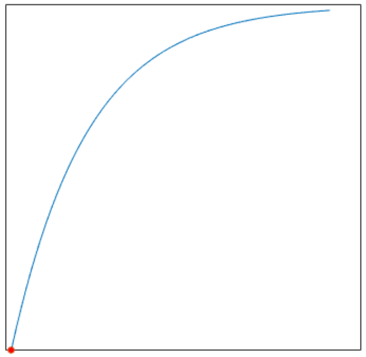
WHAT IS MRI: CONTRASTS

Once RF is turned off → Two independent processes

T1 recovery

The excited spins return to their original Mz orientation

- Longitudinal Mz
- Exponential recovery with a time constant called T1.
- Different tissues → different T1.



M_Z

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

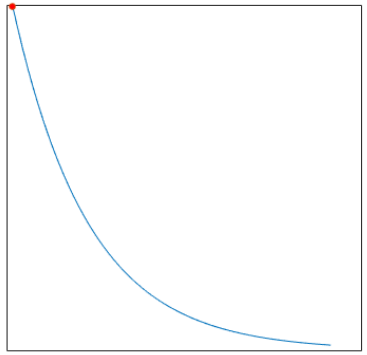
WHAT IS MRI: CONTRASTS

Once RF is turned off

T2 (*) decay

The in-phase protons start to **dephase**

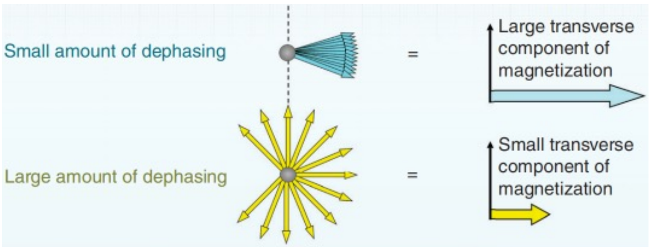
- Transverse M_{XY}
- Exponential decay with a time constant of T2 or T2*
- Different tissues → different T2.



M_{XY}

$$M_{xy}(t) = M_{xy}(0)e^{-t/T_2}$$

* Assume no field inhomogeneities



https://deepblue.lib.umich.edu/bitstream/handle/2027.42/145301/cpmib0301.pdf?sequence=1/1000

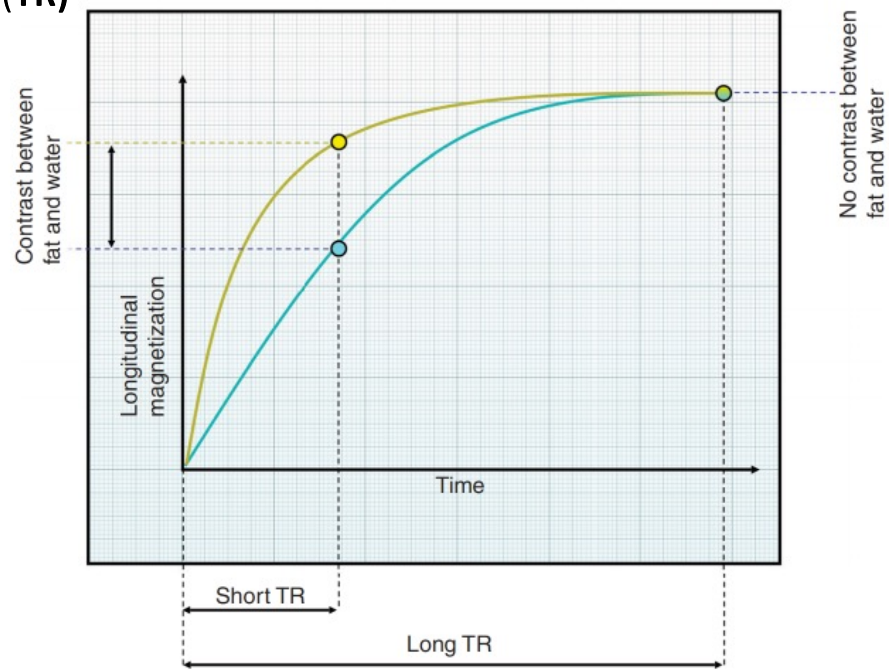
WHAT IS MRI: CONTRASTS

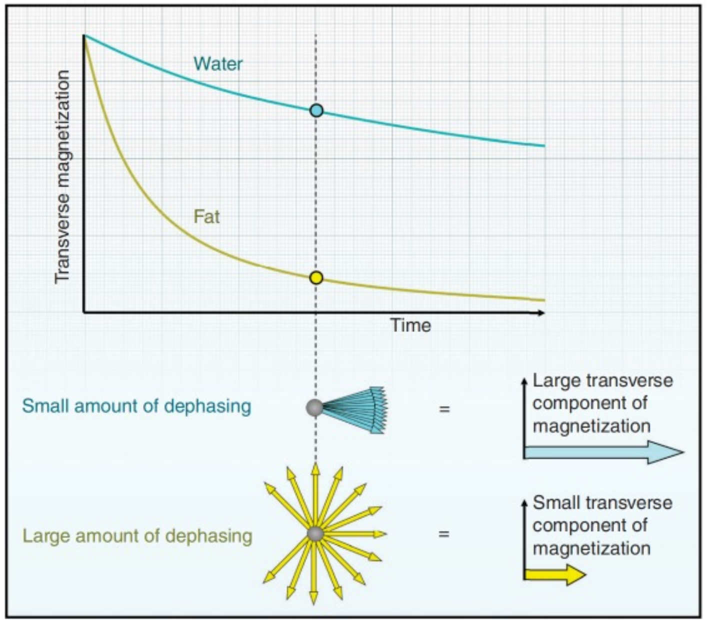
T1 recovery

- Choose **Repetition Time** (**TR)**

T2 (*) decay

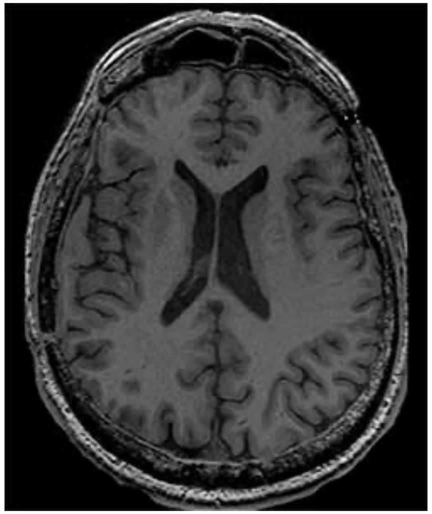
- Choose **Echo Time** (**TE)**





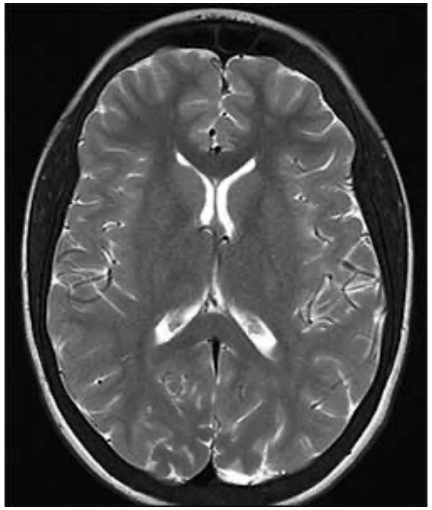
https://deepblue.lib.umich.edu/bitstream/handle/2027.42/145301/cpmib0301.pdf?sequence=1/1000

WHAT IS MRI: CONTRASTS

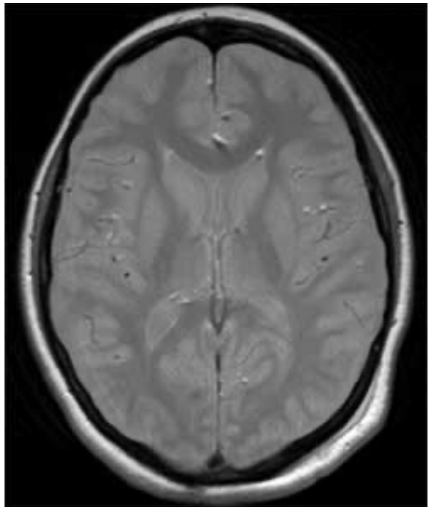


T1w
bright fat, dark fluid

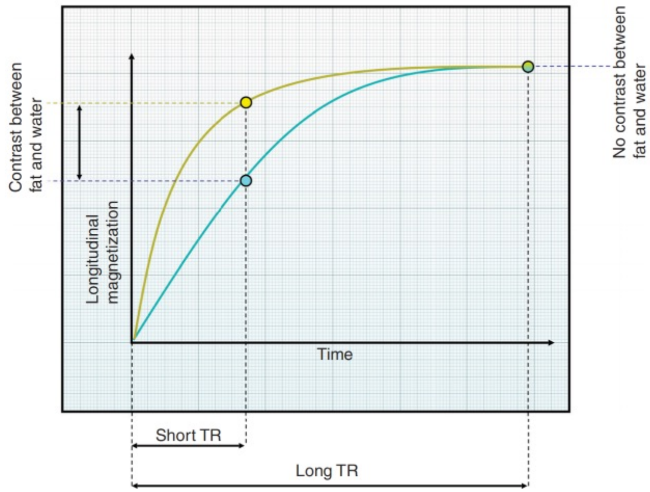
Short TR
Short TE

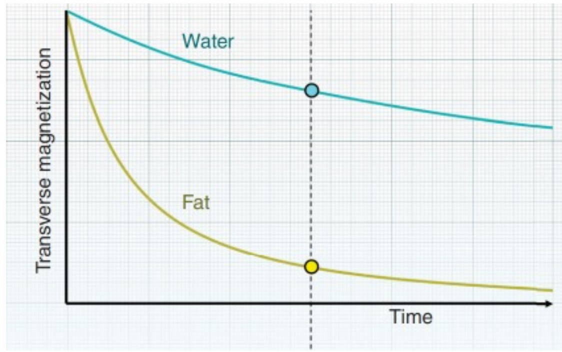


T2w
dark fat, bright fluid
Long TR
Long TE



Proton Density (PD)
minimizes T1 & T2
Long TR
Short TE





https://www.radiologycafe.com/frcr-physics-notes/mr-imaging/t1-t2-and-pd-weighted-imaging/

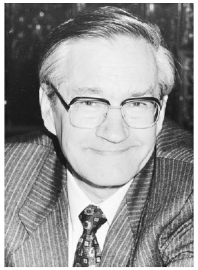
WHAT IS MRI: FROM NMR TO ENGINEERING MRI

Paul Lauterbur

1973: Turning a Signal into an Image

1973 – Chemist **Paul Lauterbur**
Introduces magnetic-field gradients.
→ enables the spatial encoding.

WHAT IS MRI: FROM NMR TO ENGINEERING MRI



(d)

(f)

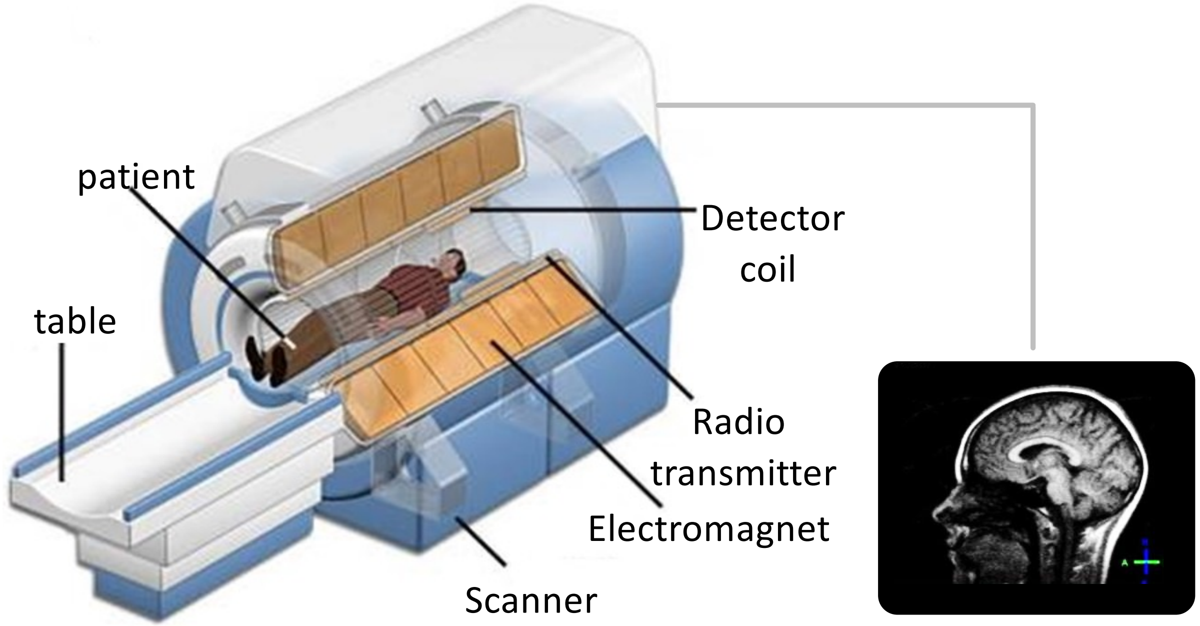
Richard Ernst **Peter Mansfield**

1974-1978 "Engineering MRI from research to clinical use"

- **Mansfield et al., 1974** – selective-slice Excitation;
  - Foundation for today's slice selection.
- **Ernst et al., 1975.** Describes 2D-FT
  - Enabling fast Cartesian reconstruction.
- **Clow & Young, 1978** – first human head MR image at **0.1 T**

MRI: A POWERFUL MEDICAL TOOL

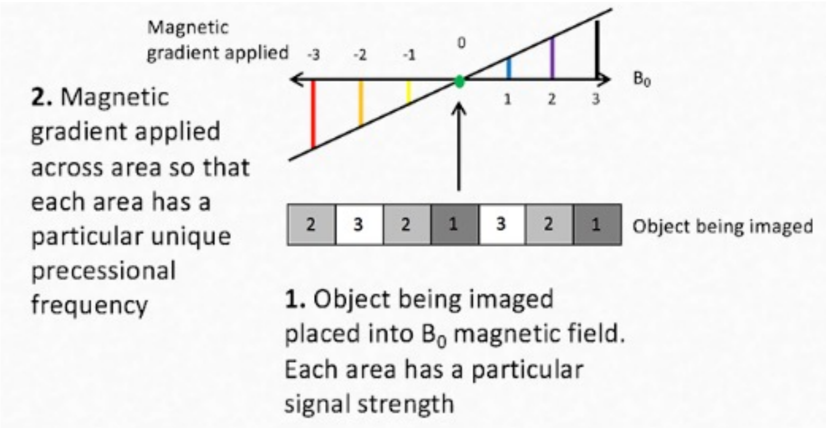
3T Siemens Prisma MRI scanner



By 2022, over 50-thousand scanners are in use worldwide.

https://pubmed.ncbi.nlm.nih.gov/34586563/

WHAT IS MRI: GRADIENTS & SPATIAL ENCODING

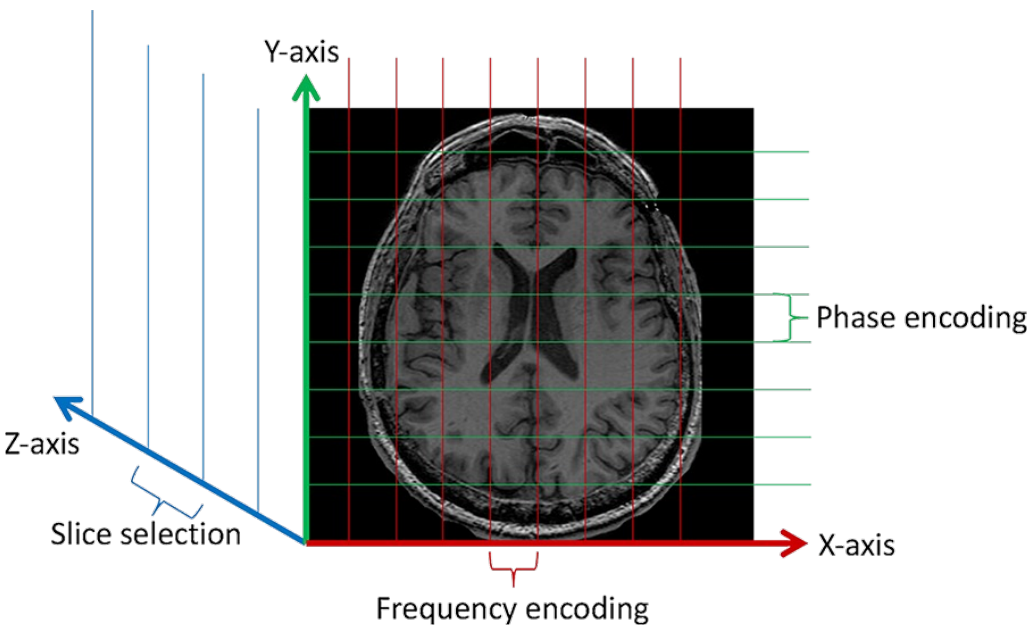


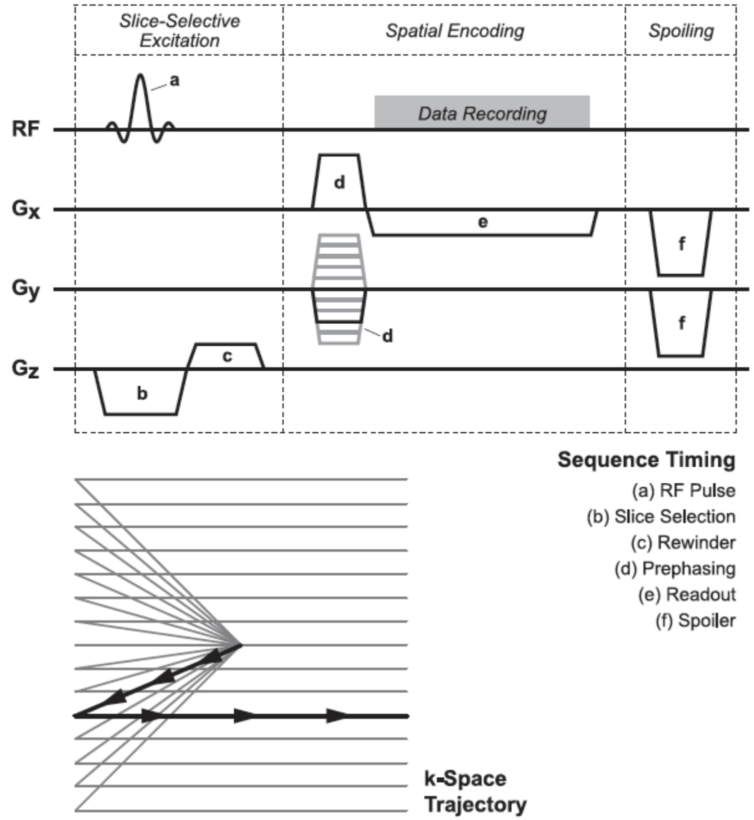
https://www.radiologycafe.com/frcr-physics-notes/mr-imaging/spatial-encoding/

WHAT IS MRI: GRADIENTS & SPATIAL ENCODING

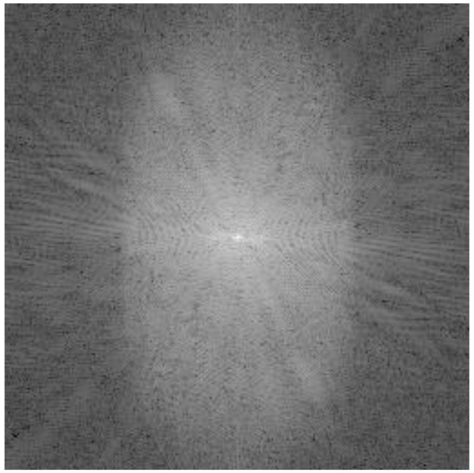
Locate voxels in 3D MRI

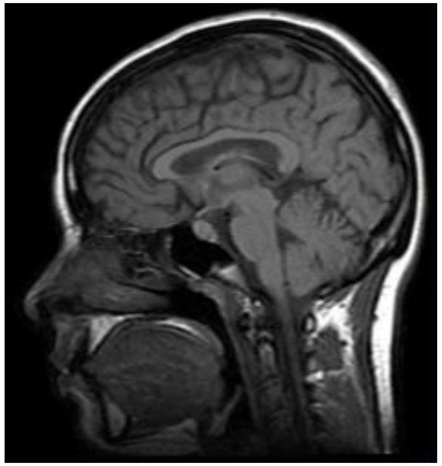
- Slice selected along z-axis
- frequency encoding along x-axis
- phase encoding along y-axis





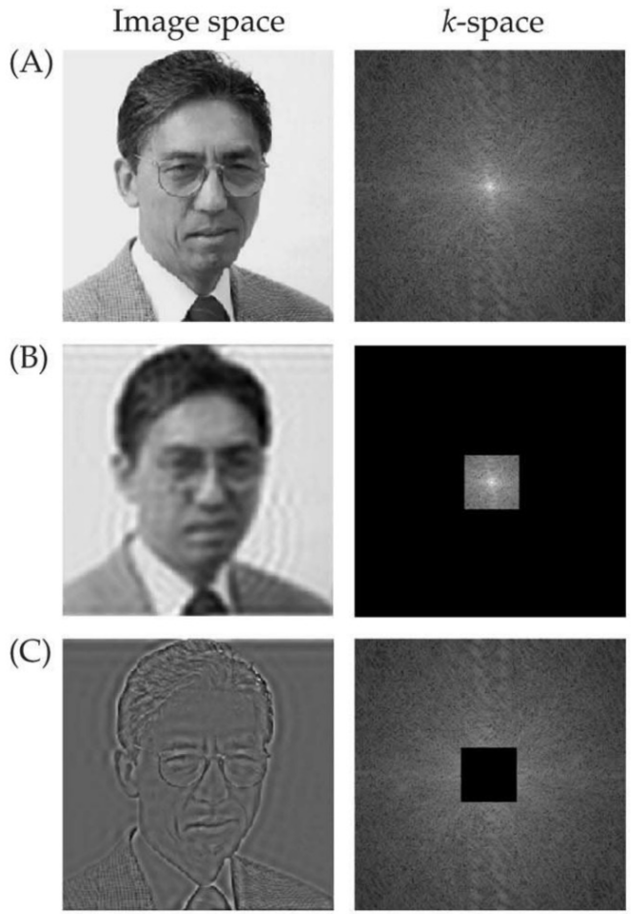
WHAT IS MRI: K-SPACE





K-Space Data → Image Data

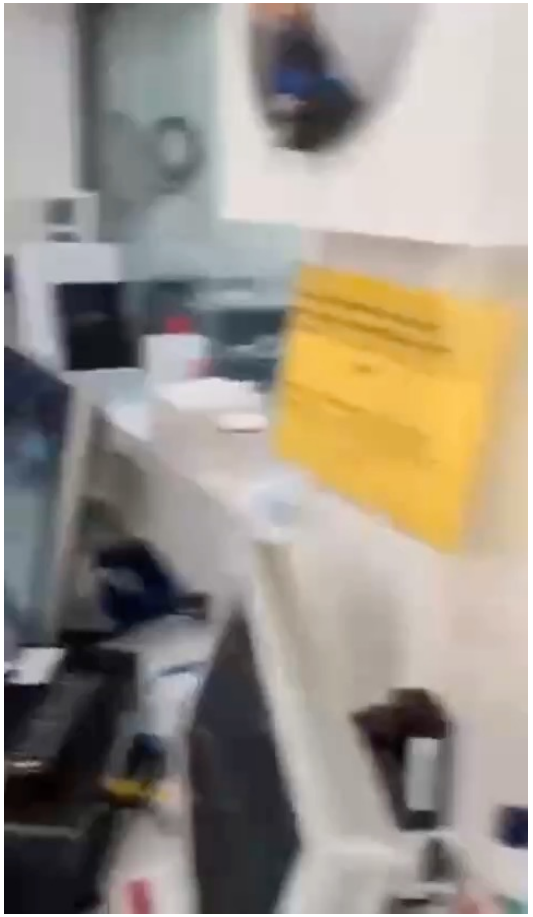
Inverse Fourier transform



EPISODE BY GRADIENTS

Gradients don't just make image.
They can make music, really!

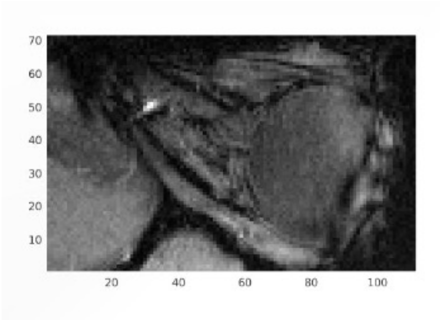
Rapid gradient switching produces acoustic vibrations in the bore.

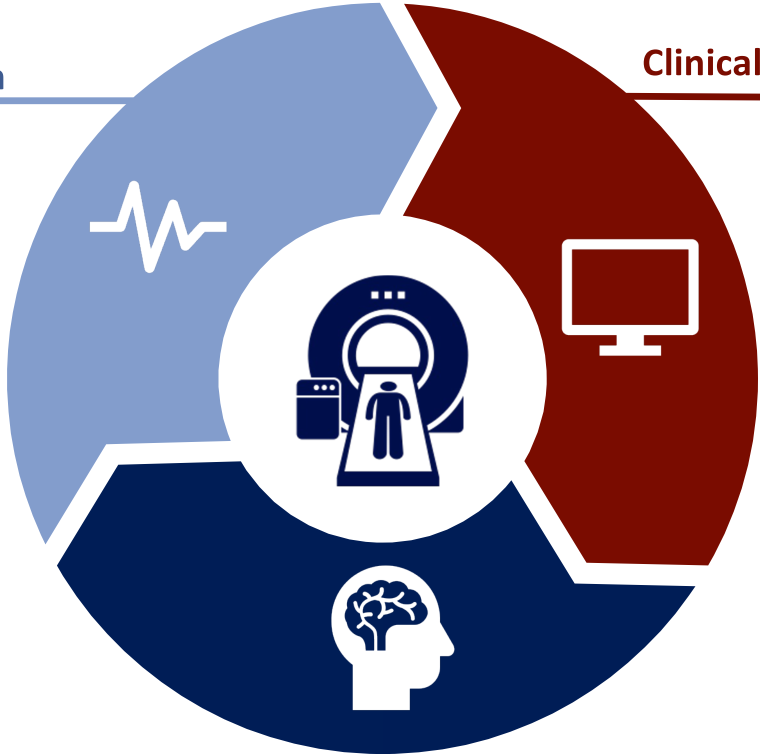


WHAT DO WE NEED TO PERFORM MR-EYE SUCCESSFULLY AND HOW CAN WE IMPROVE BRAIN IMAGING?

MR-EYE AND BRAIN IMAGING

Robust acquisition & reconstruction technique





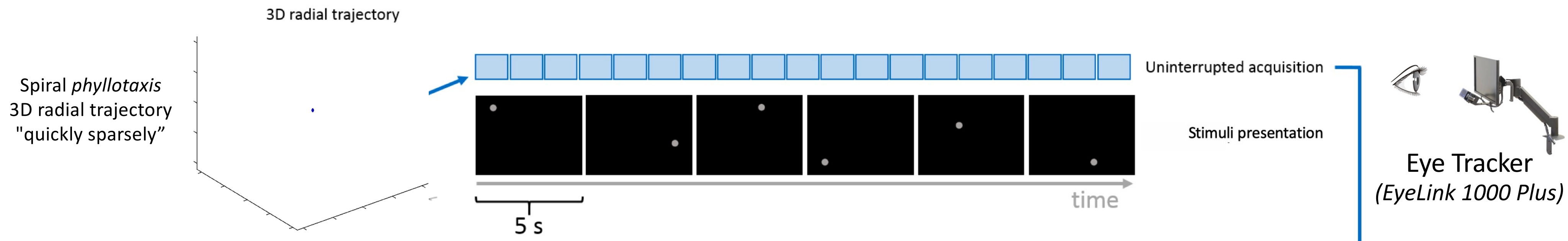
Clinically relevant post-processing algorithms

A-Eye: Automated 3D Segmentation of Healthy Human Eye

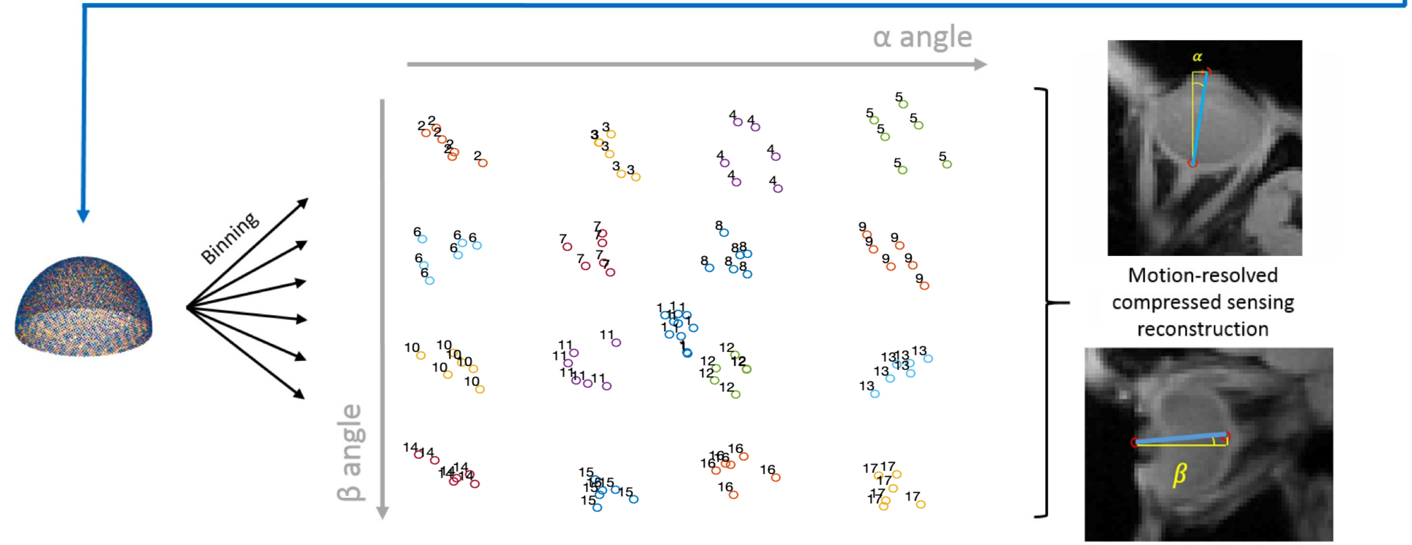
Functional MRI to assess brain and neural tissue functionality

[1] **Jaime Barranco,** et al. a, A-eye: Automated 3D Segmentation of Healthy Human Eye and Orbit Structures and Axial Length Extraction, bioRxiv 2025.05.05.652187; doi: https://doi.org/10.1101/2025.05.05.652187.

HI-FI DYNAMIC EYE IMAGING: DEPICTING THE EYE ANATOMY IN MOTION



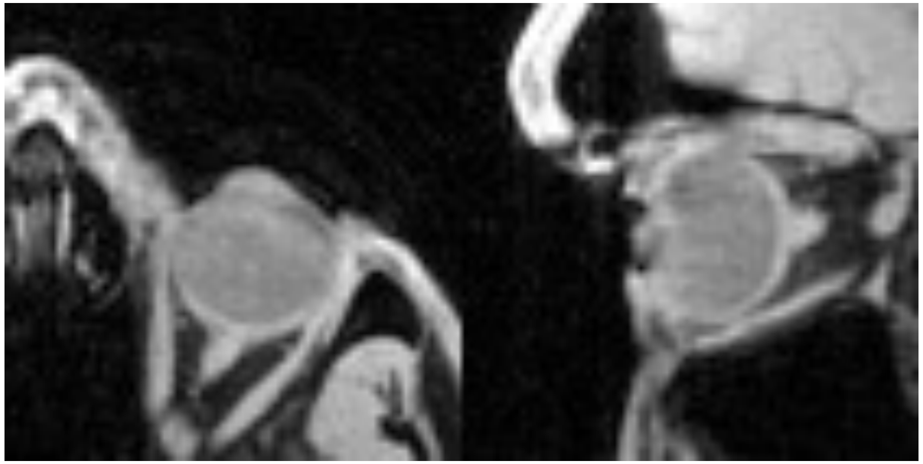
Benedetta Franceschiello



Patent: **WO2020178397**

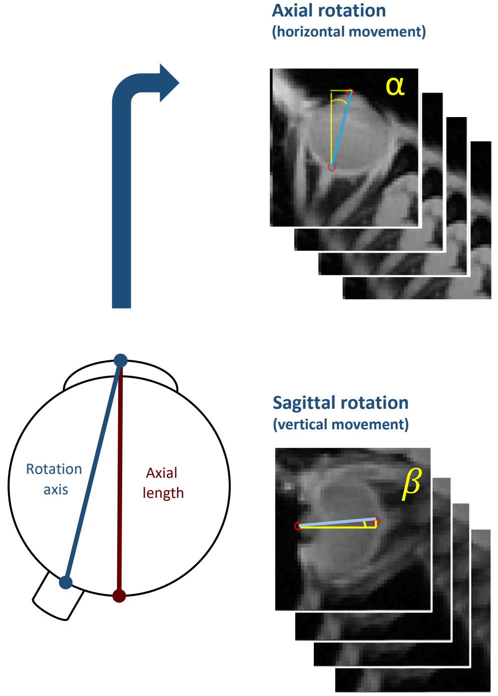
[1] ***Franceschiello*** et al, Prog. In Neuro (2020) , [2] Bastianseen et al, Magn. Reson. Med (2019), [3] Di Sopra et al, Magn. Reson. Med, (2019), [4] Piccini D et al, Magn Reson Med, (2011).

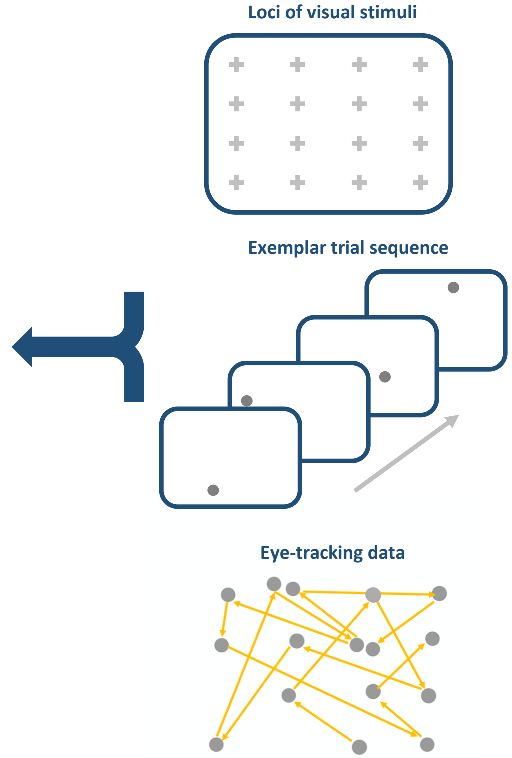
HI-FI DYNAMIC EYE IMAGING: DEPICTING THE EYE ANATOMY IN MOTION



Franceschiello et al, Progr. Neurobiology, 2020

VALIDATION WITH PHYSIO MEASUREMENTS





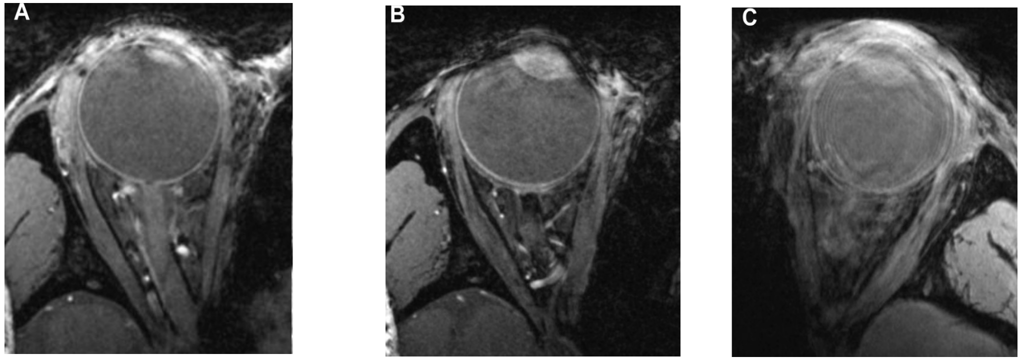
Franceschiello et al, Progr. Neurobiology, 2020

HOW DO WE MAKE IT CLINICAL?

Resolution?

Correction for eye-movement?

2.0 MR-EYE: A Motion-resolved MRI Protocol for High-resolution Ophthalmic Imaging



the eye **shut** but **not taped** the eye **open** the eye **taped** and **closed**

Yiwei Jia

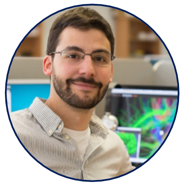
Bastien Milani

Jaime Barrancco

Helene Vitali

Eleonora Fornari

Jean-Baptiste Ledoux



Oscar Esteban

Jessica Bastiaansen

Benedetta Franceschiello

Swiss National Science Foundation

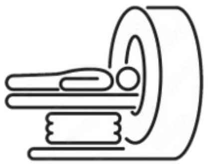
Glarin, R.K., et al. MR-EYE: High-Resolution MRI of the Human Eye and Orbit at Ultrahigh Field (7T). Magnetic Resonance Imaging Clinics *29*, 103–116. https://doi.org/10.1016/j.mric.2020.09.004.

Yiwei Jia et al.. (2025). MR-Eye: A High-Resolution Motion-Resolved MRI Protocol for Anatomical Imaging of the Human Eye. Proceedings of the ISMRM Annual Meeting, 0639.

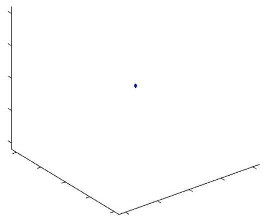
METHOD: 2.0 MR-EYE PROTOCOL

Data Acquisition Protocols

(a) 2.0 MR-Eye Protocol



MRI scanner
(*Siemens 3T PRISMA*)

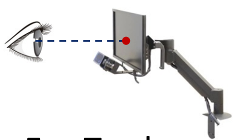


3D radial trajectory

T1w/T2w Fat-suppressed LIBRE

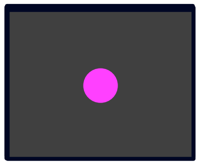
Acquired MRI raw data

Time Axis



Eye Tracker
(EyeLink 1000 Plus)

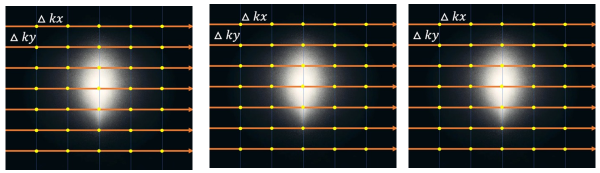
Eye fixation on central stimuli



(b) Standard clinical protocols

MRI scanner
(*Siemens 3T PRISMA*)

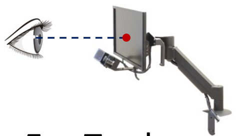
Cartesian trajectory



T1w VIBE FS/T2w TSE FS

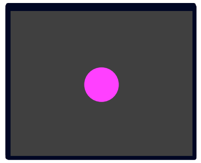
Acquired MRI raw data

Time Axis



Eye Tracker
(EyeLink 1000 Plus)

Eye fixation on central stimuli

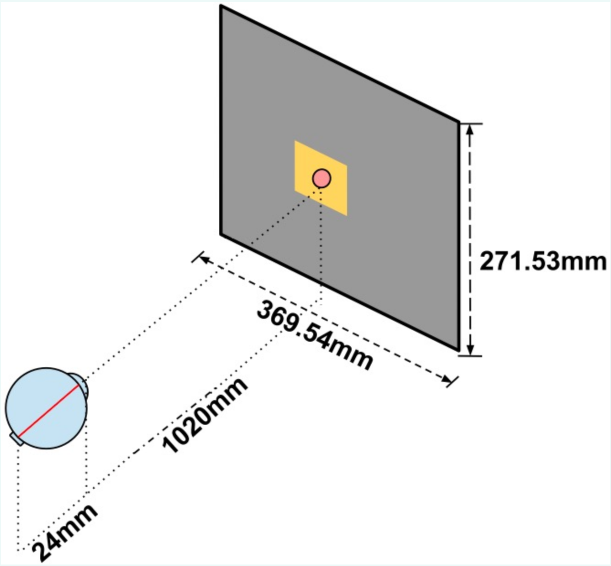


Franceschiello, B. et al. (2020). 3-Dimensional magnetic resonance imaging of the freely moving human eye. Progress in Neurobiology *194*, 101885. https://doi.org/10.1016/j.pneurobio.2020.101885.
Piccini, Davide, et al. "Spiral phyllotaxis: the natural way to construct a 3D radial trajectory in MRI." Magnetic resonance in medicine 66.4 (2011): 1049-1056.

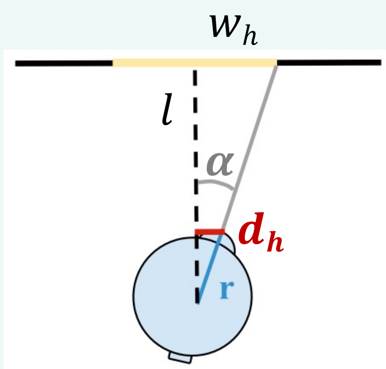
METHOD: 2.0 MR-EYE PROTOCOL

ET-guided Binning and Motion-resolved Reconstruction

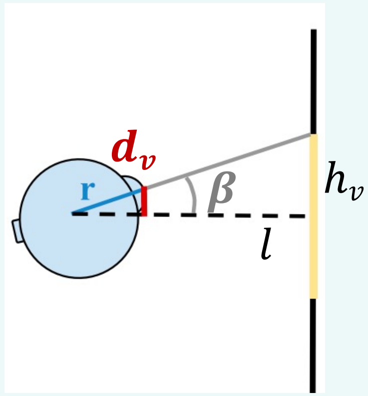
(a) Determine criterion region



Experimental setup geometry
Gaze coordinate ←→ Actual eye rotation



$d_h < \frac{1}{3}\ VoxelSize$



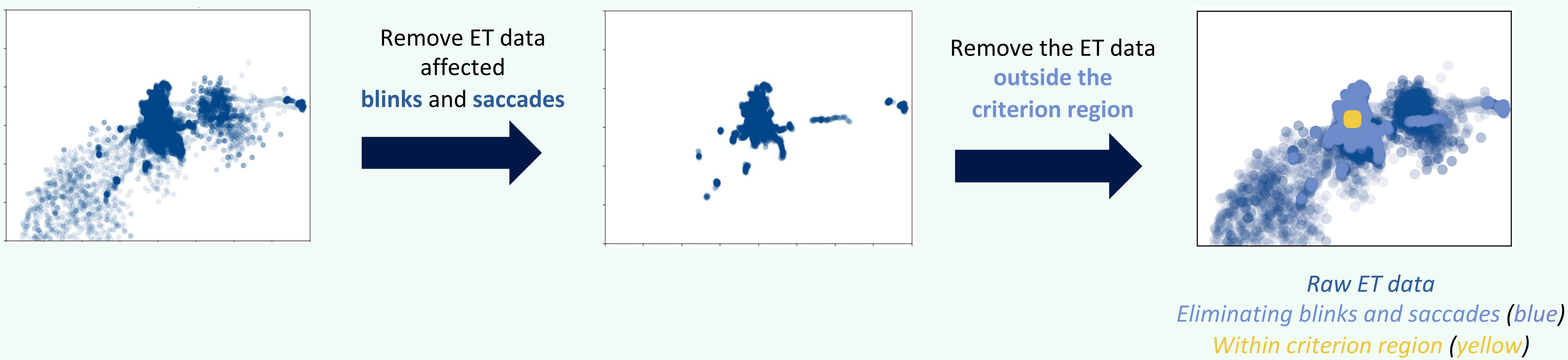
$d_v < \frac{1}{3}\ VoxelSize$

Maximum displacement calculation

METHOD: 2.0 MR-EYE PROTOCOL

ET-guided Binning and Motion-resolved Reconstruction

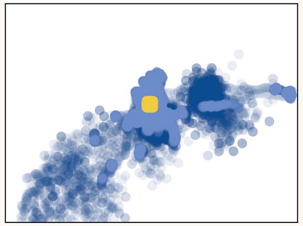
(b) ET data filtering



METHOD

Binning and Motion-resolved Reconstruction

(c) Binning and reconstruction



Eye tracking mask for classifying the gaze points

Zoom In

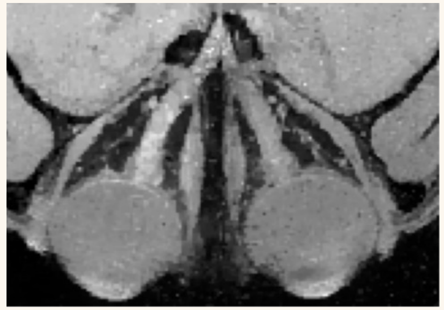
Acquired MRI data after binning

Time Axis

ET mask
1ms / sample

Binning mask
TR = 8.01ms

Monalisa toolbox



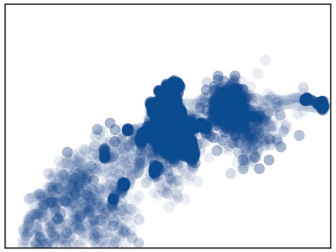
Compressed sensing (CS) reconstruction with motion-resolved binning mask

nIter=15, delta=1, rho=10
L1 spatial regularization

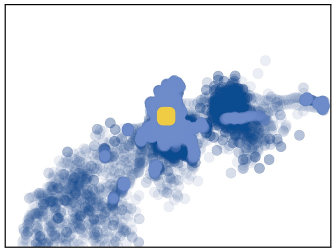
ET-GUIDED BINNING IN 2.0 MR-EYE

ET coordinates

All readouts

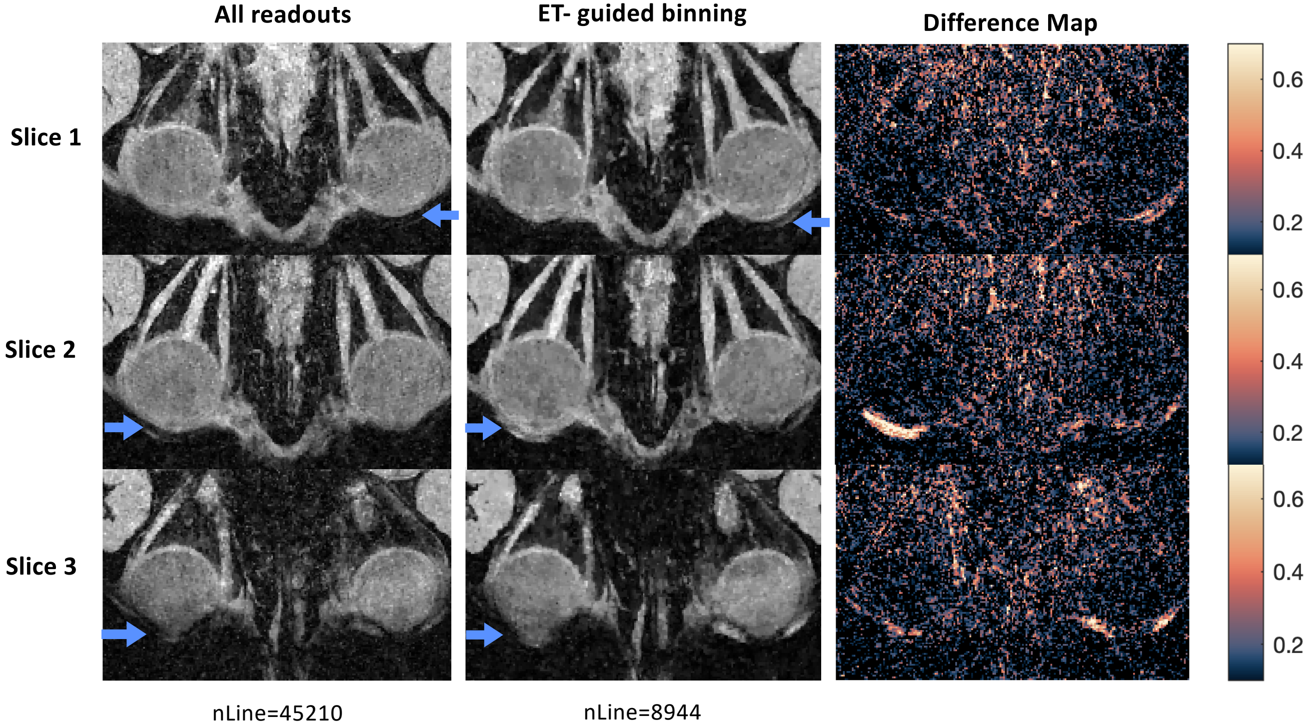


Center



2.0 MR-Eye protocol

T1w LIBRE without vs. with ET-guided binning

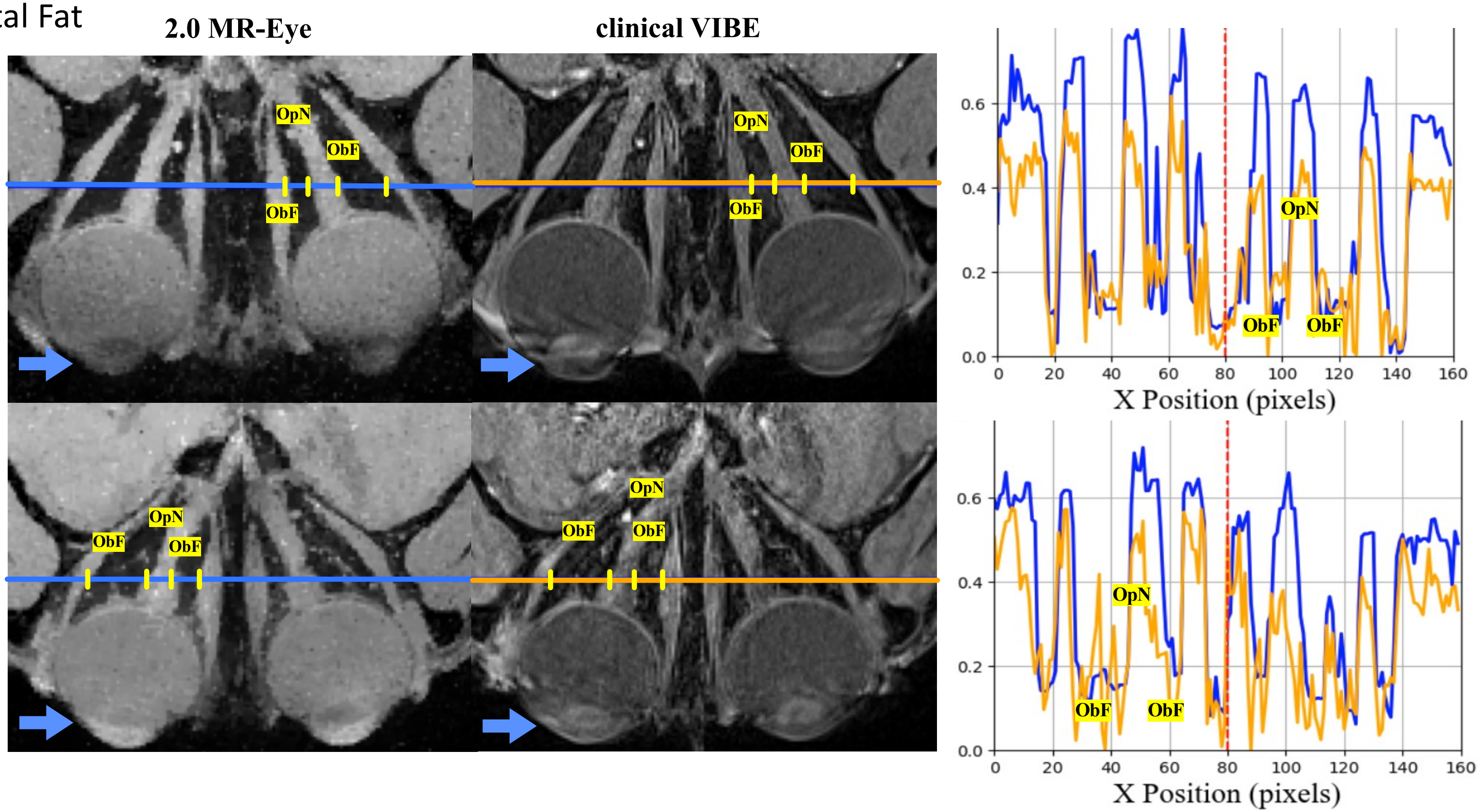


Reconstructed images using ET-guided binning masks showed **more structural details** compared to non-binned images.

RESULTS: 2.0 MR-EYE VS CLINICAL (T1W)

OpN: Optic Nerve

ObF: Orbital Fat



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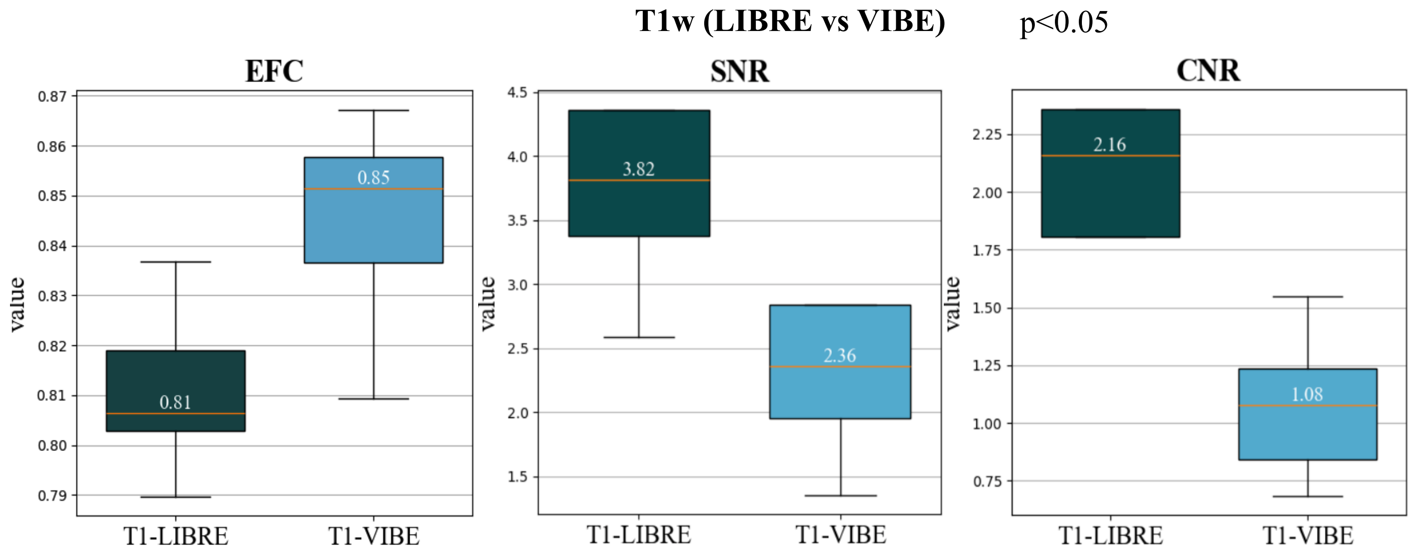
DISCUSSION

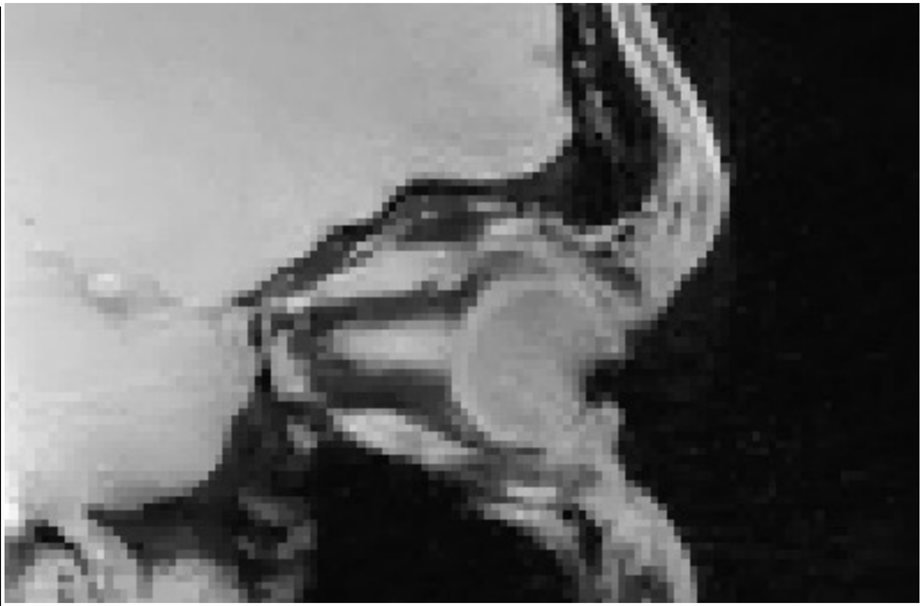
Samples
120 paired slices from 3 subjects

Metrics
- Entropy Focus Criterion (EFC ↓) **Lower**
- SNR: **Higher**
- CNR: **Higher**



CONCLUSION

- Fewer **motion artifacts**
- Enhanced **structure visibility**
- **Clinical potentials**: Compared to current clinical protocols



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The QIS team

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Hélène Vitali

Mat-Tech Lab

Hes·so VALAIS WALLIS School of Engineering

the sense innovation and research center

QUANTITATIVE MR IMAGING SCIENCE LAB

UNIVERSITÄT BERN

SEQUENCE PARAMETER

2.0 MR-Eye protocol							
Protocol	**TR/TE(ms)**	**Voxel Size(mm)**	**FoV(mm)**	**FA**	**TA(min)**	**Base Resolution**	**Bandwidth** (Hz/Px)
T_1w-LIBRE	8.01/3.62	0.5×0.5×0.5	120×120×120	8°	06:02	240	496
Standard clinical protocol							
Protocol	**TR/TE(ms)**	**Voxel Size(mm)**	**FoV(mm)**	**FA**	**TA(min)**	**Base Resolution**	**Bandwidth** (Hz/Px)
T_1w-VIBE FS	20.00/3.92	0.4×0.4×0.4	200	12°	05:57	512	140

Bastiaansen, J.A.M., and Stuber, M. (2018). Flexible water excitation for fat-free MRI at 3T using lipid insensitive binomial off-resonant RF excitation (LIBRE) pulses. Magn Reson Med *79*, 3007–3017. https://doi.org/10.1002/mrm.26965.