MRI physics and physiology

Turku PET Centre Brain Imaging Course 2025

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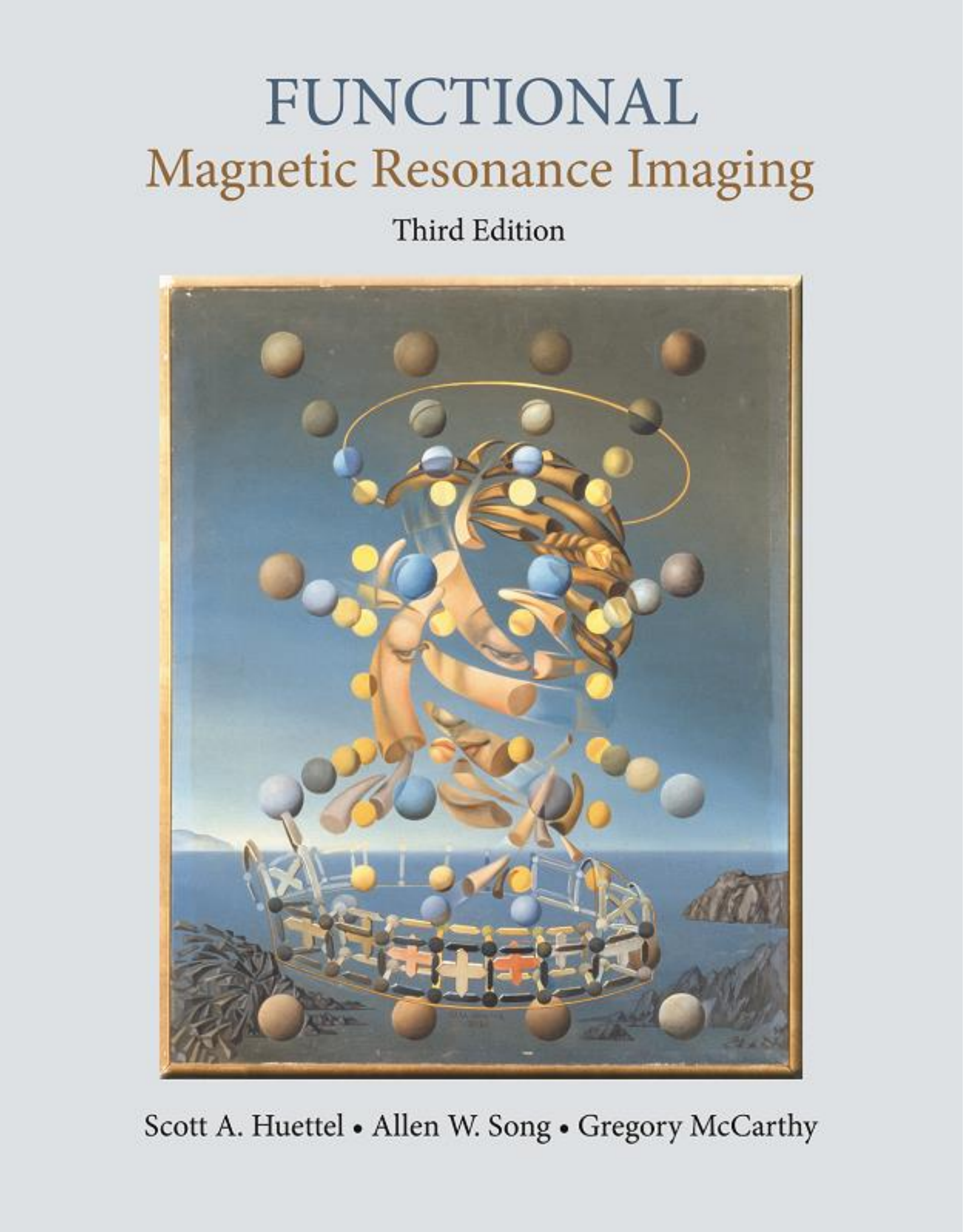
Organization of the lecture

Chapters 1-7, pp 1-270



Warmup

Part I:
- Historical overview (Ch. 1)
- Key concepts, principles of MRI scanners and safety (Ch. 2)

Part II:
- Spins and how they orient in a magnetic field (Ch. 3)
- Principles of MR image formation (Ch. 4)
- Relaxation processes and tissue contrast (Ch. 5)

Part III:
- Neurovascular coupling and the hemodynamic response function (Ch. 6 – 7)

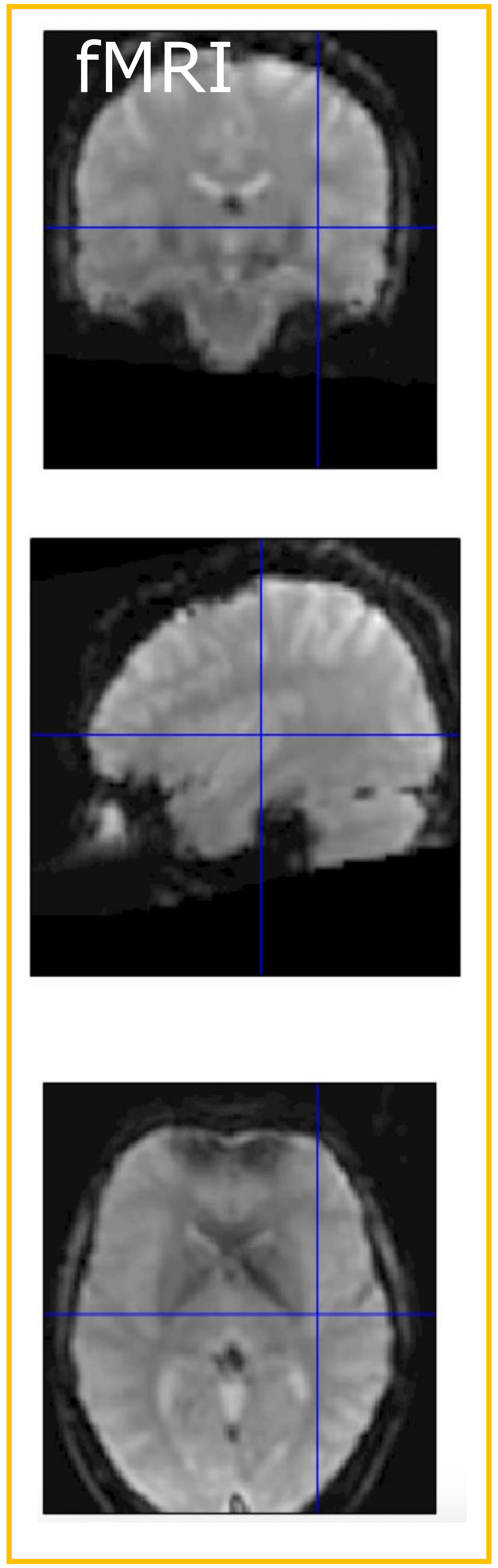
Functional Magnetic Resonance Imaging Third Edition, by Scott A. Huettel, Allen W. Song, and Gregory McCarthy
https://learninglink.oup.com/access/huettel-fmri3e

What is MRI and fMRI?

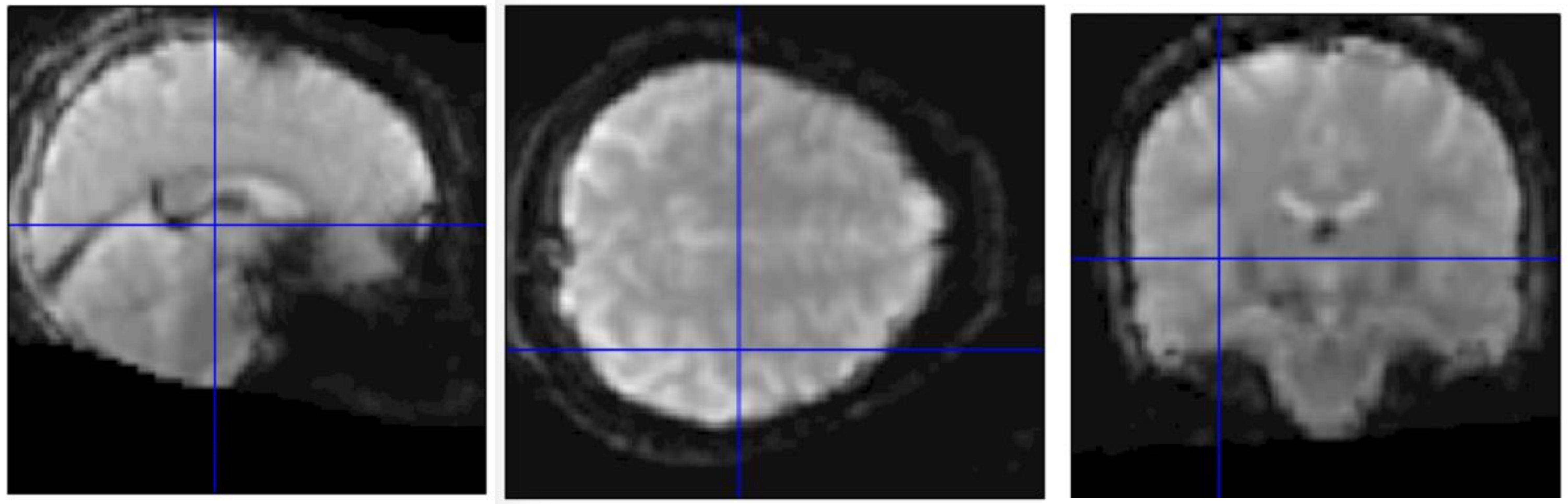
- Images taken with MRI scanner (Magnetic Resonance Imaging)

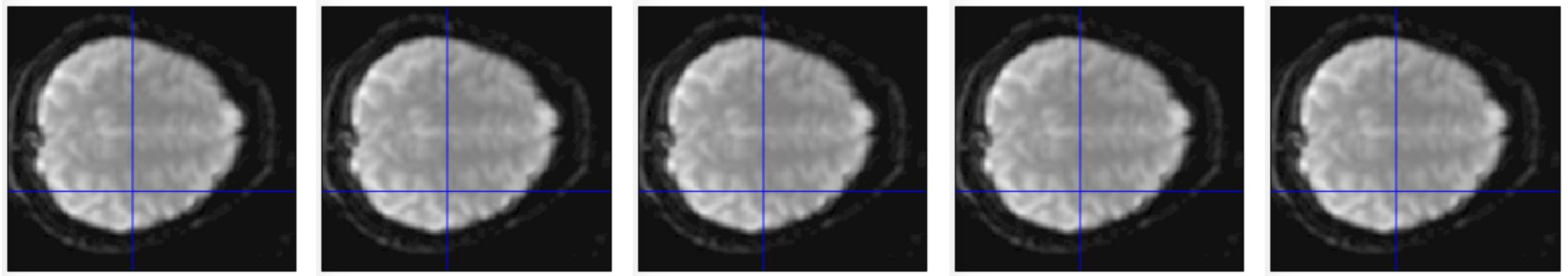
- **Anatomical MRI:** anatomical image gives structure (but they cannot reveal short-term physiological changes)

- **fMRI:** functional images
  - measure fluctuations in subjects' brains function while they are focusing on a task in a MRI scanner or try not to do anything
  - Purpose
    1) finding specific part of the brain where mental process happens
    2) patterns of brain activation associated with mental processes
  - signal based on rapid changes in blood oxygenation over time on specific areas
    - the signal is coming from nuclear level, fMRI measurements are noninvasive and are not interfering with neuronal firing or blood flow



Raw fMRI data, 1 volume

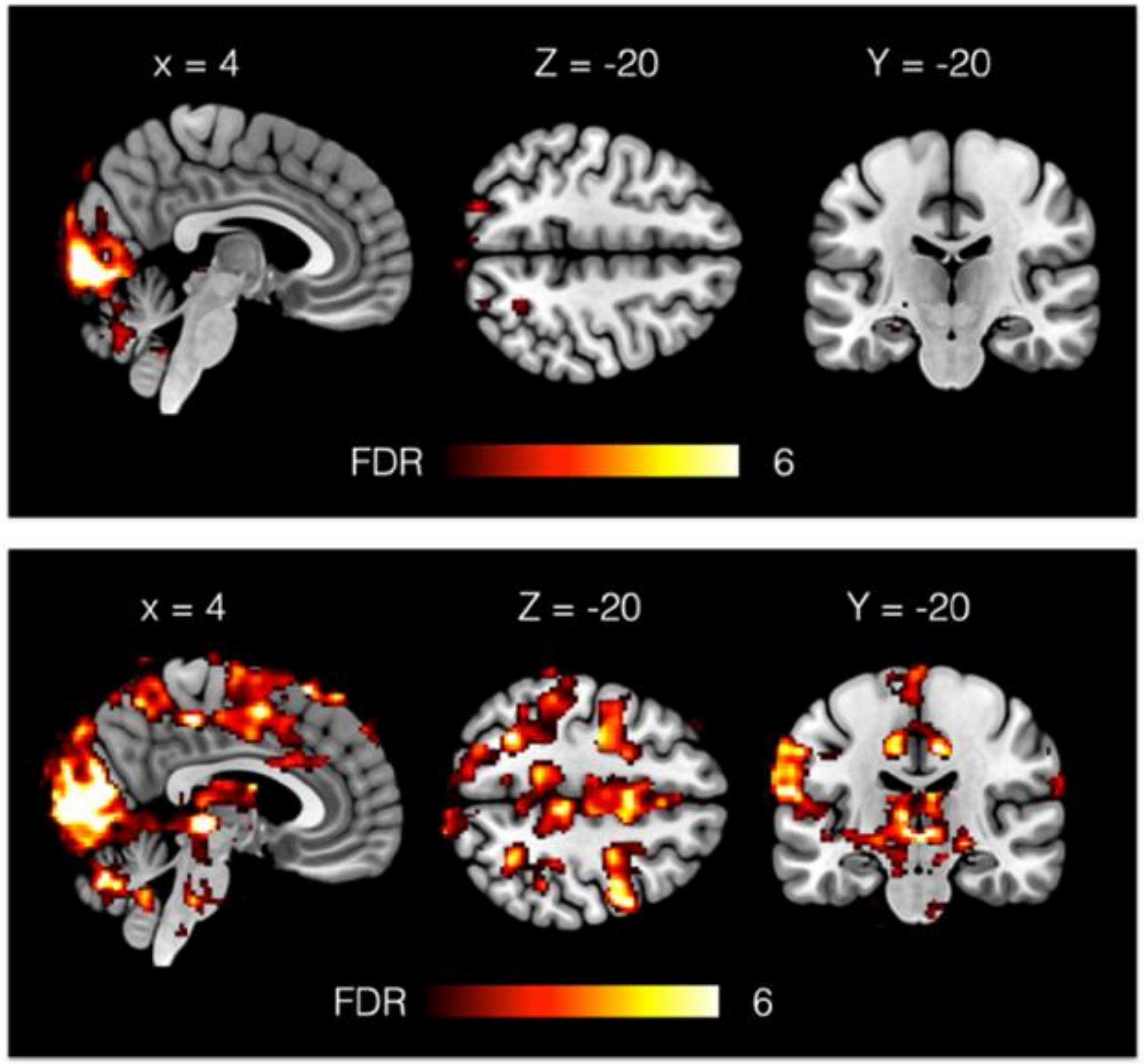


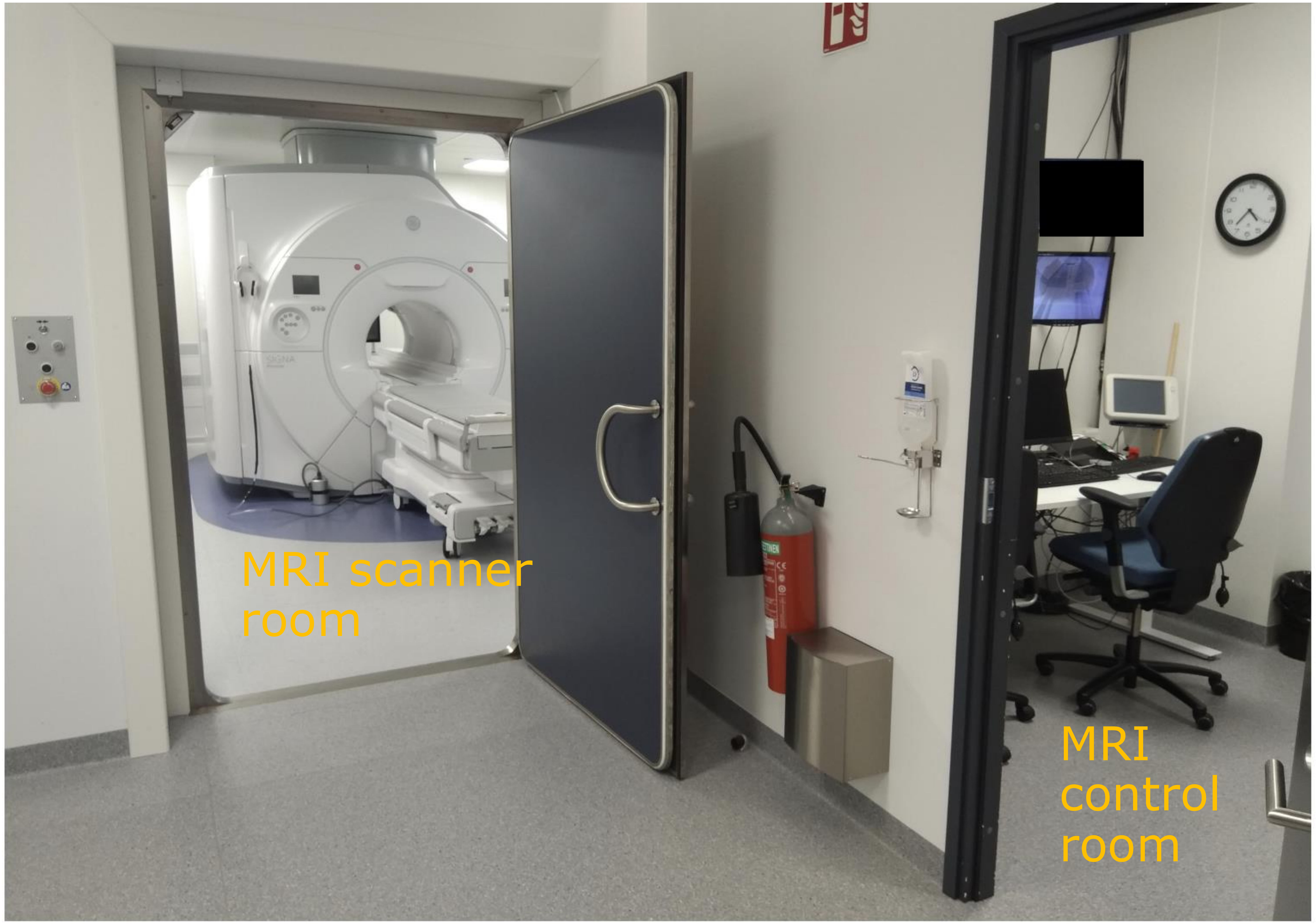


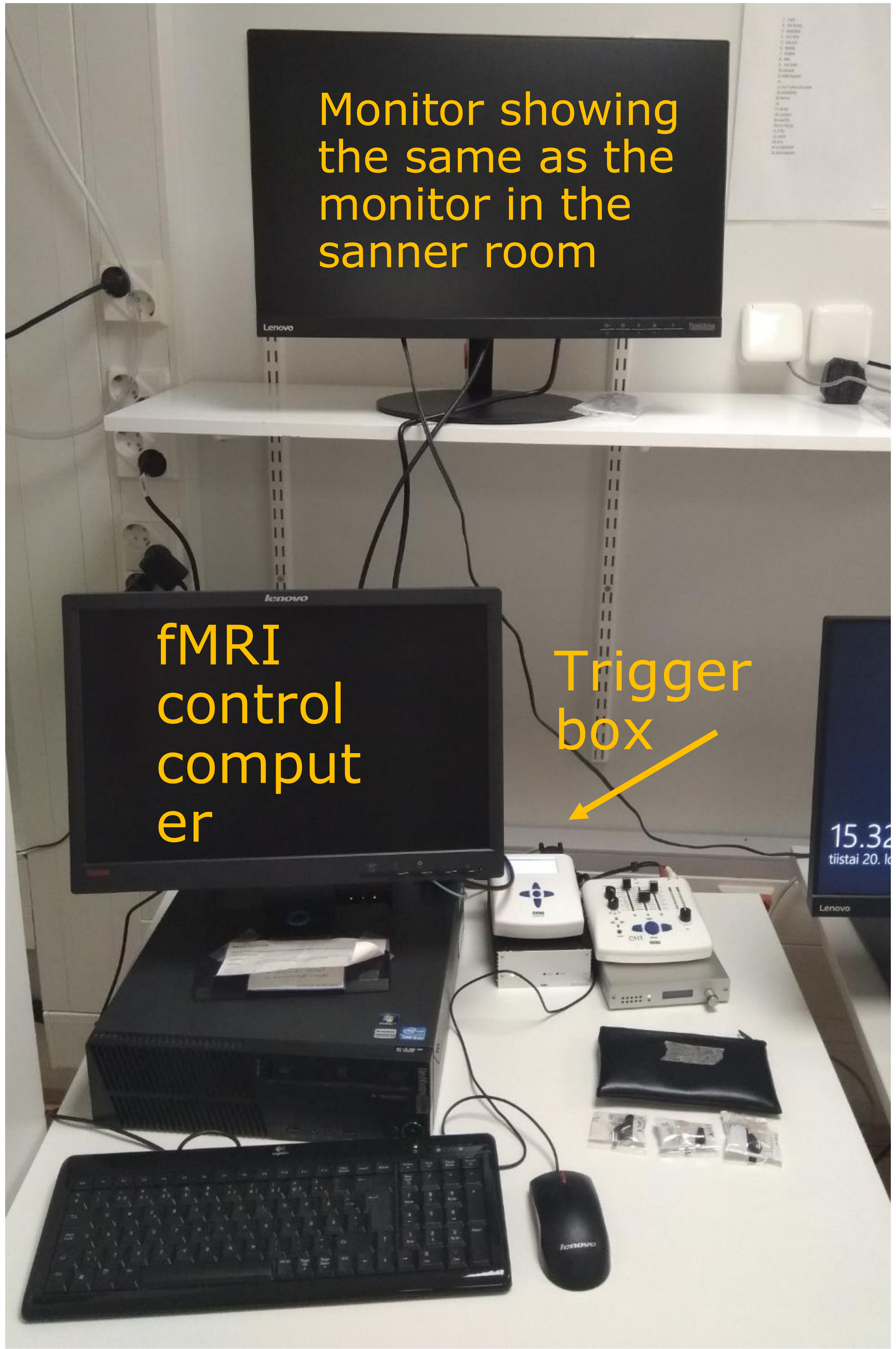
Collect enough volumes over time

Preprocessing + statistics

Parametric fMRI images




MRI scanner room
MRI control room


Monitor showing the same as the monitor in the sanner room
fMRI control comput er
Trigger box

Siemens MAGNETOM Sola 1.5 T

https://www.siemens-healthineers.com

Siemens MAGNETOM Vida 3 T

Philips Ingenia 1.5 T

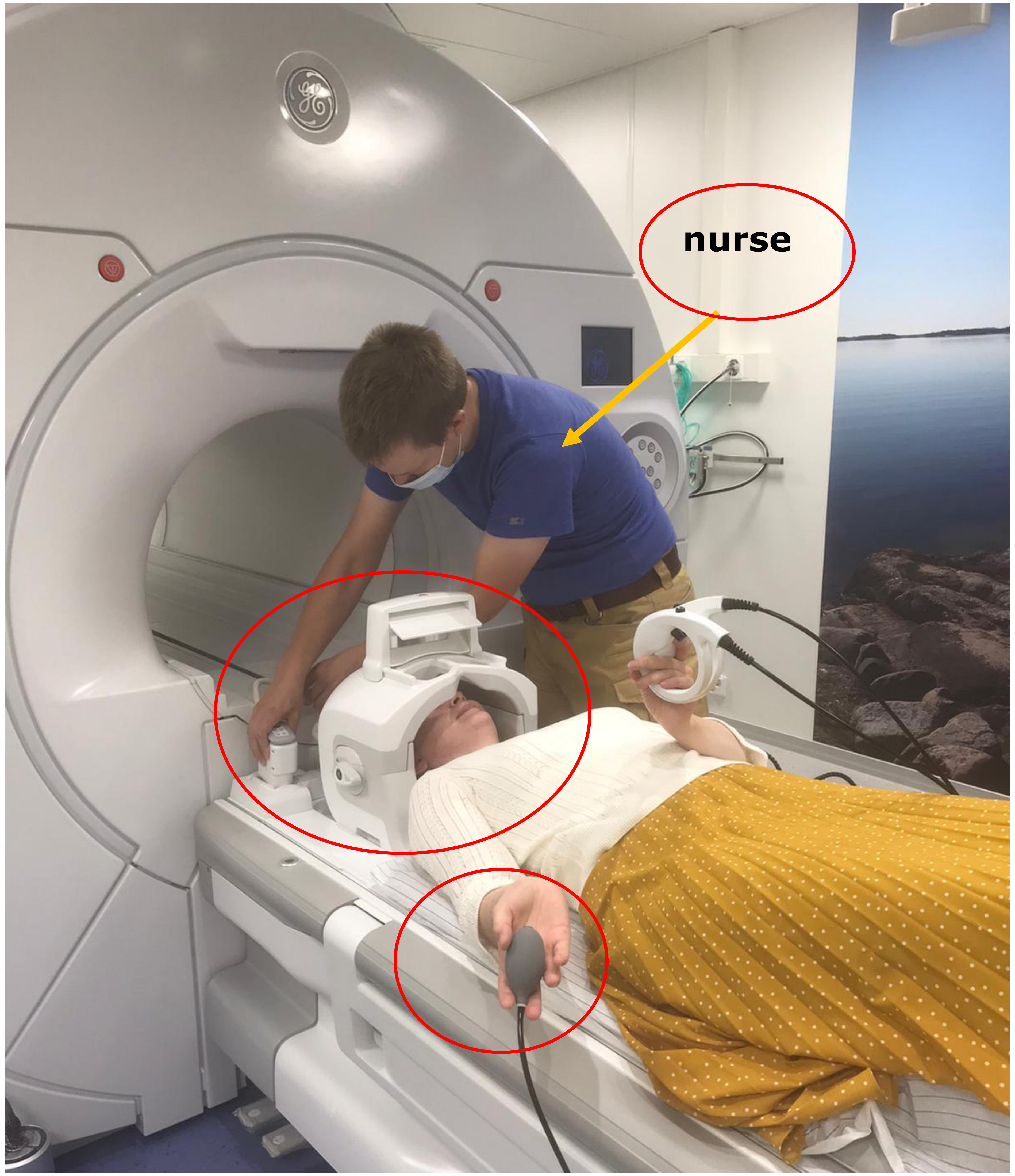
https://www.philips.fi/

Philips Ingenia 3 T

GE SIGNA 1.5 T

www.gehealthcare.com/products/magnetic-resonance-imaging/

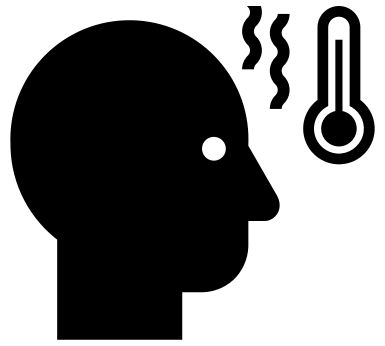
GE SIGNA 3 T



Prepare the subject on the table

Some sites ask the subjects to change clothes, some not, please follow the rules on your own laboratory

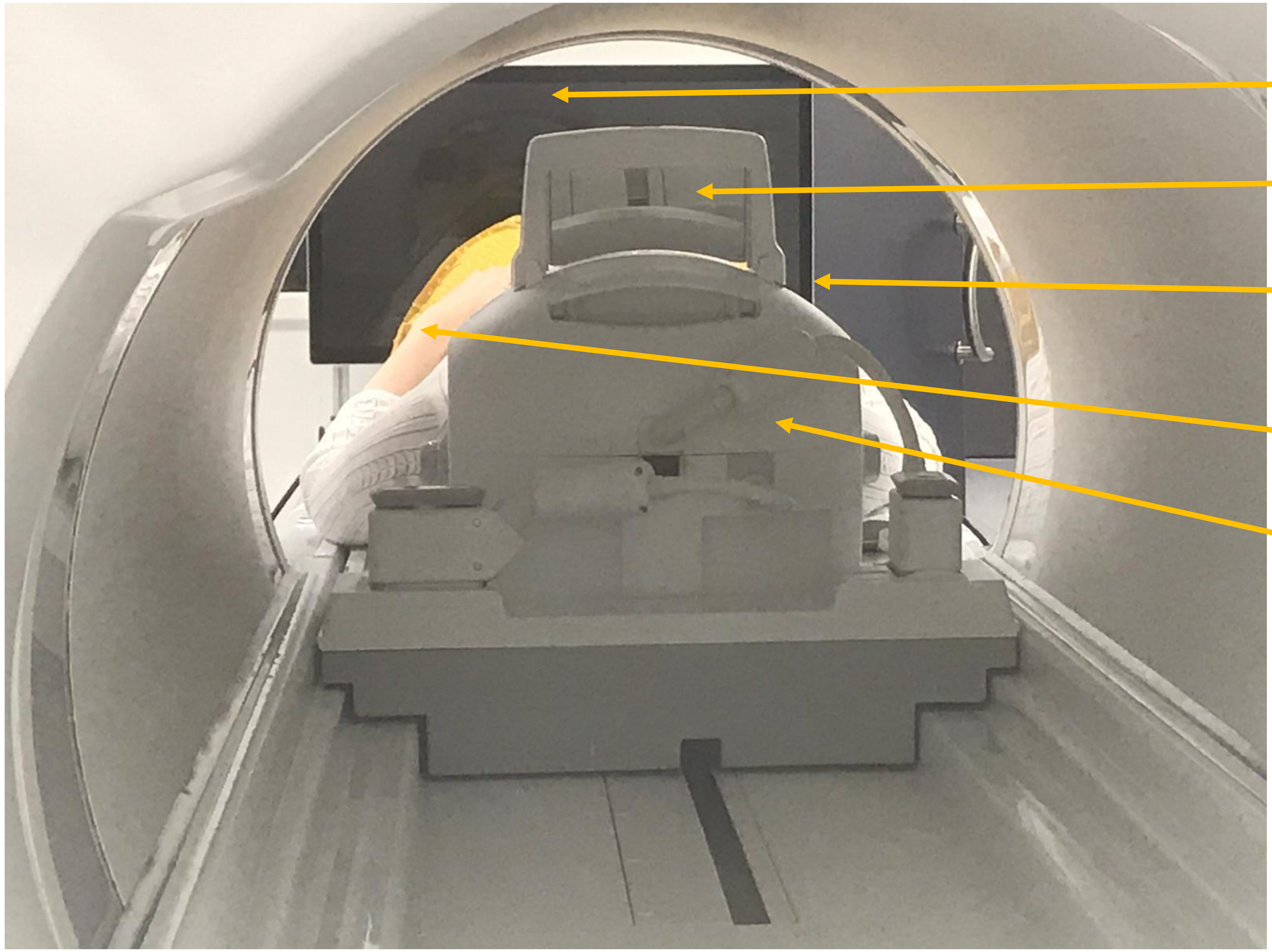
While scanning:



- Noise → double ear protection
- Claustrophobia → communicate
- SAR (specific absorption rate) → no patients with fever
- Careful screening: tattoos, implants, ear rings, etc.

Place the subject into the scanner

Important: ensure that the subject feel comfortable



Screen for showing stimuli

Mirror to see the stimuli

Panick button sitting on a easy-reach place

Hands holding the buttons for tasks

Head in head coil, ears protected

Nice and comfortable positioning, the subject is ready to start the task

1) **Place the subject** into the MRI scanner in strong magnetic field

2) Sent a **radio wave in**

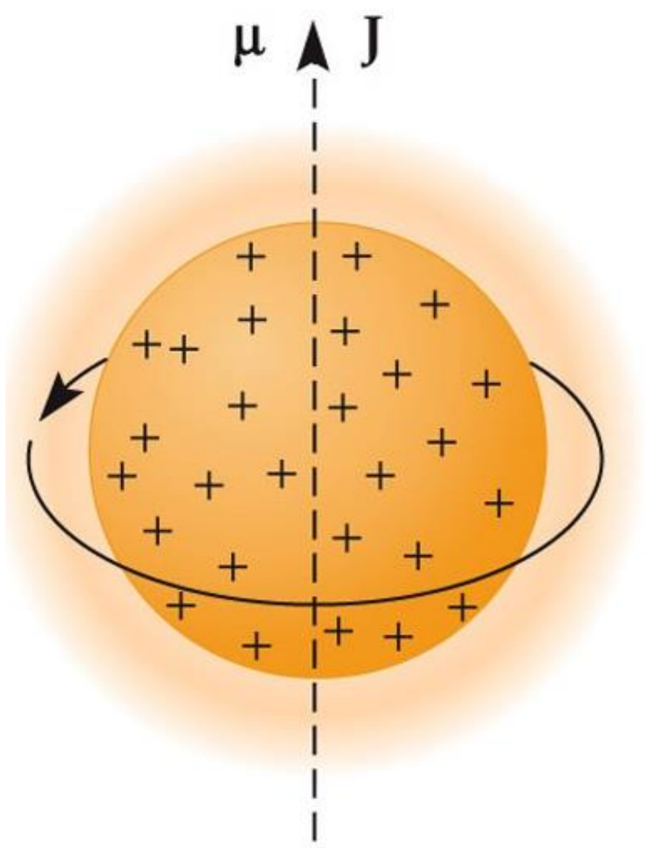
3) Turn the **radio wave off**

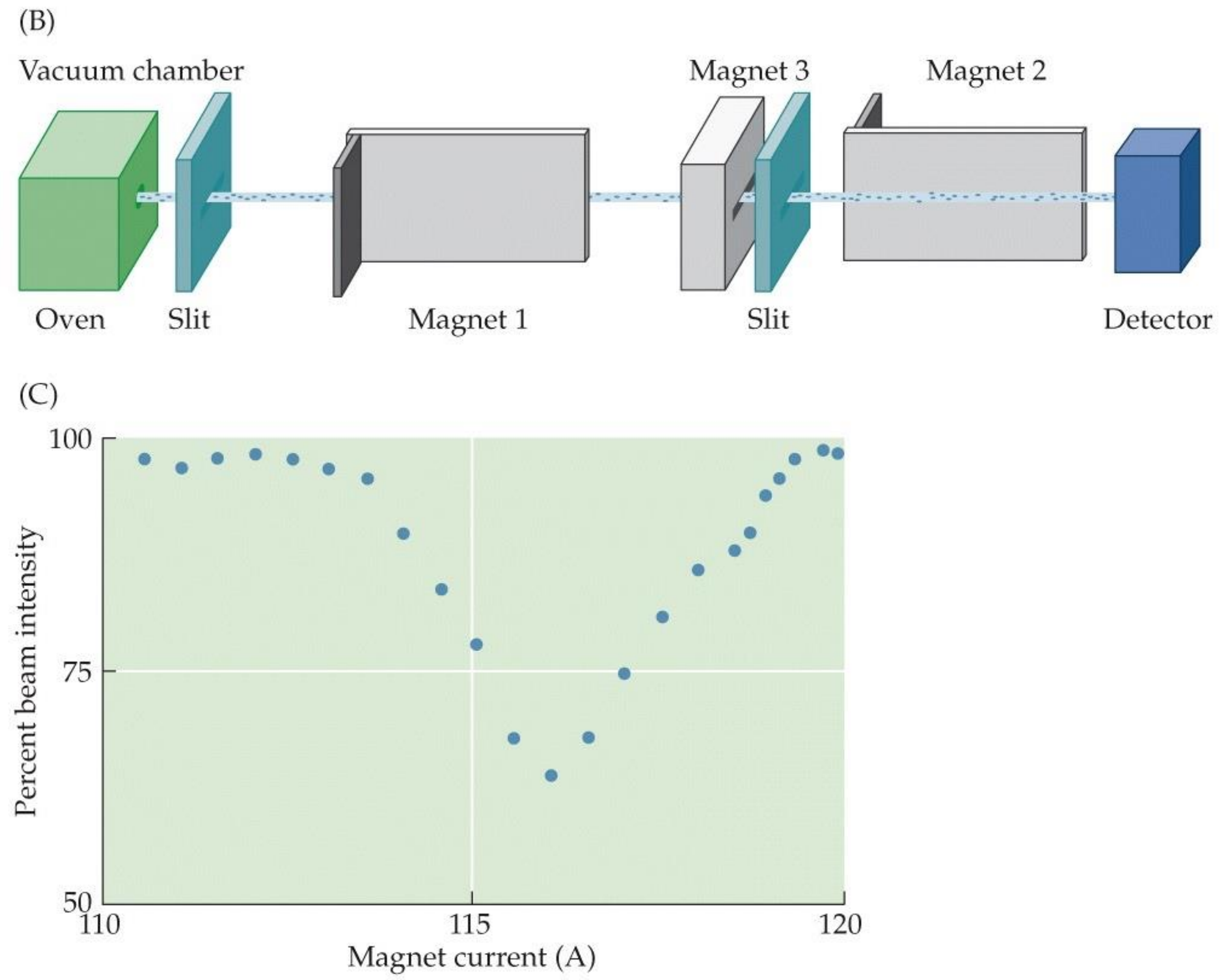
4) The **subject emits a signal** for head coil to catch

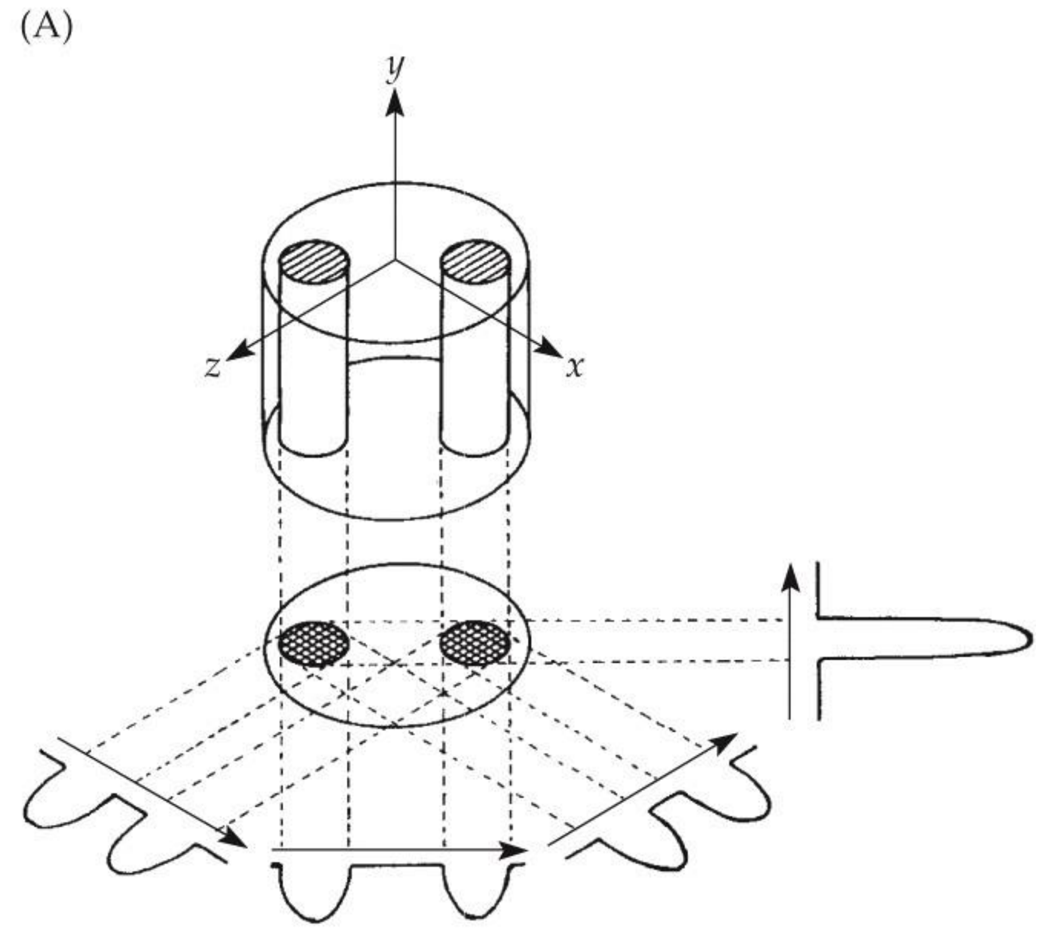
5) **Reconstruct** the image

Physical Background of MRI

Part I







FUNCTIONAL MAGNETIC RESONANCE IMAGING 3e, Figure 1.11
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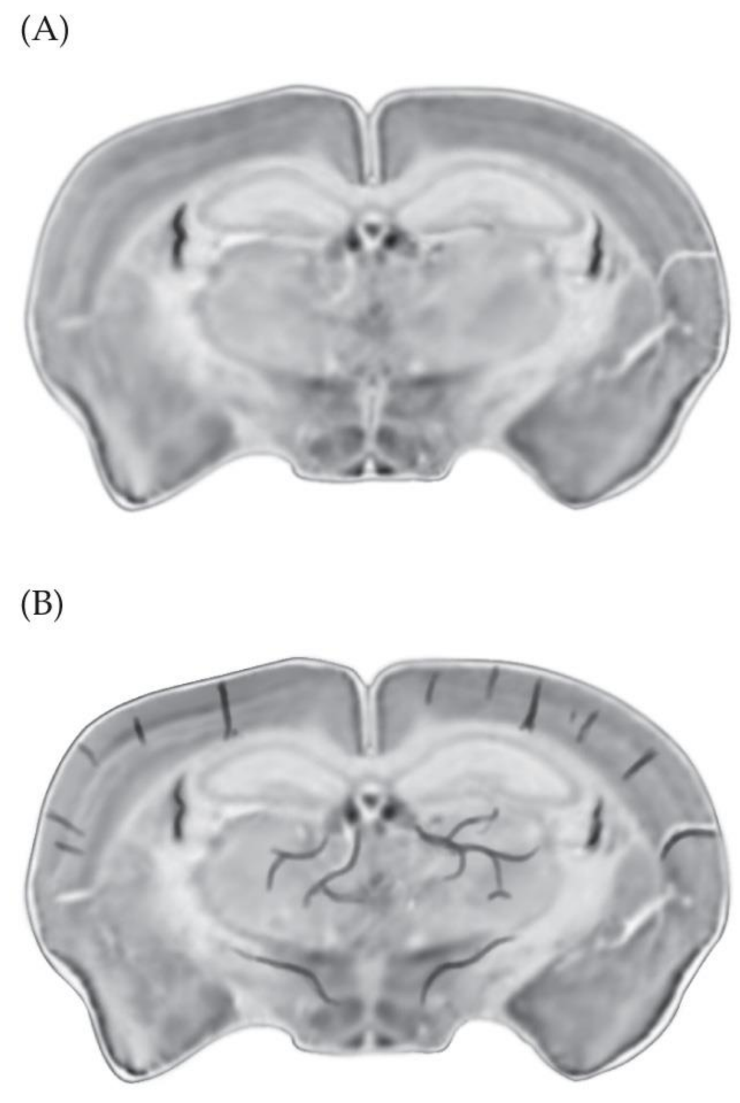

FUNCTIONAL MAGNETIC RESONANCE IMAGING 3e, Figure 7.2
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1920s | 1940s | 1960s | 1970s | 1990s

I*dea of* magnetic properties of atomic nuclei and their manipulation experimentally

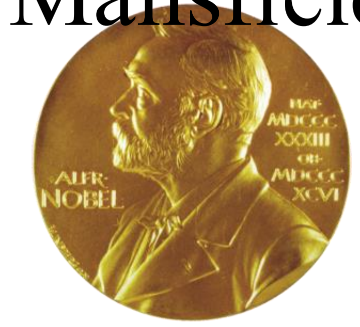
Phenomenom of *nuclear magnetic **resonance*** (NMR) in gases and solid matter

First biological MR ***images*** after advances in signal acquisition methods

Discovery that changes in **blood oxygenation** can influence MR images

Nobel prizes in physics: Stern (1943), Rabi (1944), Bloch & Purcell (1952)

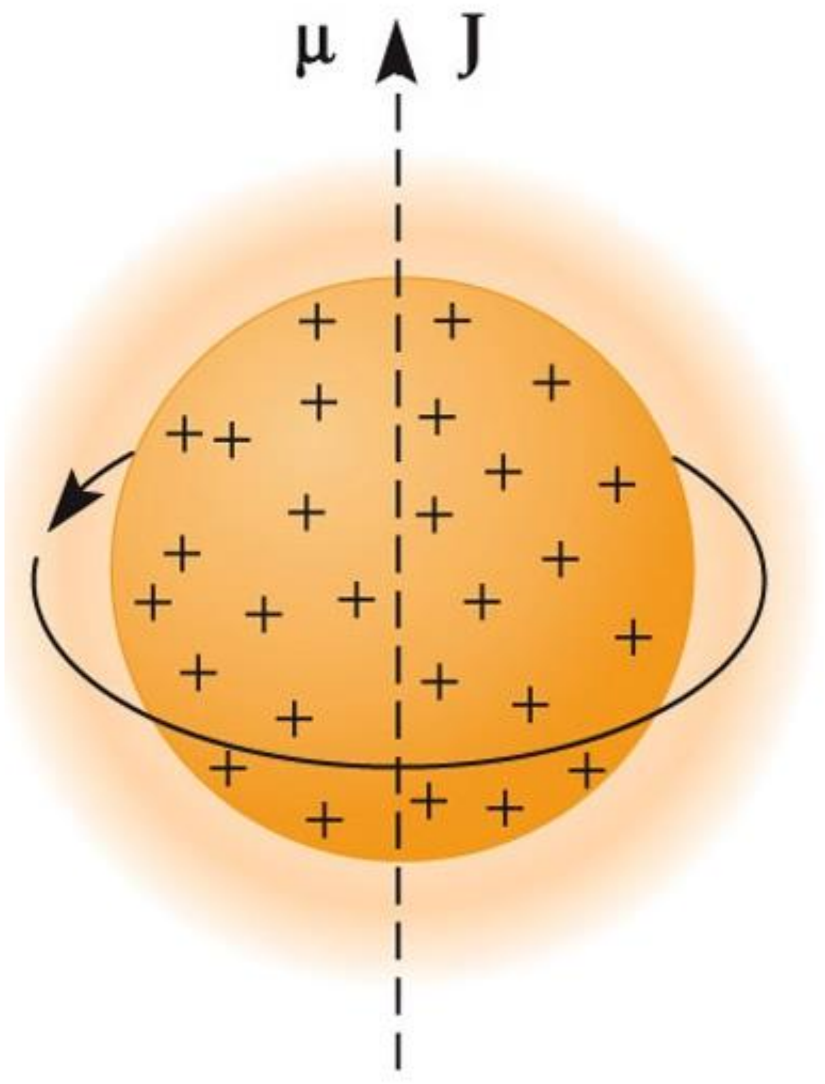
Nobel prize in physiology/medicine: Lauterbur & Mansfield (2003)



History of fMRI

Key concepts

- **Nuclear magnetic resonance** (NMR) property
  - Hydrogen (^1H) nuclei consist of a single proton
  - Proton "spins" on its axis generating magnetic moment (μ) and angular momentum (J)
  - This makes proton, the most abundant nuclei in the body, visible to MRI scanner
- Strong static magnetic field (B_0, unit Teslas (T))
  - Used for alignment of spins and induction of net magnetization (M_0)
- Oscillating magnetic field (B_1, radiofrequency)
  - Used for transmitting electromagnetic energy at resonant frequency
- Magnetic field gradients (G)
  - Used for varying the strength of B_0 systematically over space
- Detector coil
  - Used for measuring the electromagnetic energy emitted back to the environment

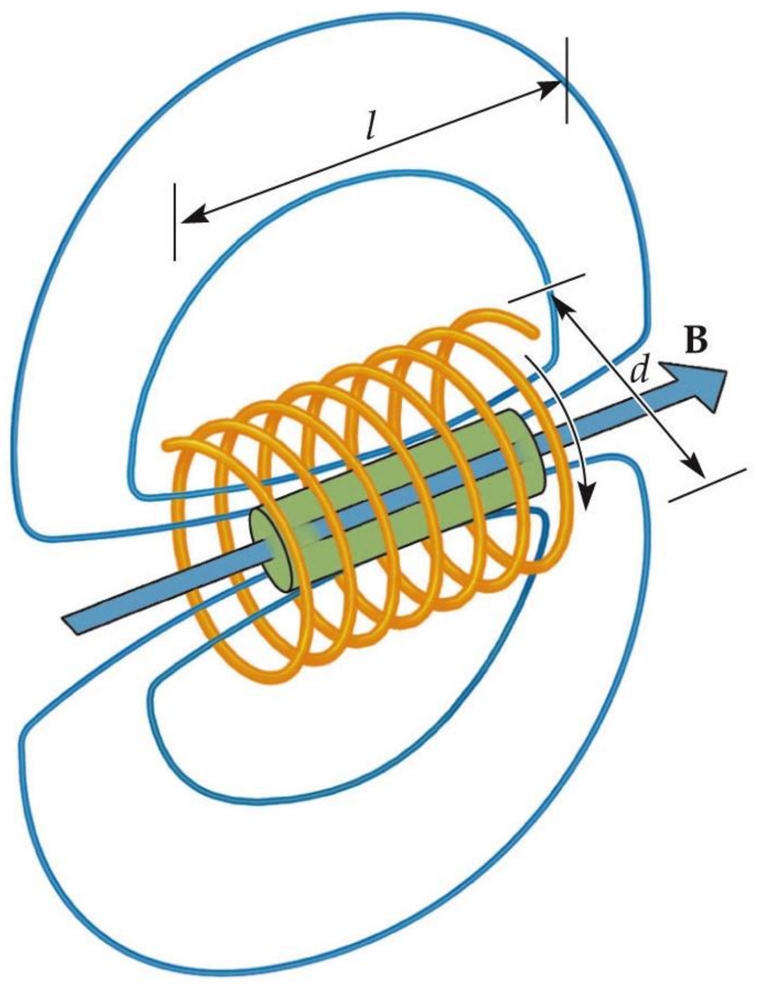


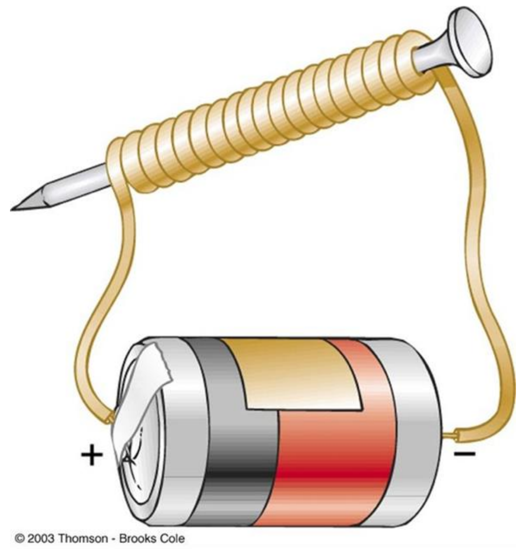
Functional Magnetic Resonance Imaging Third Edition, by Scott A. Huettel, Allen W. Song, and Gregory McCarthy

Components of an MRI scanner

- **M** = **M**ain static **M**agnetic field (B_0, homogeneous)
  - Generated by a series of electromagnetic coils (niobium-titanium wire winding) carrying very large electric currents
- **R** = **R**esonance frequency of the targeted nuclei (^1H)
  - Energy generated and received by radiofrequency coils
- **I** = **I**mage formation requires alteration of the magnetic field strength over space
  - Additional electromagnetic coils (gradient coils) are switch on and off to produce magnetic gradients superimposed to the strong static field

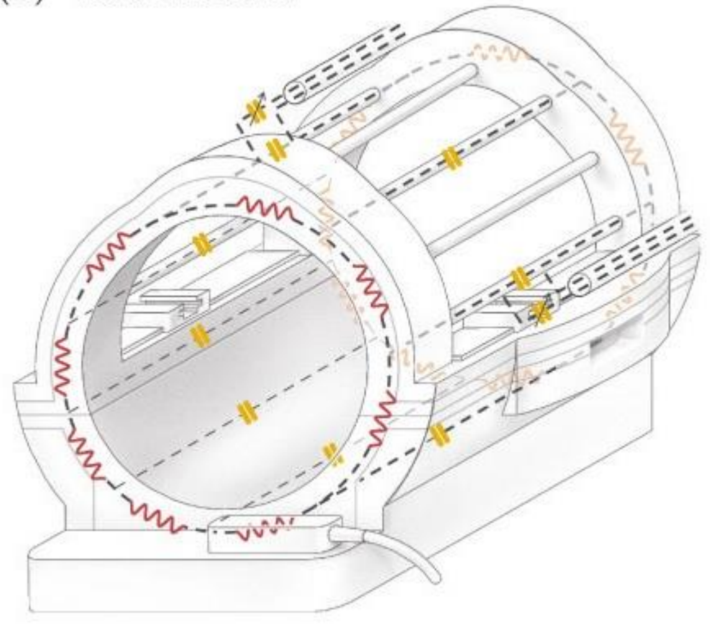
M



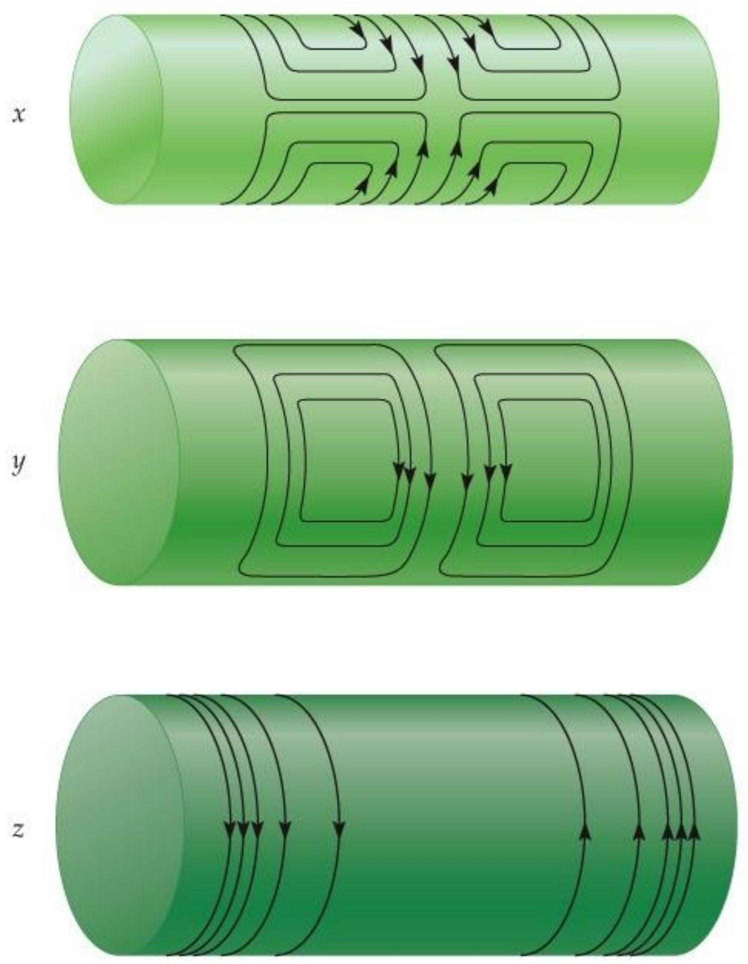


(B) Volume coils

R



I



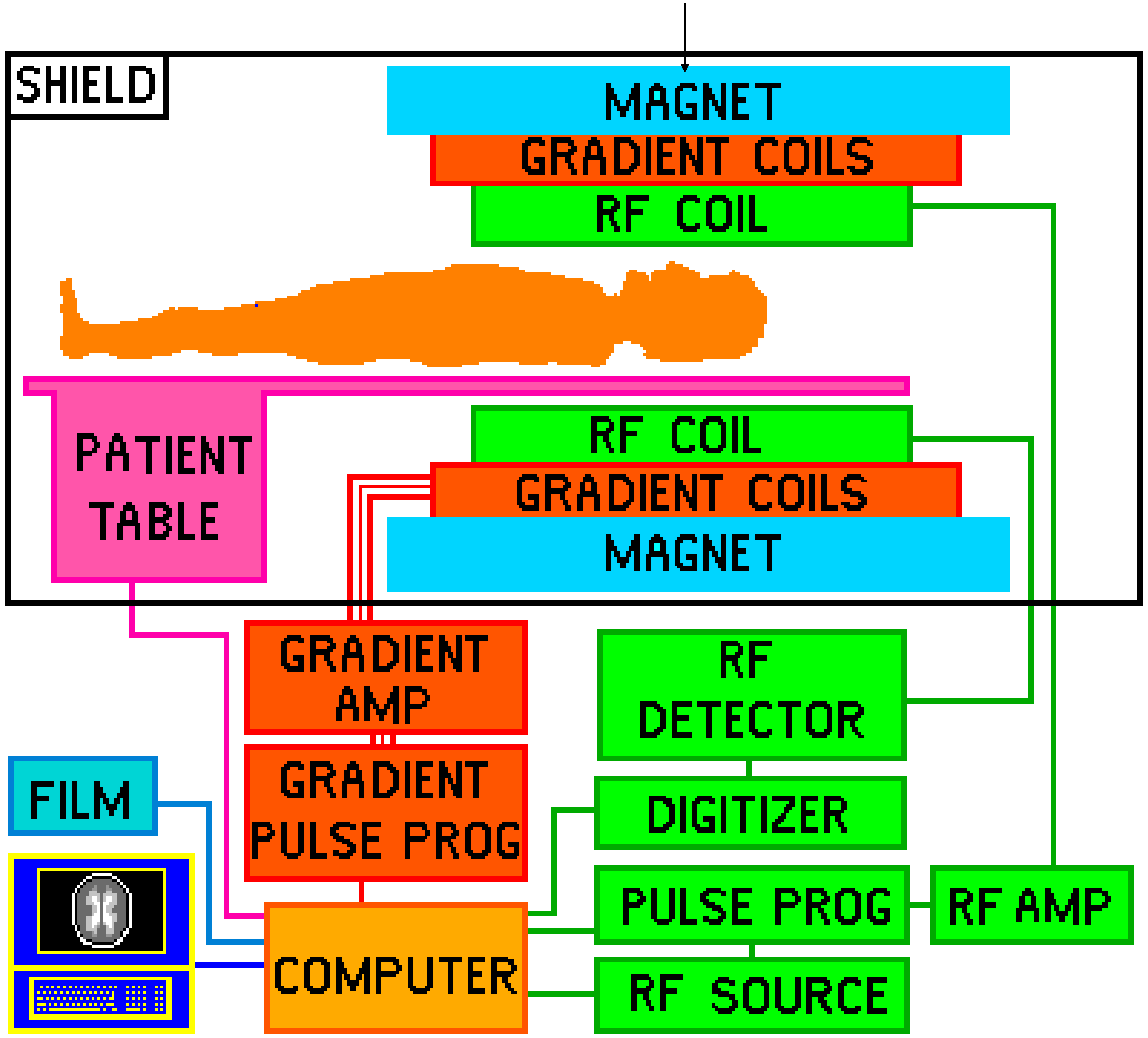
Functional Magnetic Resonance Imaging Third Edition, by Scott A. Huettel, Allen W. Song, and Gregory McCarthy

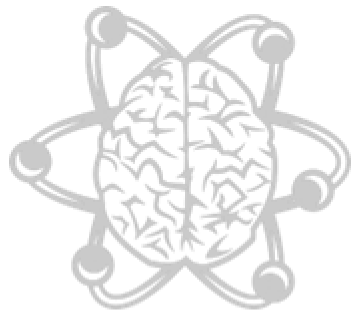
Components of an MRI scanner

- Static magnetic field (B_0)
  - 3T (usually)
- Radiofrequency field "rf" (B_1)
  - 128 MHz, 5-35 kW
- Magnetic field gradient (G)
  - 50 mT/m, 200 T/m/s

$$B_0 + B_1 + G \Rightarrow MRI$$

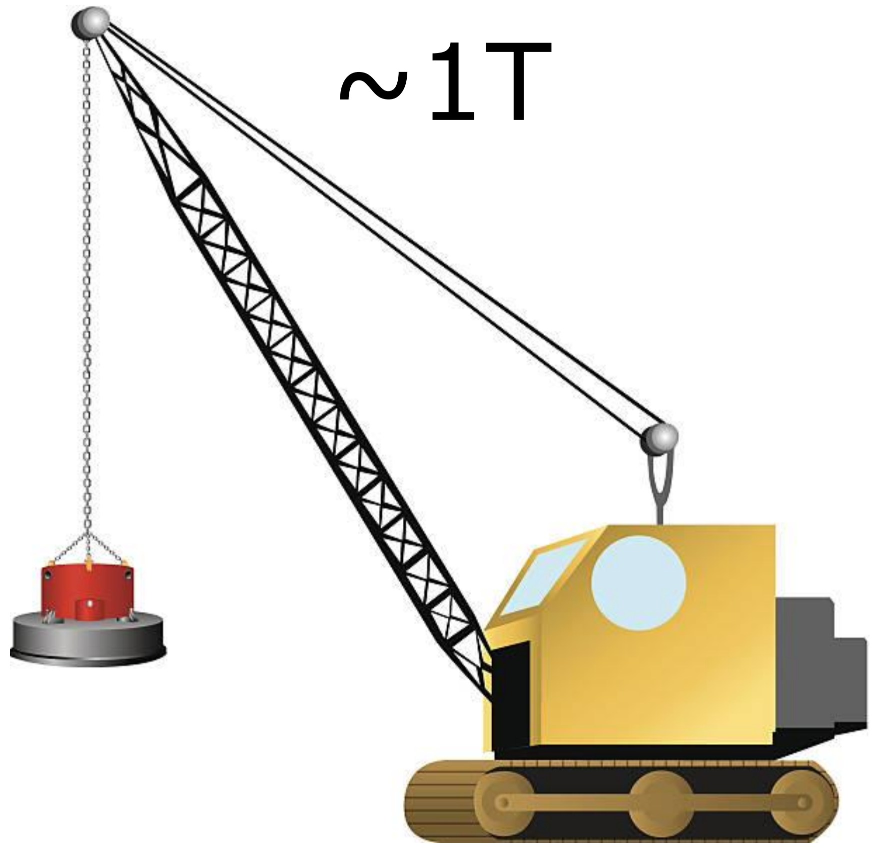
Liquid helium (-261°C) for superconductivity



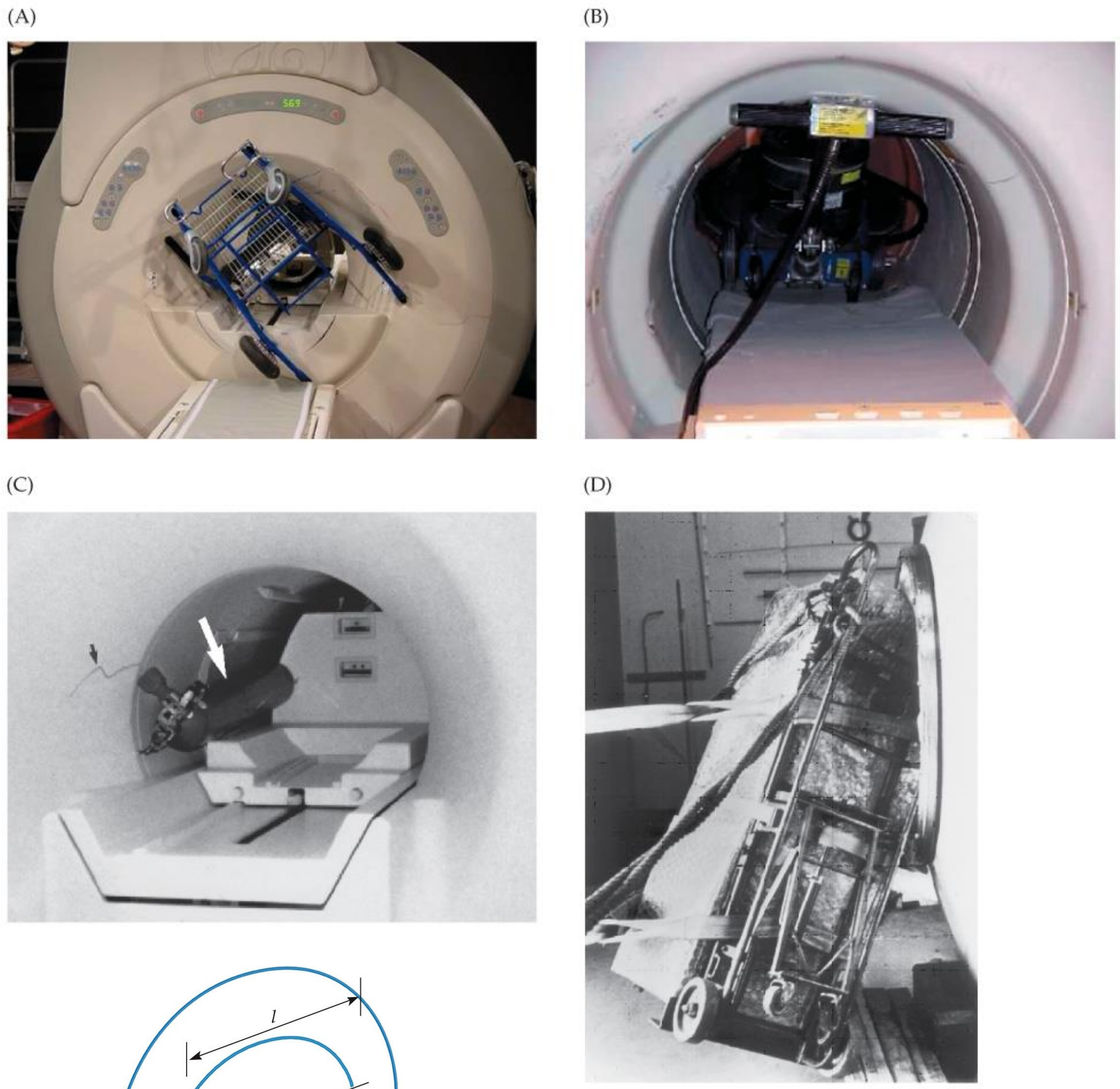


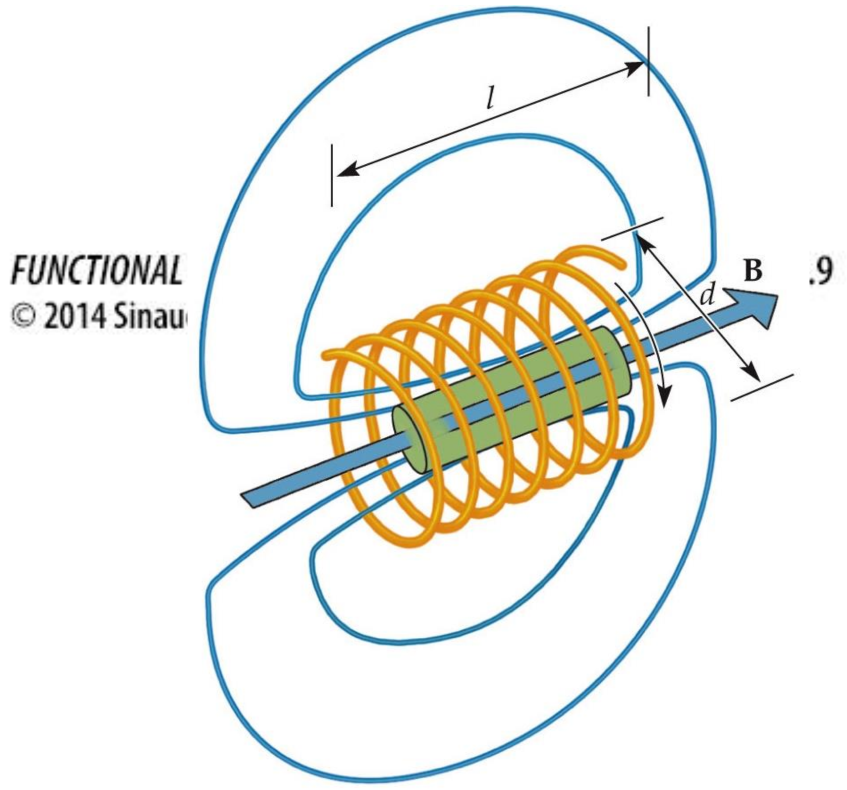
Greger Orädd

MRI safety



- Static field, B_0 (1.5 – 7T)
  - No proven biological effects
  - **Projectile effect**; magnet is always on and pulls ferromagnetic objects at very high velocity toward the scanner
  - Magnet room is a **controlled environment**
    - Every person entering the scanner room should be informed about the risks and queried about implants and foreign objects in the body
    - Think twice what you are carrying or waring when entering the room (e.g. guns)





MRI safety

- Gradient magnetic field effects
  - Rapidly changing magnetic field (~200 T/m/s) can induce electric currents in the human body and subsequently peripheral nerve stimulation (PNS)
  - Rapid changes of current in gradient coils induces very loud knocking or tapping noises (~95dB); participants should always wear ear protection
- Radiofrequency field effects
  - Absorbtion will cause heating of the body; SAR (specific absorbtion rate)
  - Metal necklaces, other jewelry, and even some tattoos can focus radiofrecuency energy

body Region	Normal mode [W/kg]	1st level [W/kg]	2nd level [W/kg]
Whole body	2	4	> 4
Partial body	2-10*	4-10*	> 10
Head	3.2	3.2	> 3.2
Local (head, trunk)	10	10	> 10
Local (extremities)	20	20	> 20
body core temperature rise	**0.5°C**	**1°C**	**> 1°C**

Greger Orädd

Physical background of MRI

Part II

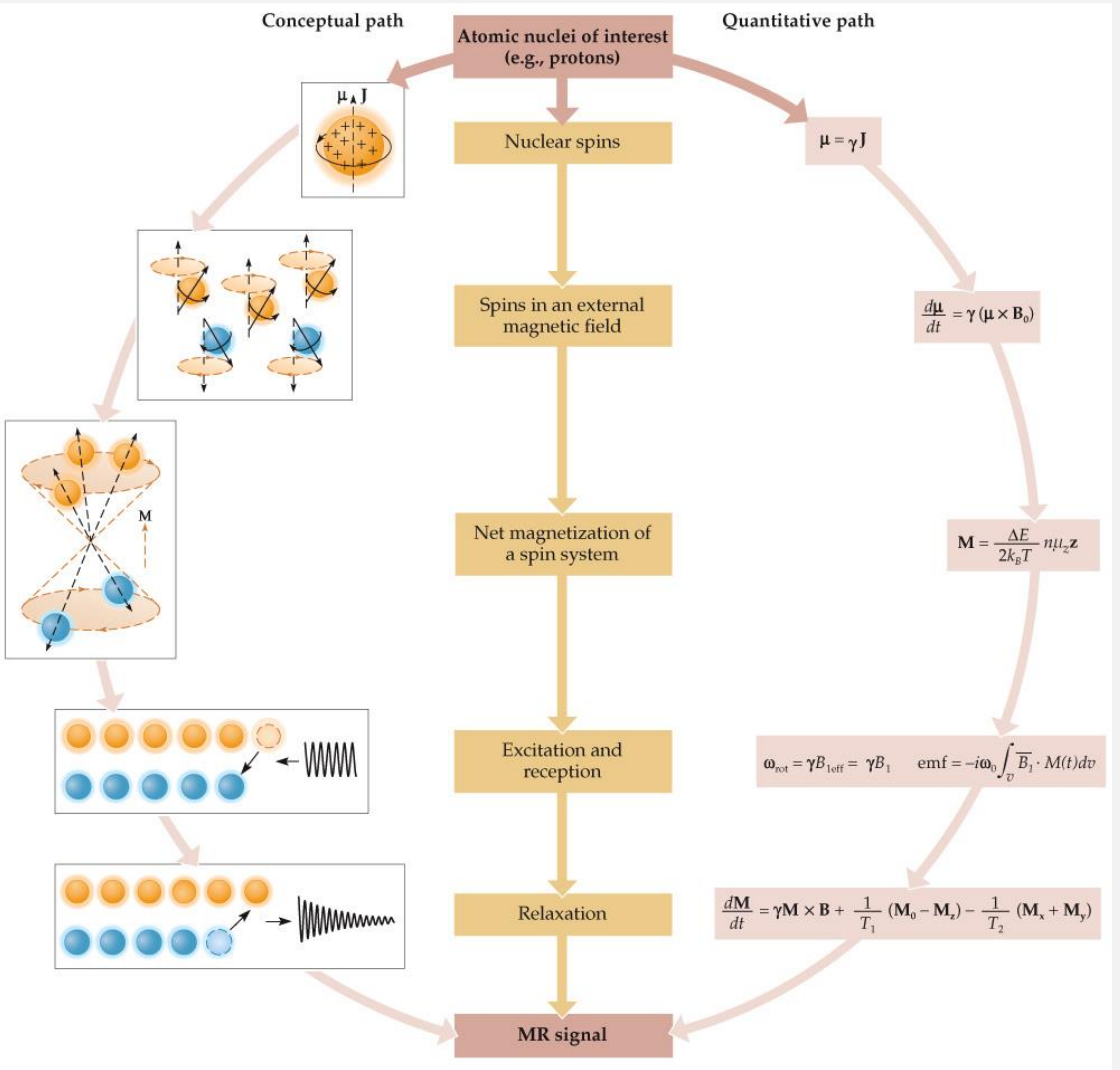
Spins and how they orient in a magnetic field (Ch. 3)

Principles of MR image formation(Ch. 4)

Relaxation processes and tissue contrast (Ch. 5)

Overview: Spins and how they orient in a magnetic field

- Conceptual path emphasizes the underlying principles using illustrative analogies

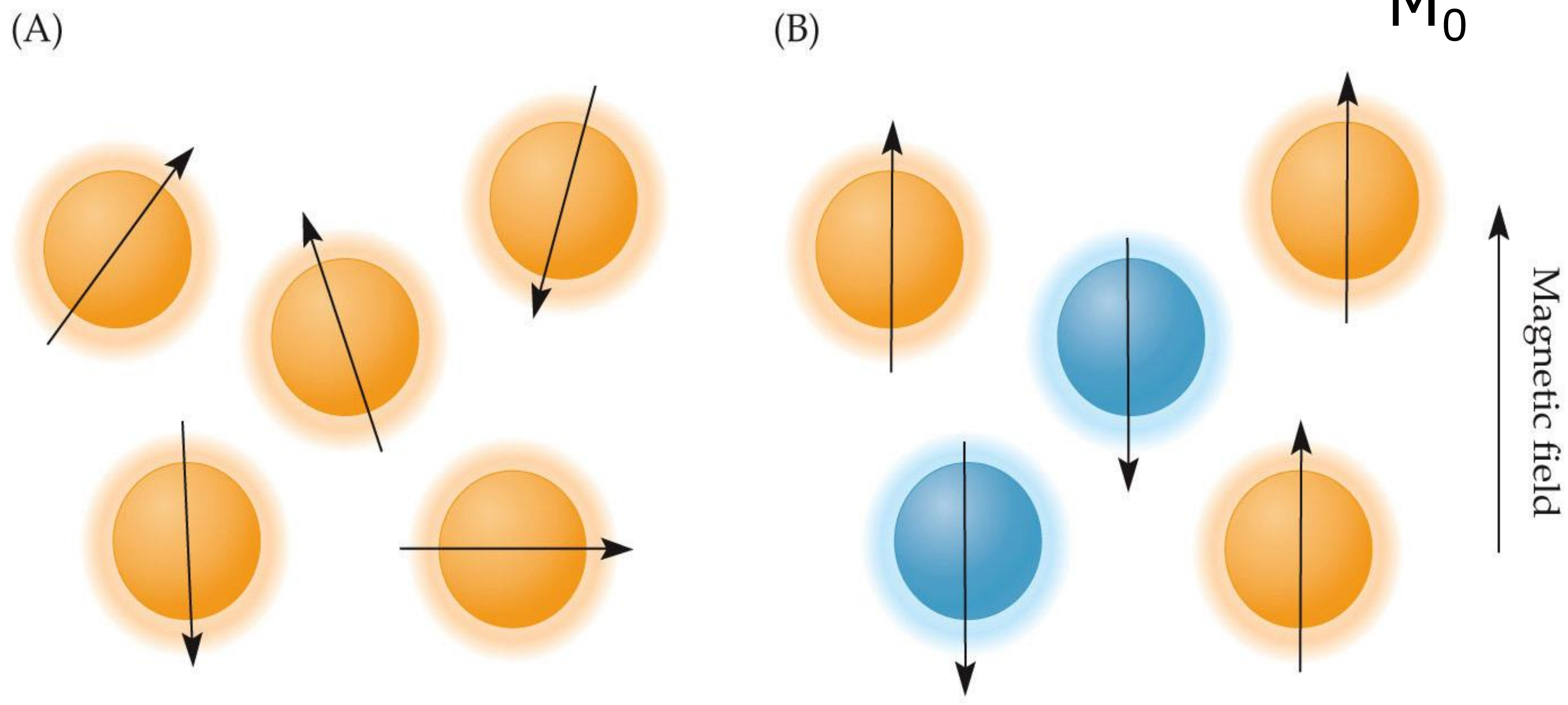


FUNCTIONAL MAGNETIC RESONANCE IMAGING 3e, Figure 3.1

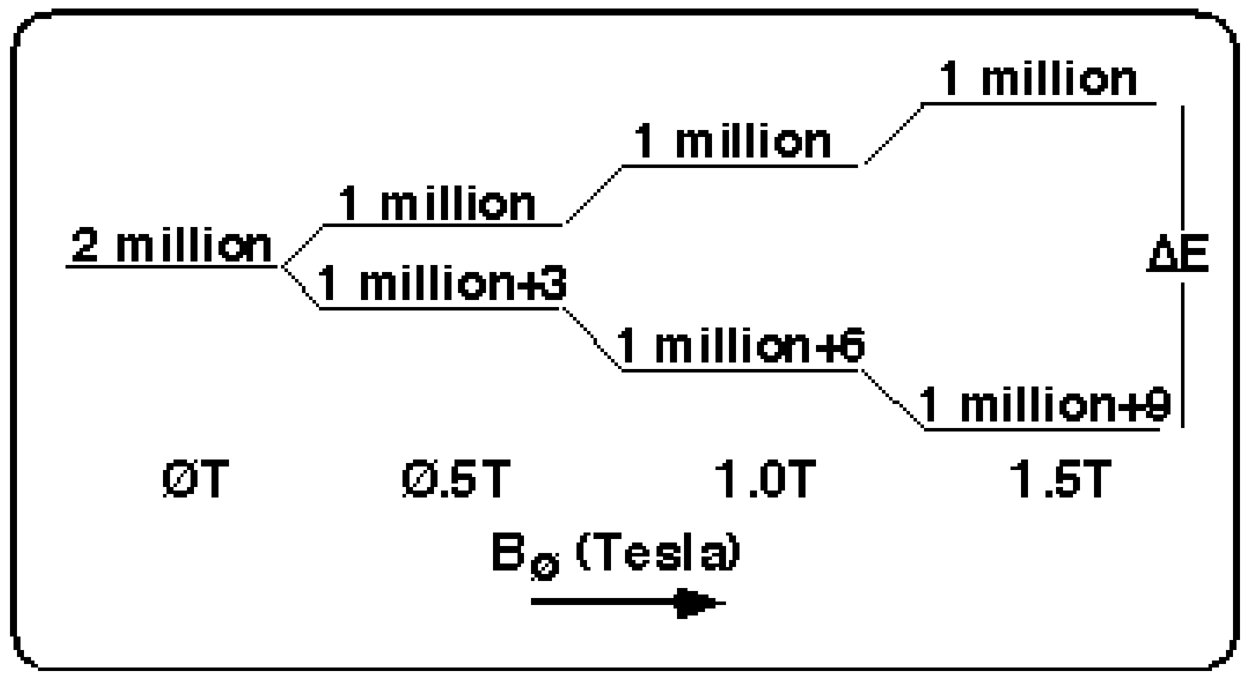
Nuclear spins in an external magnetic field

- ^{1}H nuclei (a single proton) is spinning on its axis inducing a *magnetic moment*
- In normal conditions no *net magnetization* (**M**) is present (*A*)
- In strong external magnetic field each proton's axis of spin tends to align either parallel or antiparallel to the magnetic field (*B*)
- Net magnetization (M_0) is introduced since more protons enter the parallel (low energy) state
- **Net magnetization is not measurable under equilibrium conditions ➔ the spin system must be perturbed**

M_0



FUNCTIONAL MAGNETIC RESONANCE IMAGING 3e, Figure 3.3



Energy is proportional to frequency..

$\Delta E = h\nu$

- X-rays: $\nu \approx 10^{19}$
- Ultra-violet: $\nu \approx 10^{16}$
- Visible Light: $\nu \approx 5 \times 10^{14}$
- Radio Waves: $\nu \approx 10^{7}$ (MRI)

http://simplyphysics.com/page2_2.html

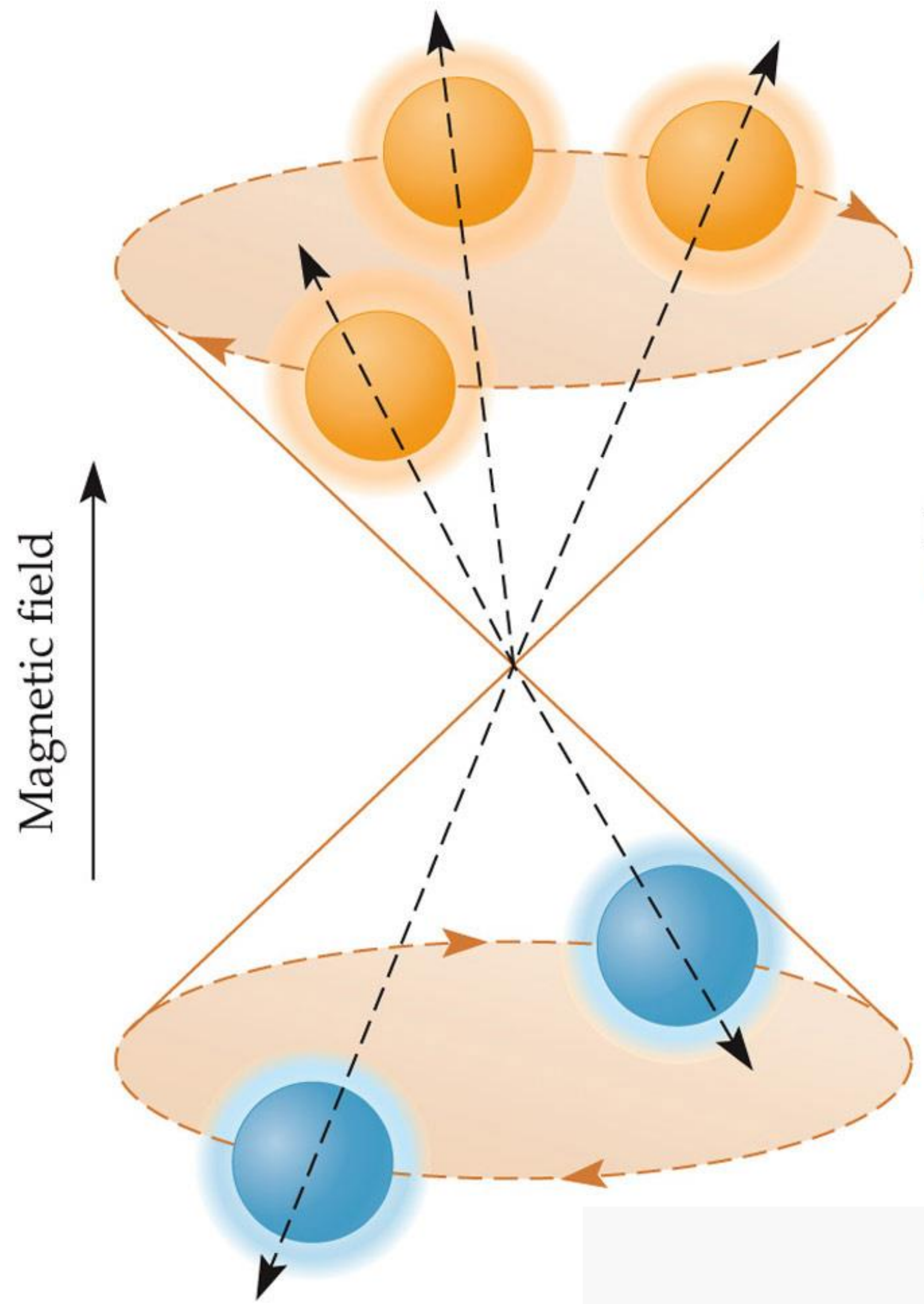
Magnetization of a Spin System

- Net magnetization has two components:
  - **Longitudinal** parallel to B_0
  - **Transverse** perpendicular to B_0 (cancel out at equilibrium)
- Net magnetization of a spin system **precesses** (c.f. spinning top) at the characteristic frequency of individual spins; the **Larmor** frequency (proton):

$$f = \frac{\gamma}{2\pi} B_0 \approx 43 \text{ MHz/T}$$

where γ is the gyromagnetic ratio unique to every atom.

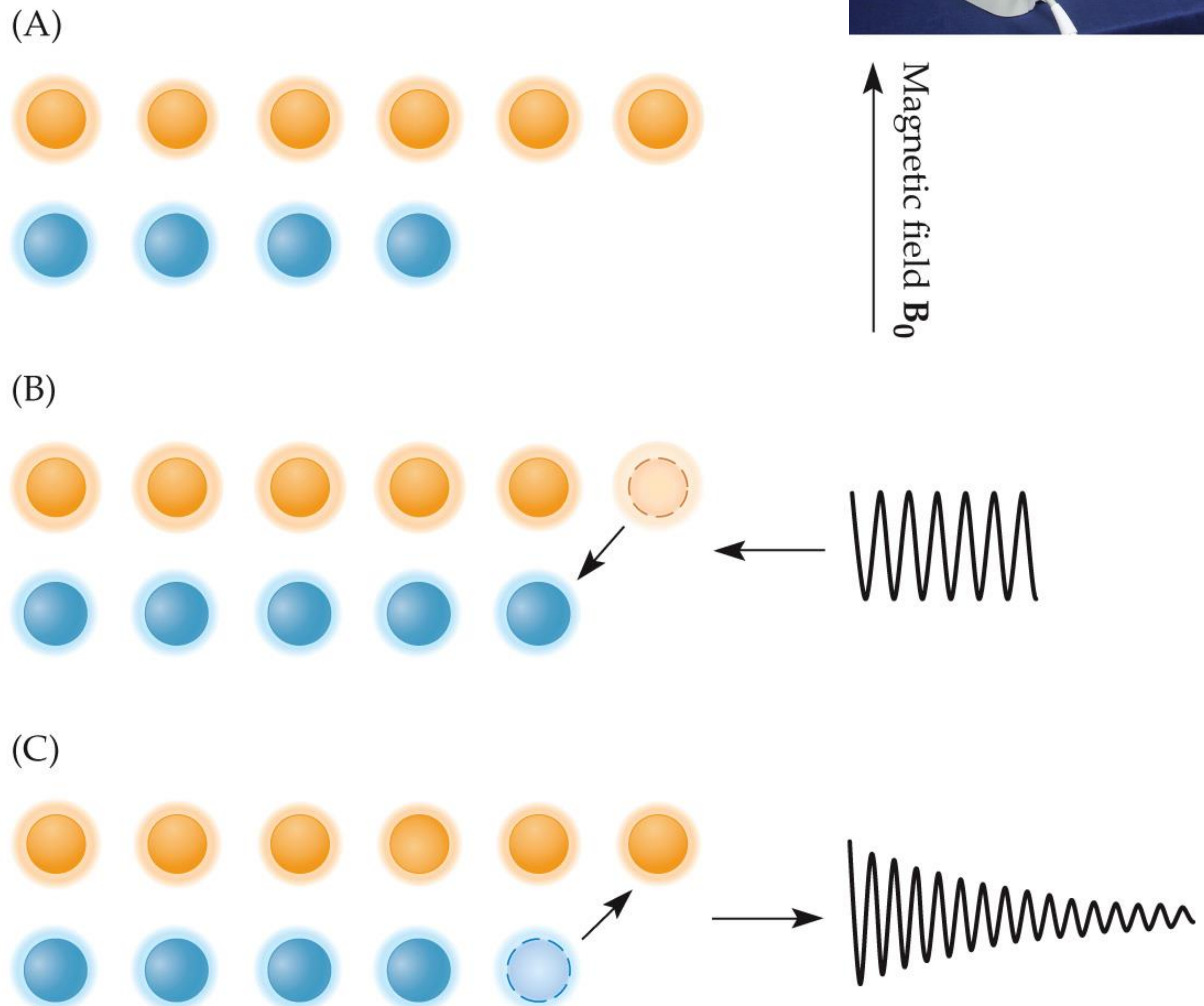
- Electromagnetic waves at **resonant frequency** interact with the spin system and **excites** some low-energy spins into high-energy state (c.f. giving push to a swing set)



FUNCTIONAL MAGNETIC RESONANCE IMAGING 3e, Figure 3.8

Excitation of a Spin System and Signal Reception

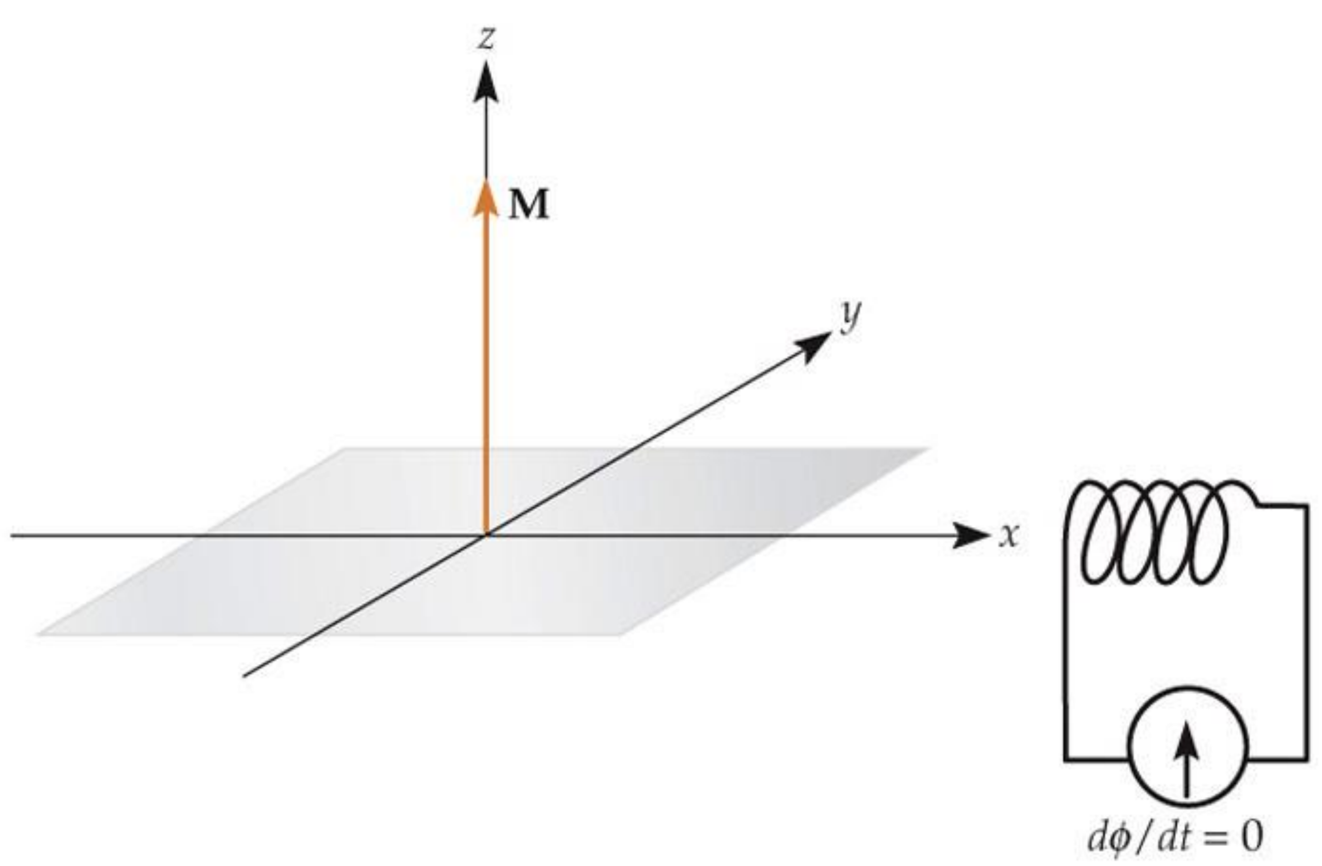
- In magnetic field (B_0) more spins will be at low energy state (orange; A)
- If electromagnetic pulse wave is transmitted at resonant frequency some spins will absorb the energy and jump to the high-energy state (blue; B)
- After stopping the excitation pulse some high-energy spins will release the absorbed energy as a radiofrequency wave with the same frequency as the excitation pulse (C)

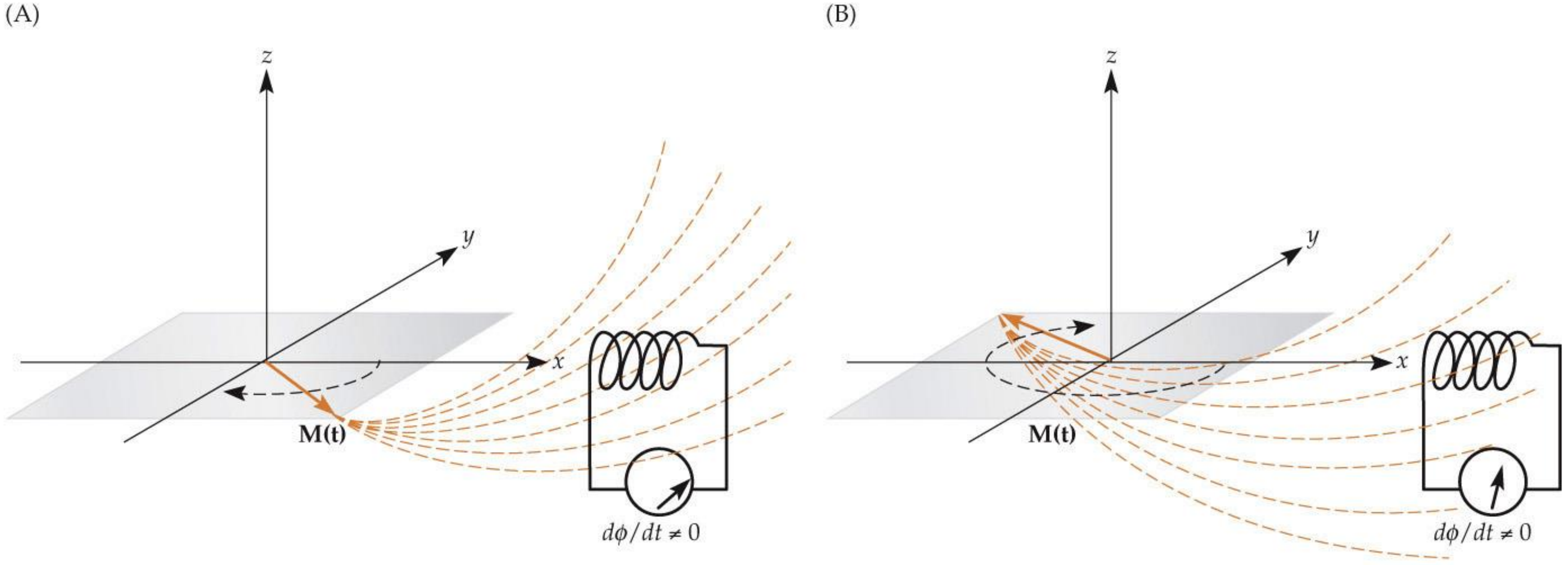


FUNCTIONAL MAGNETIC RESONANCE IMAGING 3e, Figure 3.10

Excitation of a Spin System and Signal Reception

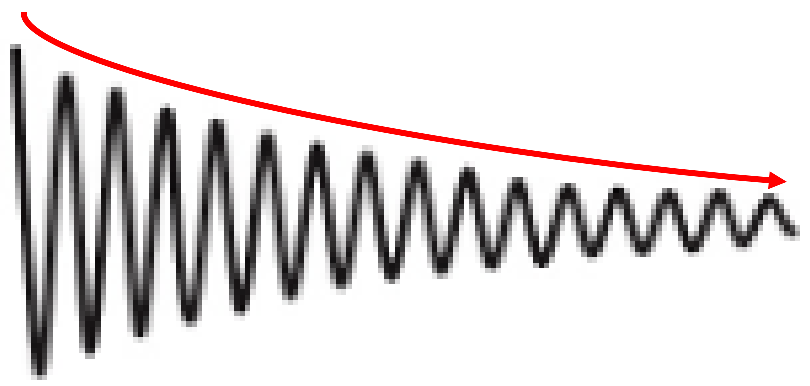
- The change in net magnetization from the longitudinal axis to the transverse plane (excitation) is critical for the **reception** of the MR signal
- When the net magnetization is along the long axis no ***electromotive*** force is detected (A, top)
- When the net magnetization precesses along the transverse plane (bottom, A-B) electromotive force, oscillating at the Larmor frequency is detected



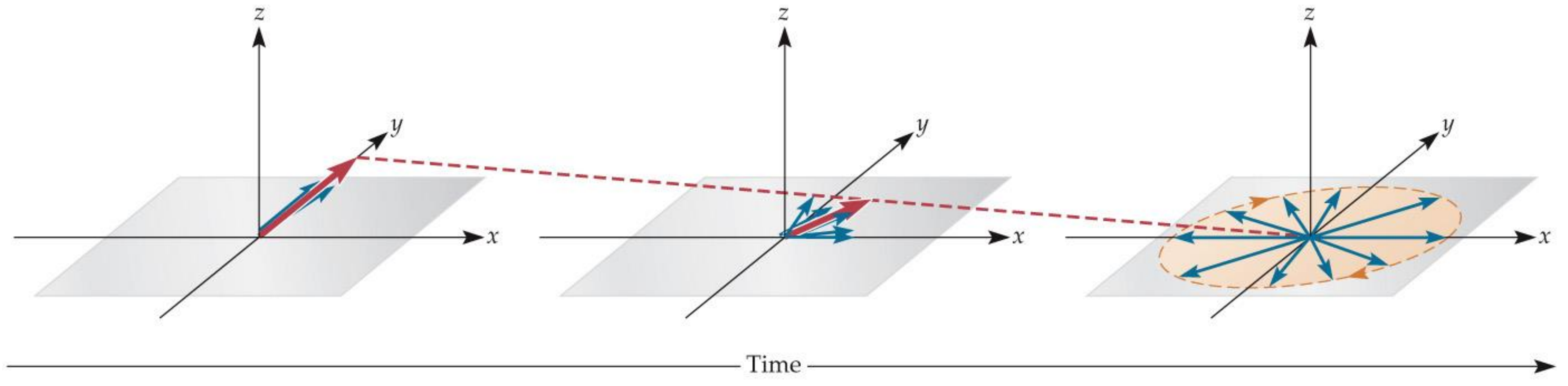


FUNCTIONAL MAGNETIC RESONANCE IMAGING 3e, Figure 3.19

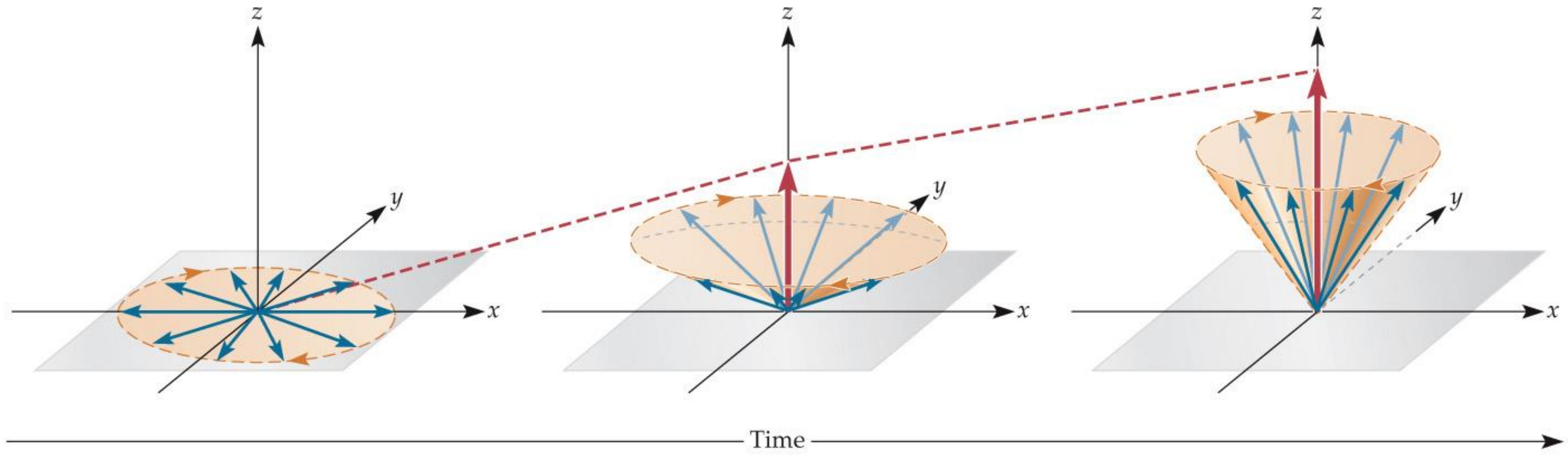
Relaxation mechanisms of the MR signal



- An excited spin system exhibits relaxation (decrease of signal amplitude) in two ways
  - **Transverse** magnetization <u>quickly</u> decays due to the loss of phase coherence of the spins (Top); the time constant of transverse decay (specific to each tissue) is called T_2
  - **Longitudinal** magnetization recovers (Bottom); the time constant is called T_1 (typically an order of magnitude longer than T_2)



FUNCTIONAL MAGNETIC RESONANCE IMAGING 3e, Figure 3.11



FUNCTIONAL MAGNETIC RESONANCE IMAGING 3e, Figure 3.12

Relaxation times and contrast

- Detectable MR signal (transverse magnetization) is governed by:

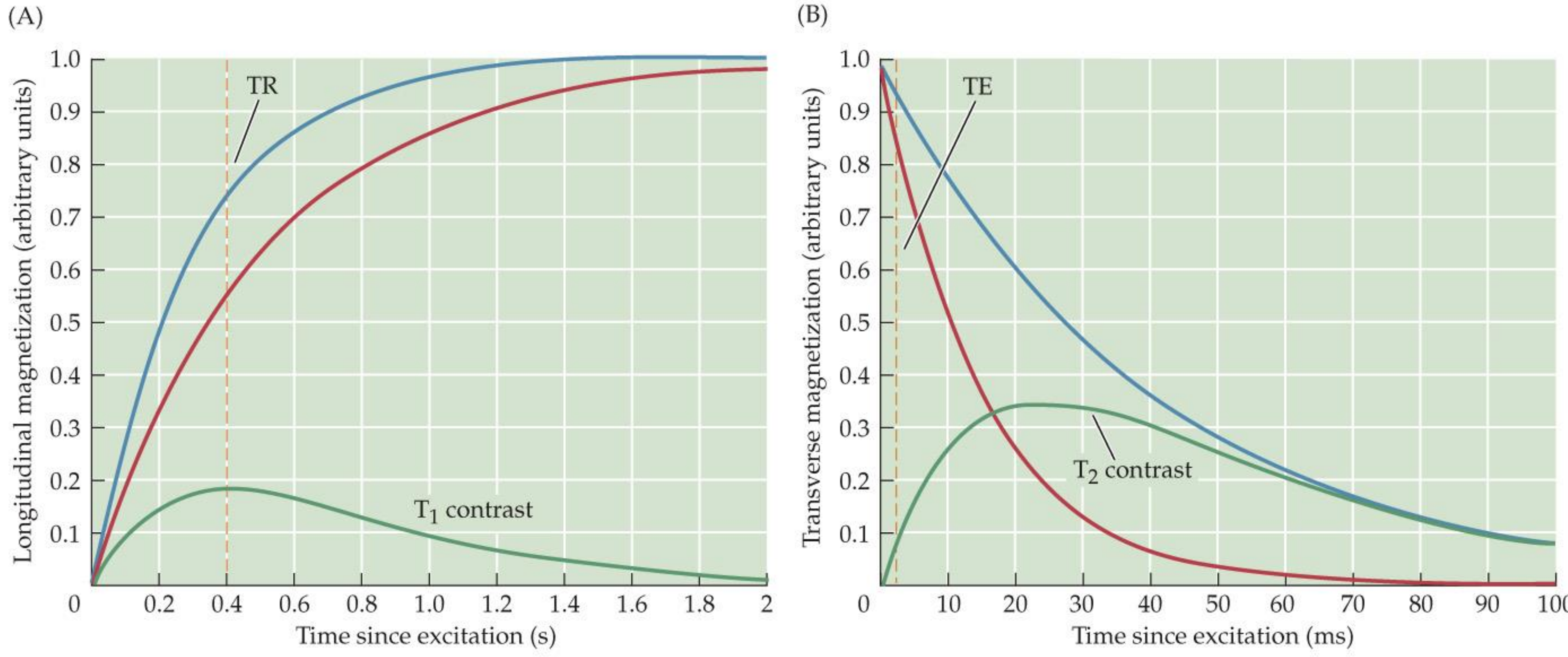
$$M_{xy}(TE) = M_0\left(1 - e^{-TR/T_1}\right)e^{-TE/T_2}, where\ TR = rep.time, TE = echo\ time$$

- For maximally T_2 weighted imaging
  1. Minimize T_1 dependent component: long TR
  2. Maximize T_2 dependent component: intermediate TE
- For maximally T_1 weighted imaging
  1. Minimize T_2 dependent component: TE🡐0
  2. Maximize T_1 dependent component: intermediate TR

Table 5.1 Rough Values for the Time Constants T_1 and T_2 at a Field Strength of 3 T

	Gray Matter	White Matter
T_1	1400 ms	1100 ms
T_2	70 ms	55 ms

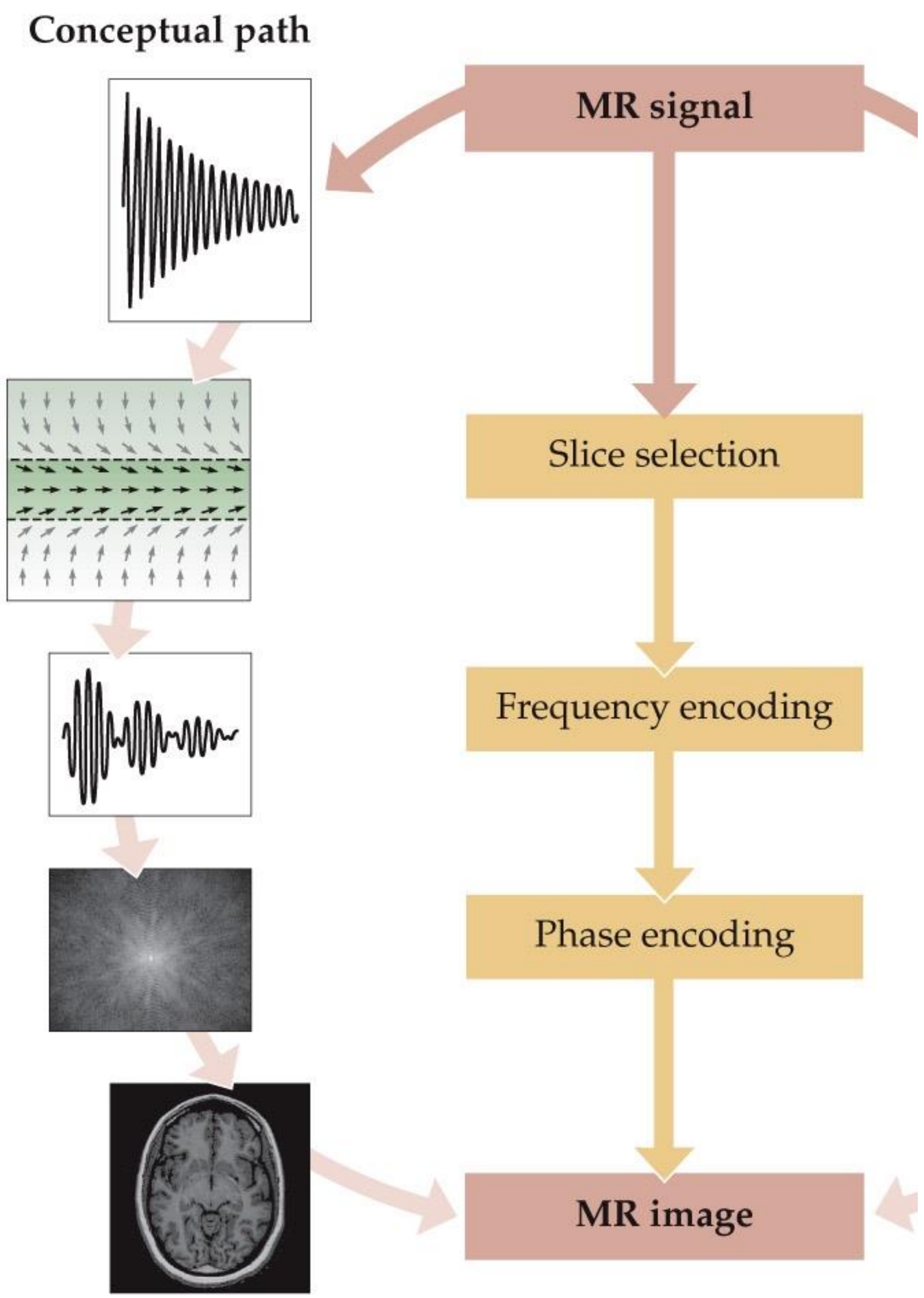
FUNCTIONAL MAGNETIC RESONANCE IMAGING 3e, Table 5.1



FUNCTIONAL MAGNETIC RESONANCE IMAGING 3e, Figure 5.5

Overview: Principles of MR image formation

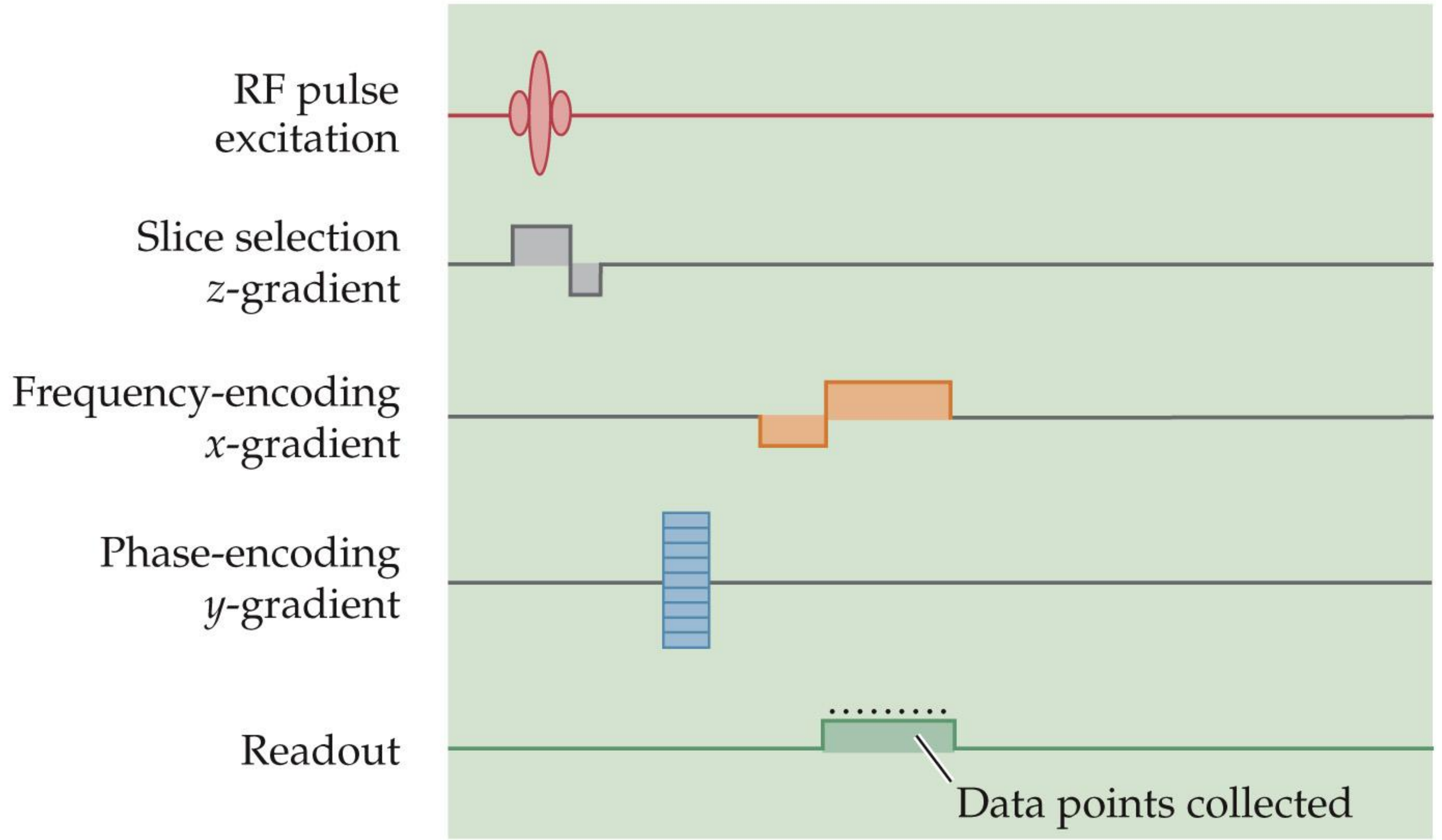
- Precisely controlled spatial variation in the magnetic field allows localization of the MR signal
  - **Gradient** coils are used to introduce variation
  - **Precession** frequency is proportional to magnetic field strength (Larmor equation) resulting in frequency differences in emitted MR signal
- All fMRI studies stack 2D **slices** (slabs) to represent 3D volumes of the brain



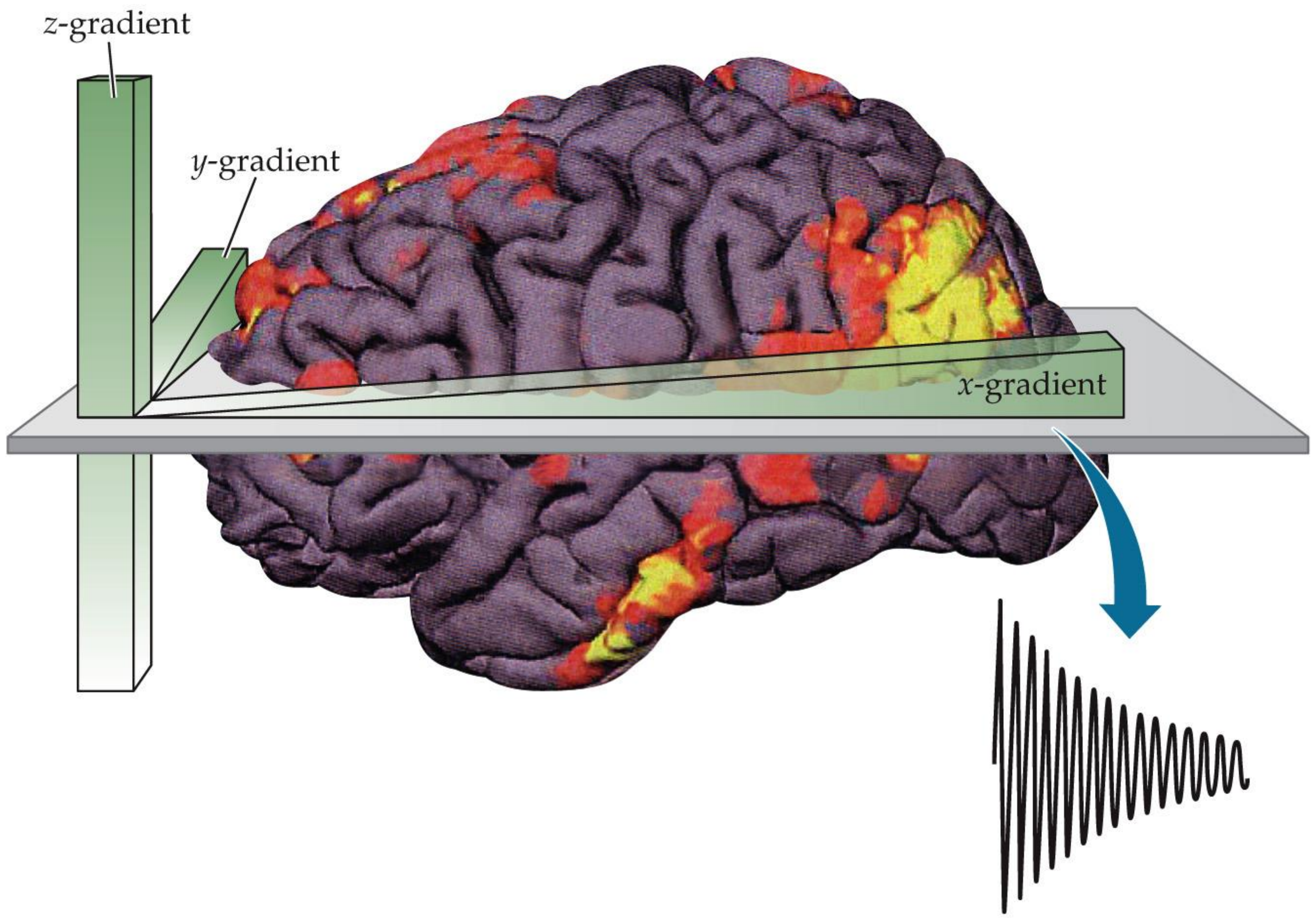
FUNCTIONAL MAGNETIC RESONANCE IMAGING 3e, Figure 4.1

Slice selection and frequency and phase encoding

- In slice selection a (on-frequency) RF pulse and z-gradient is given simultaneously to excite spins within a specific slice
- Frequency encoding involves an x-gradient that changes precession frequencies over space
- Phase encoding involves an y-gradient that generates differential phase offsets over space
- **Note**: Using the present pulse sequence (top), 256 excitations are needed to collect an image with 256 x 256 resolution (one row of data in the x-direction is collected for each excitation, c.f. filling of k-space)



FUNCTIONAL MAGNETIC RESONANCE IMAGING 3e, Figure 4.7



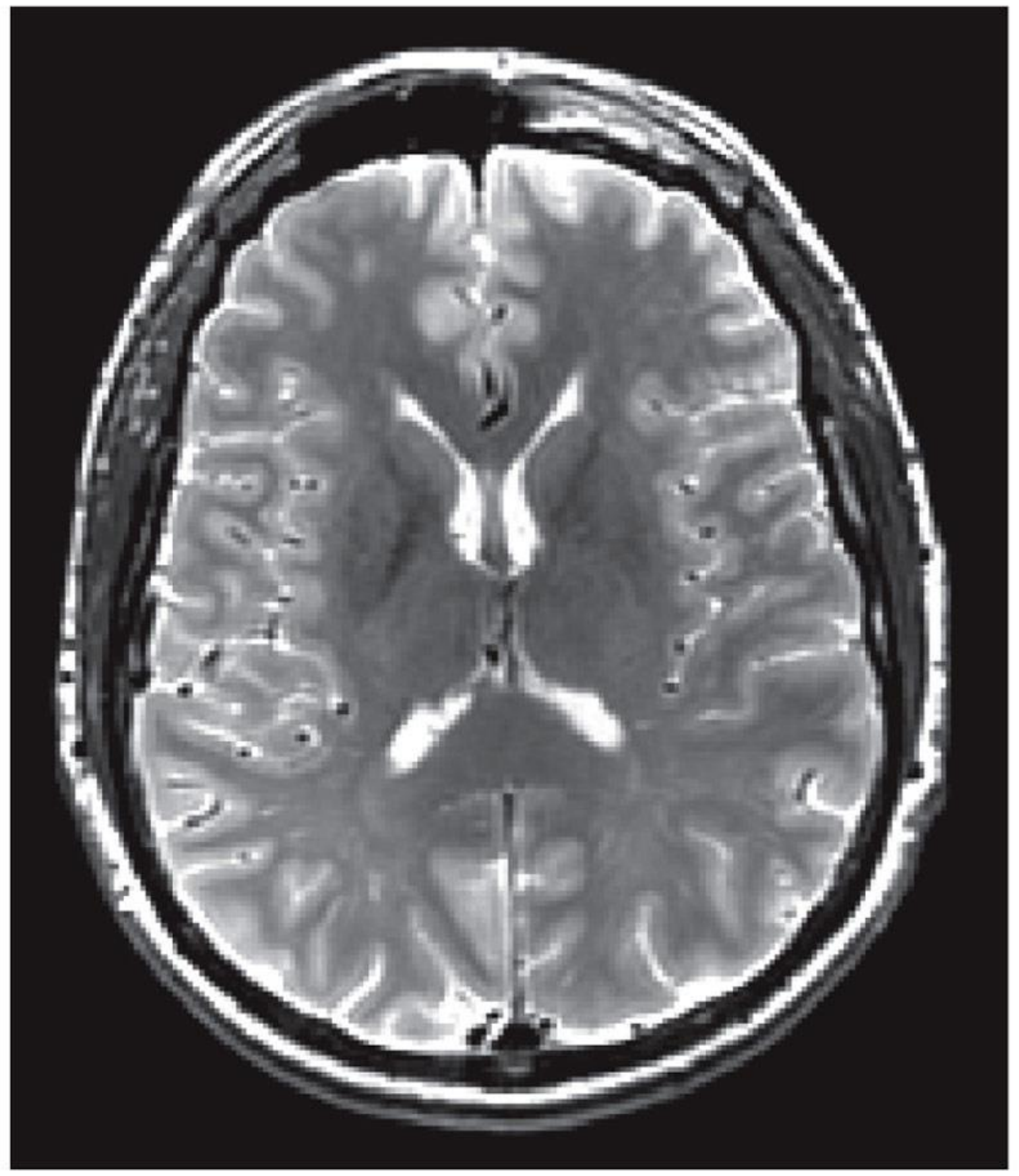
FUNCTIONAL MAGNETIC RESONANCE IMAGING 3e, Figure 4.8

Tissue contrast

- Imaging contrast is the intensity difference between different quantities in the image
- MR scanners can collect images of a wide range of contrasts
  - Proton density
  - Different tissues have different relaxation times: T_1, T_2
- The image contrast depends on the time interval between excitations (repetition time, TR) and time interval between excitation and data acquitision (echo time, TE)

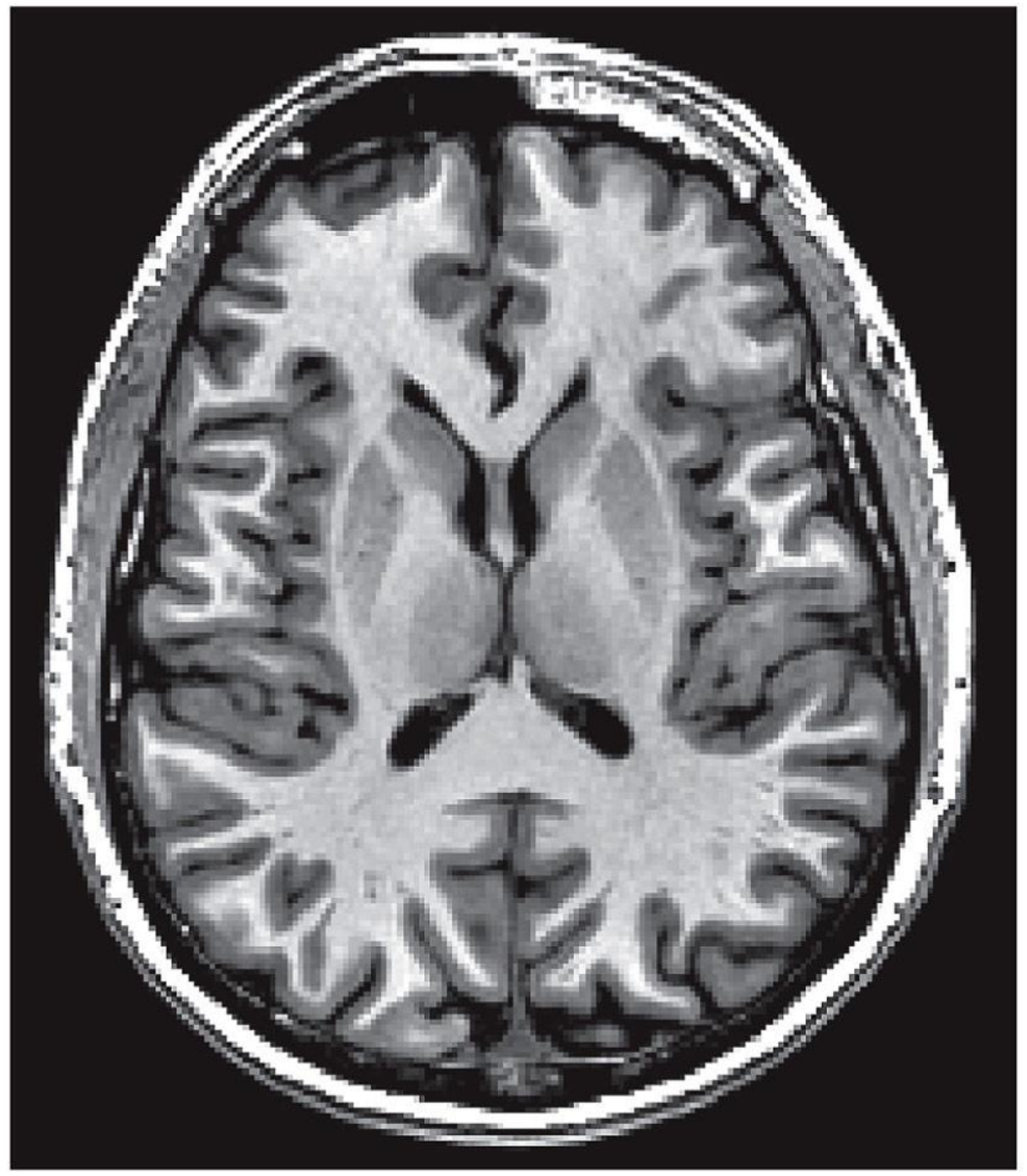
(B)

T_2



(B)

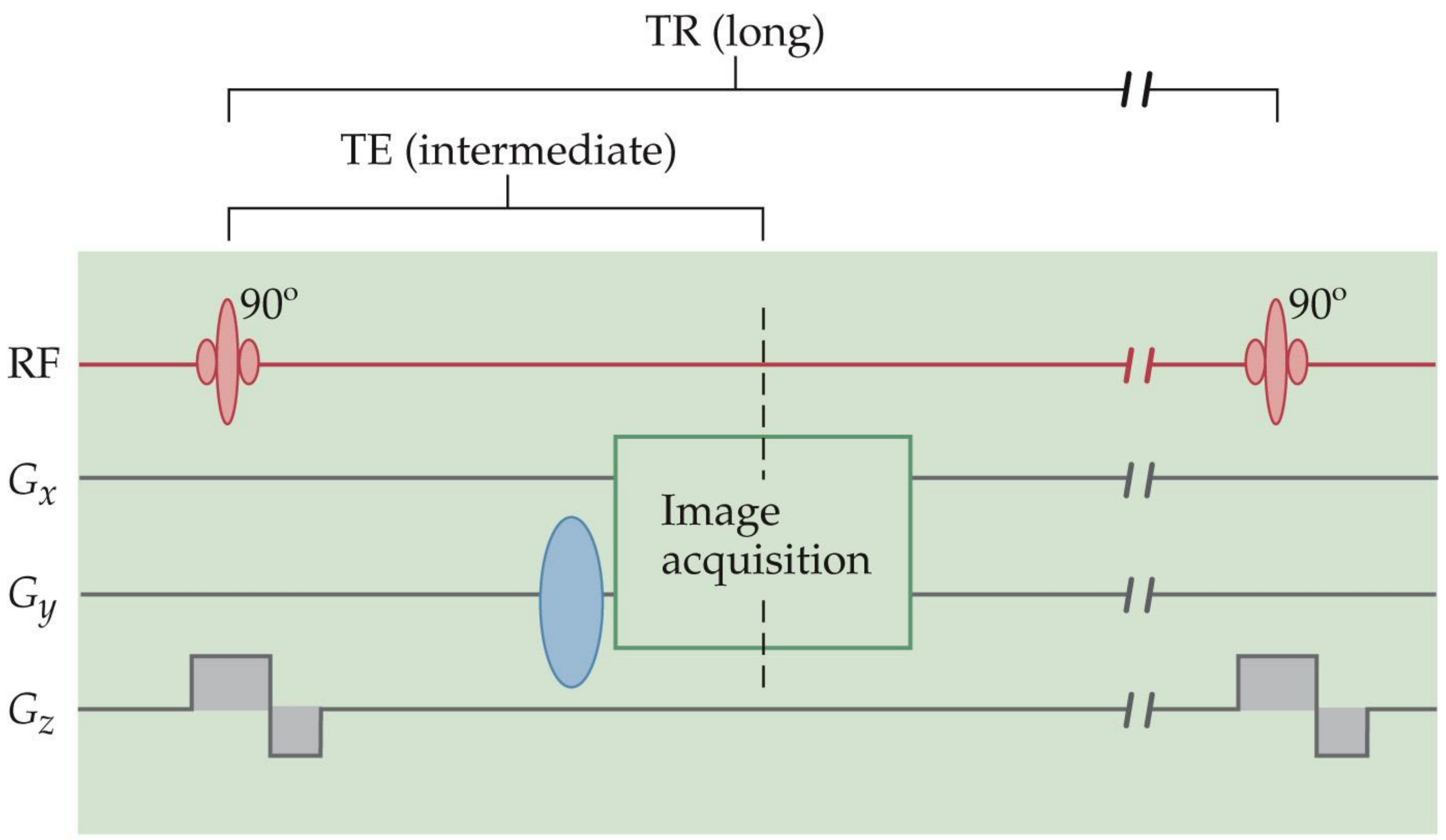
T_1



FUNCTIONAL MAGNETIC RESONANCE IMAGING 3e, Figure 5.6 (Part 2)

T_2*-weighted contrast

- Transverse relaxation depends on
  - spin-spin interactions (T_2)
  - local magnetic field inhomogeneities
- T_2* is a sum of both and sensitive to the deoxygenated hemoglobin ➔ T_2* decay is always faster than T_2
- Instead of spin echo, a gradient echo sequence is typically applied to **retain sensitivity to inhomogeneities**



FUNCTIONAL MAGNETIC RESONANCE IMAGING 3e, Figure 5.11
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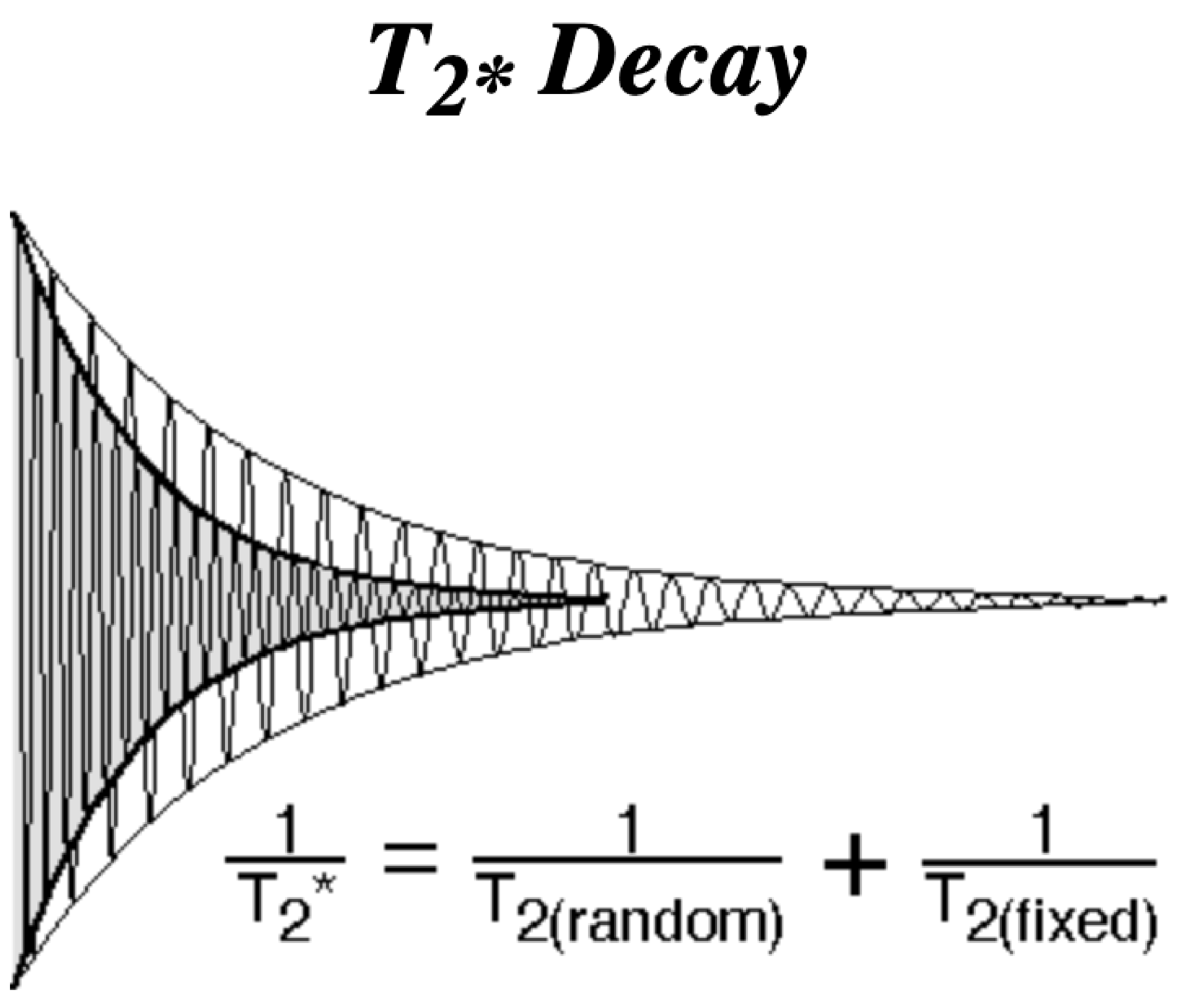
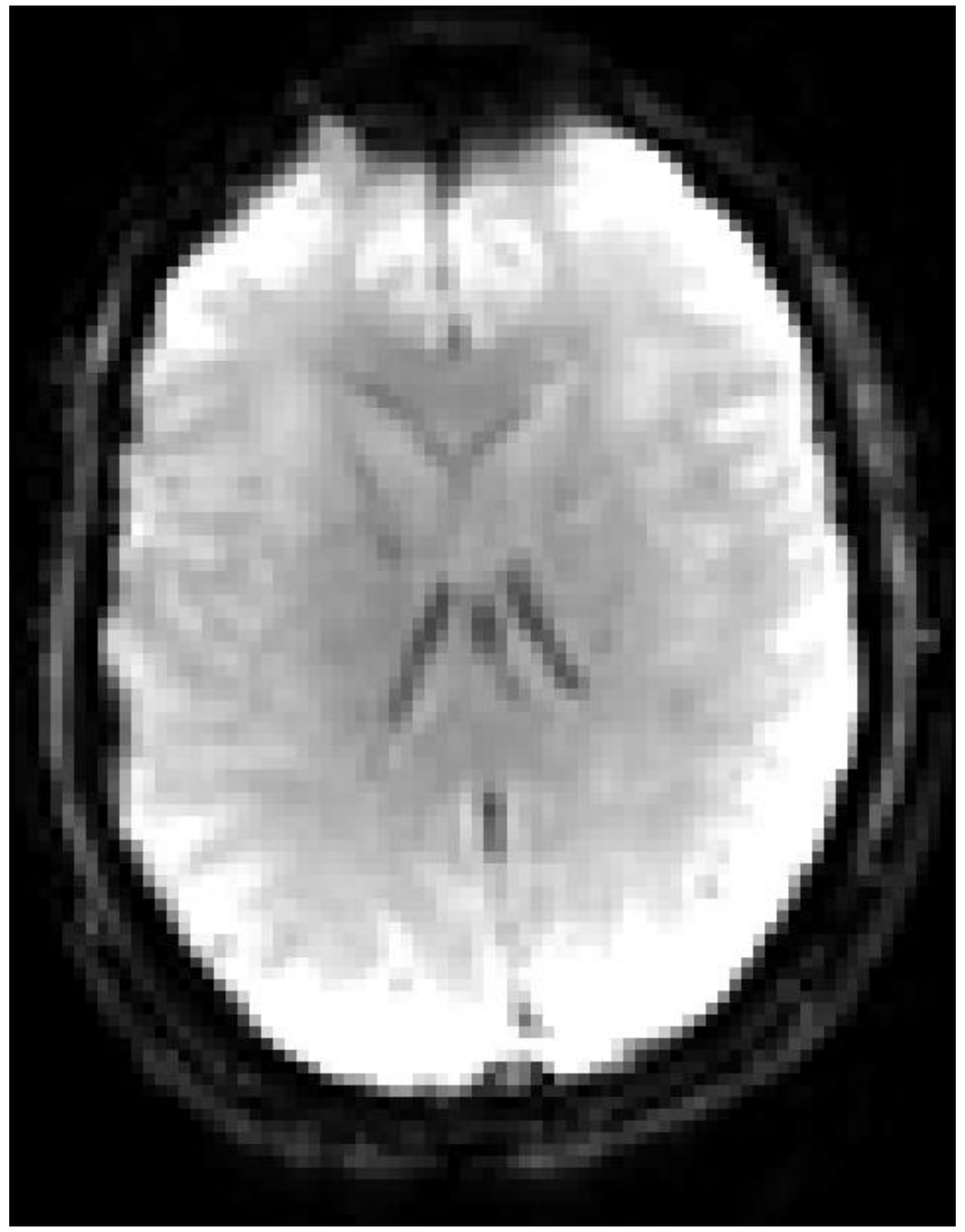




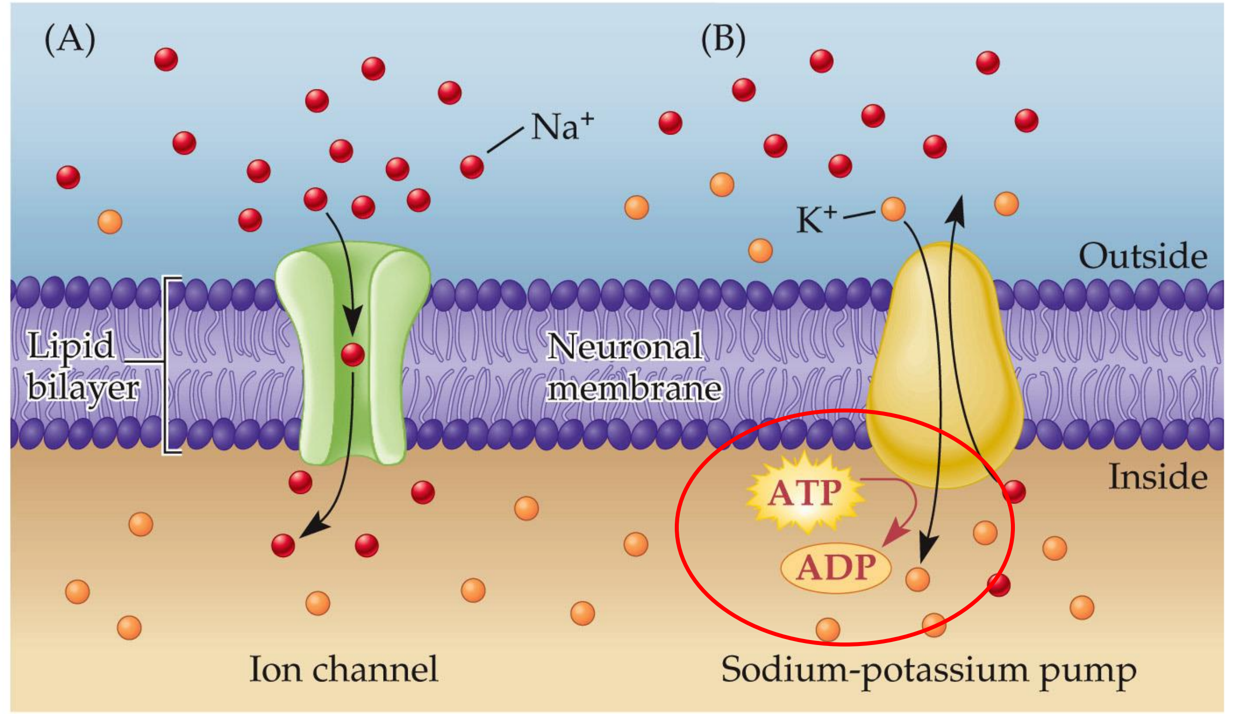
Physiological background of fMRI

Part III

Neurovascular coupling and the hemodynamic response function (Ch. 6 – 7)

From neuronal to hemodynamic activity

- Majority of brain's energy budget goes to **restoration of concentration gradients** following action potentials and postsynaptic potentials
- Increased neural activity is associated with increased metabolic demands
- The vascular system is responsible of delivery of glucose and oxygen



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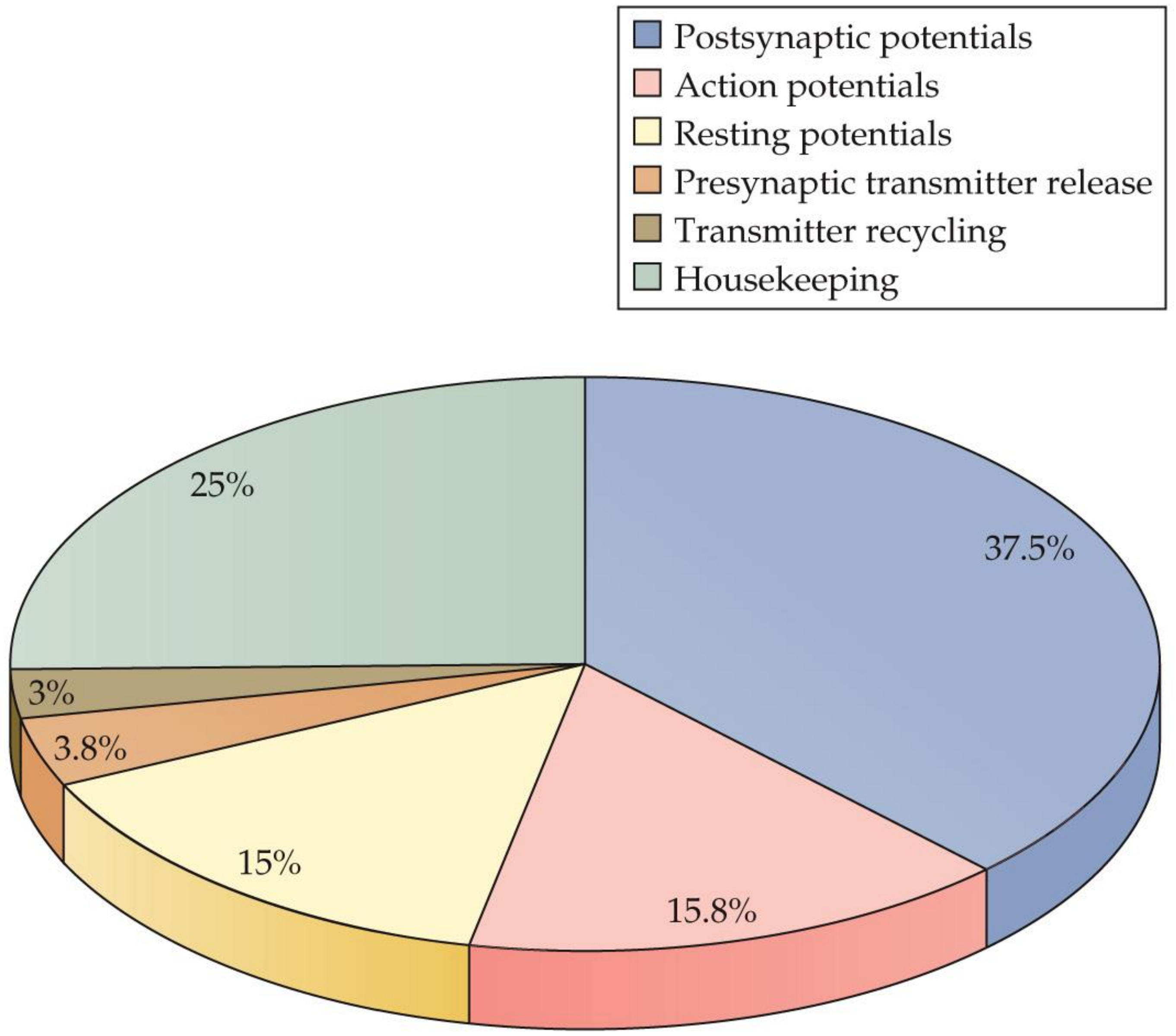

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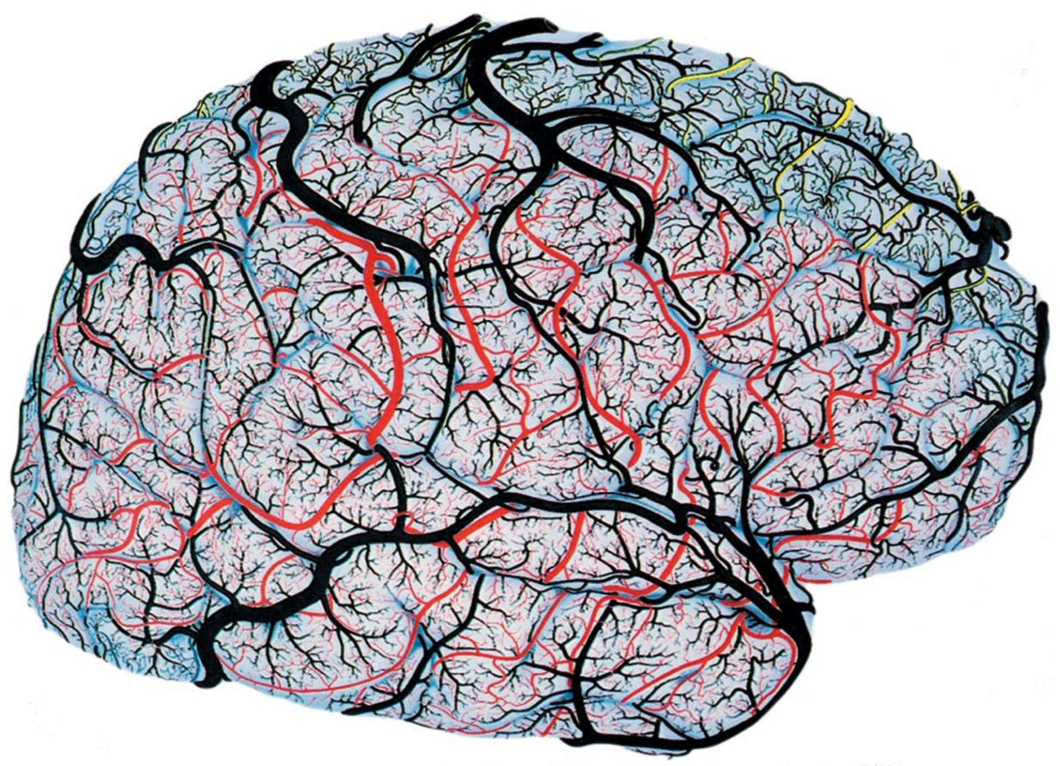

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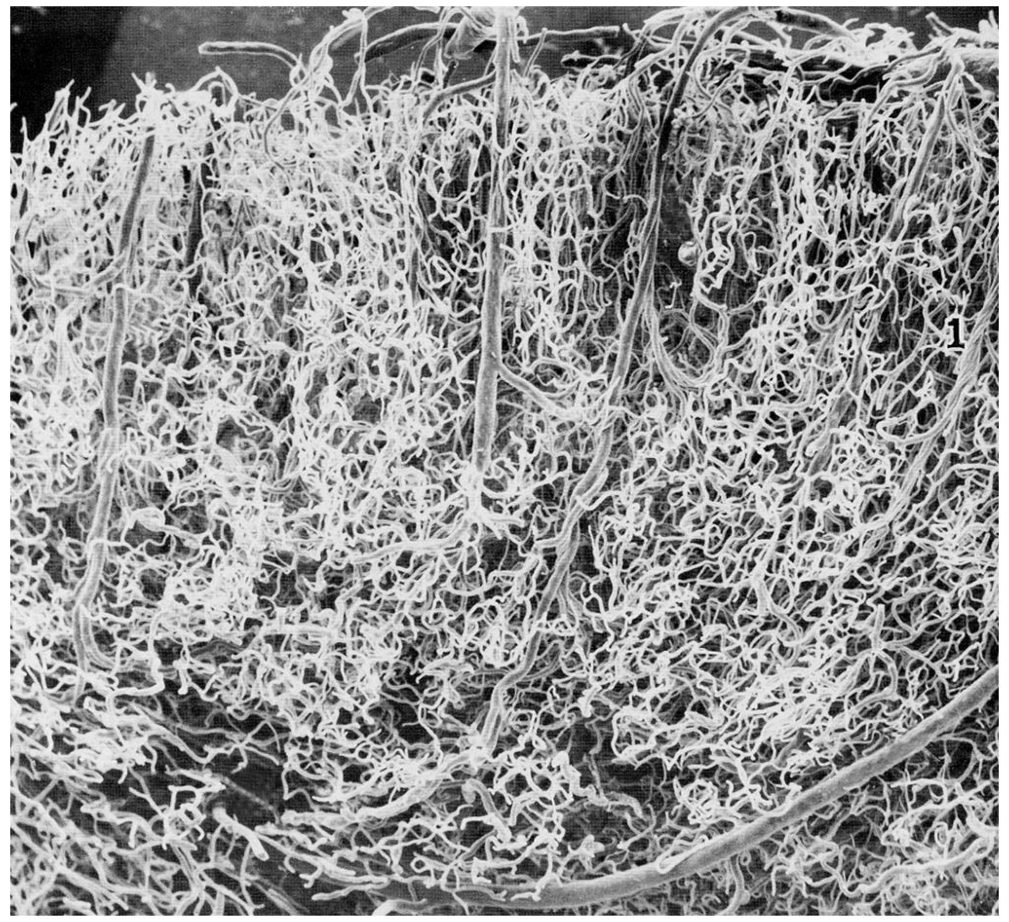

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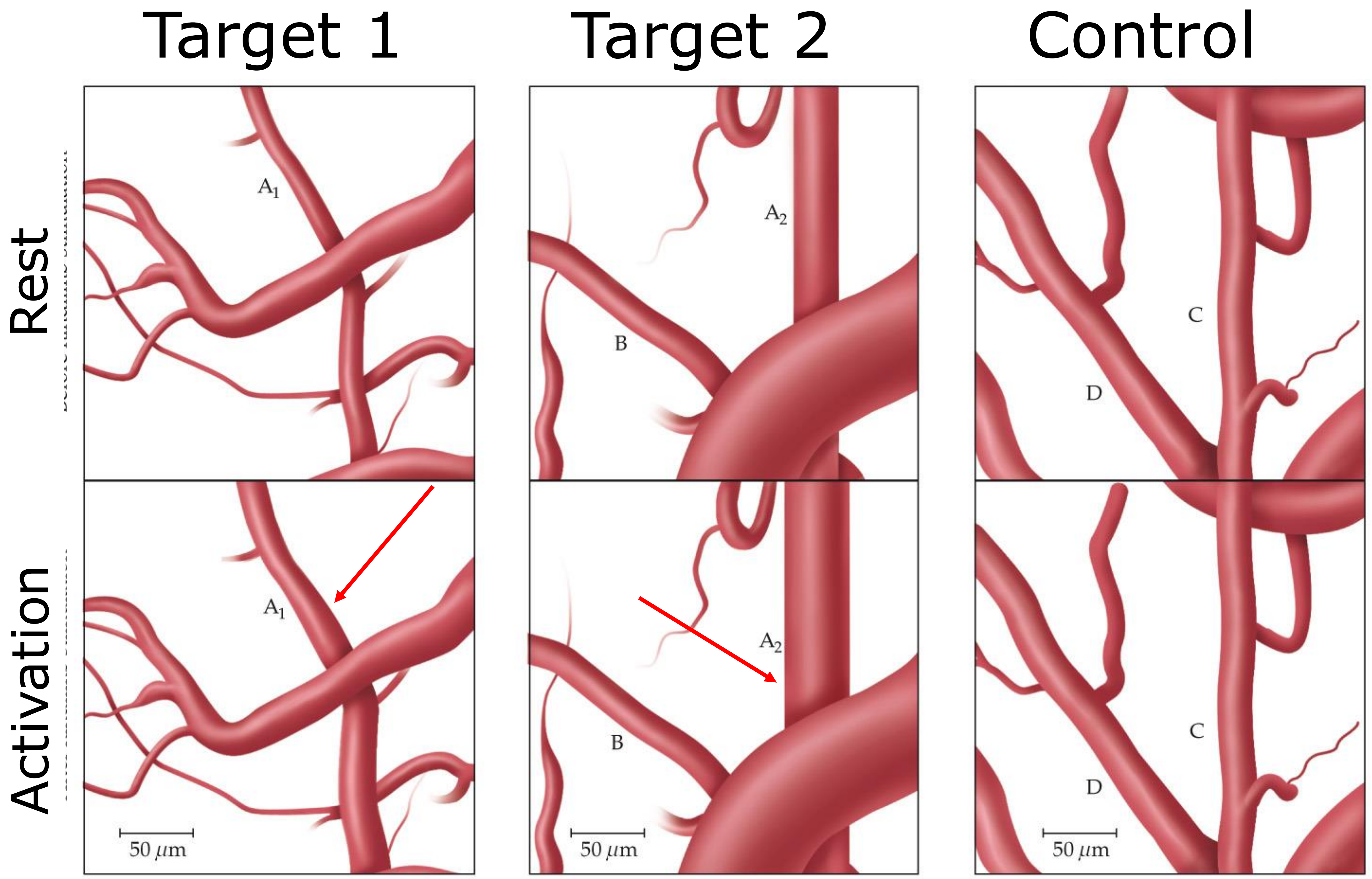
Neurovascular coupling

- Local activation associates with localized vasodilatory response
- Vasodilation results in increased perfusion through increased blood flow and blood volume
- Neurovascular unit: neuronal processes may influence vascular tone directly or indirectly through astrocytes
- Functional hyperemia: local increase in blood flow in response to stimulation



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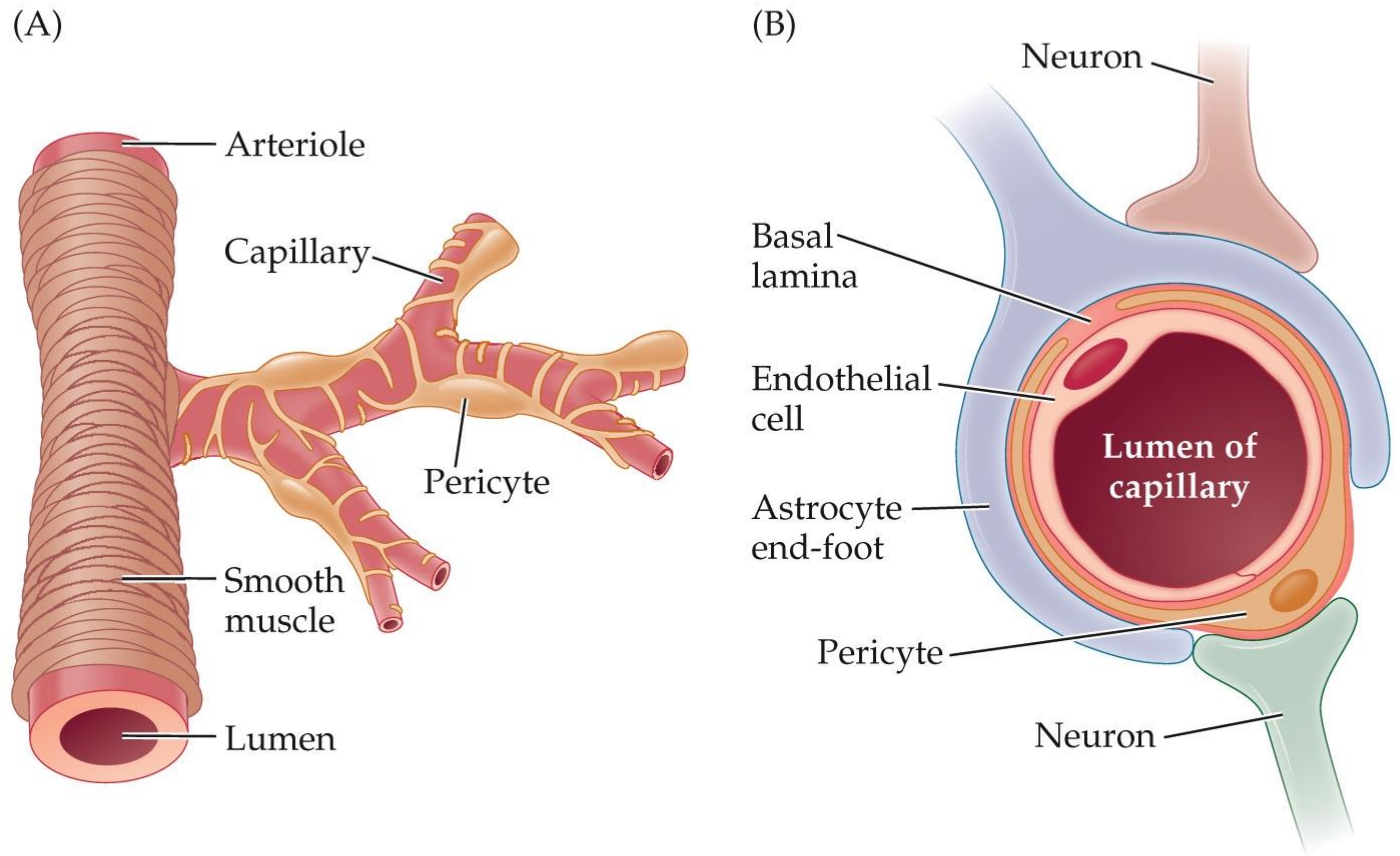
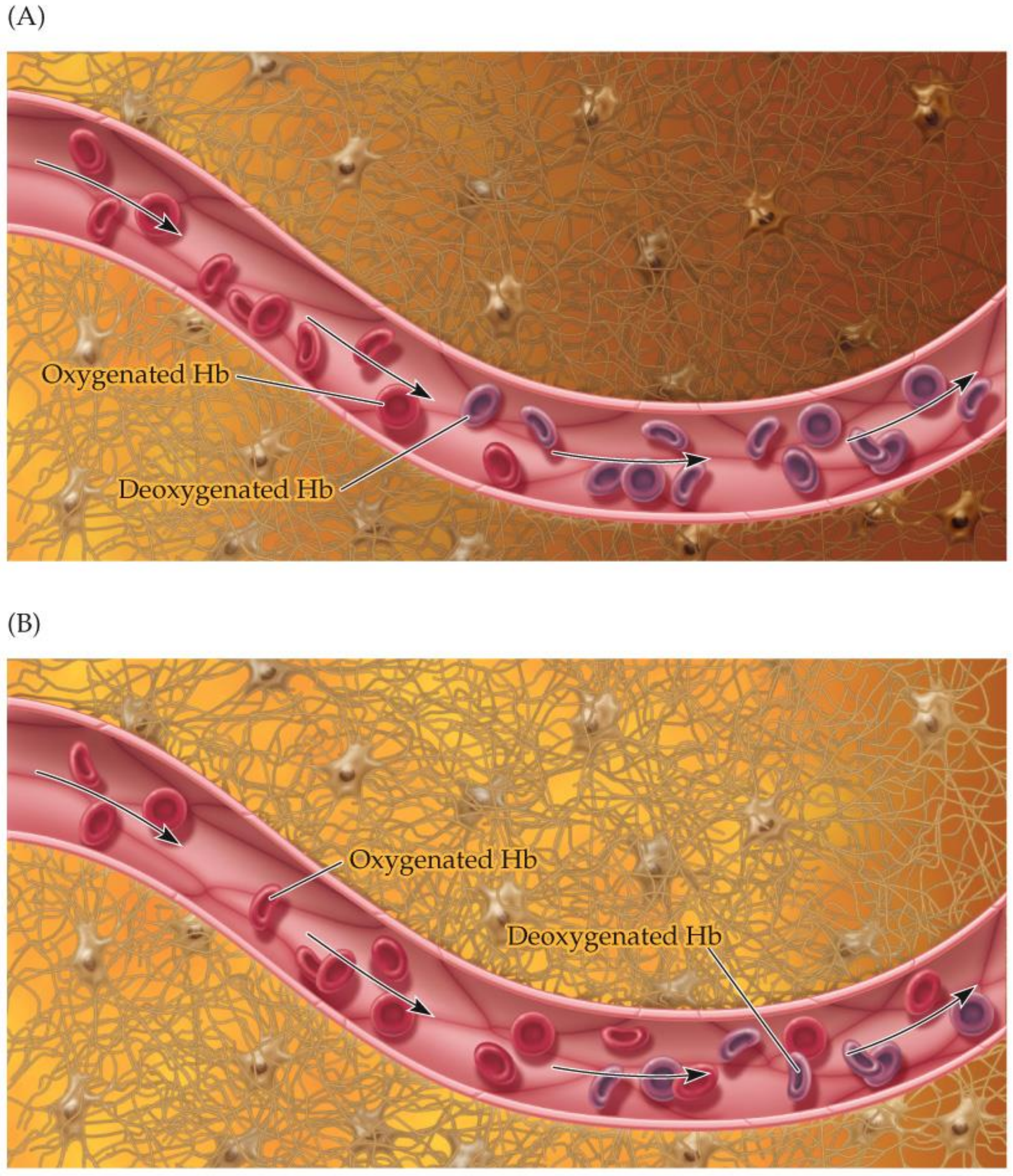


Balance between oxygenated and deoxygenated hemoglobin

- Increased blood flow (e.g. due to neural activity) is associated with decreased concentration of deoxygenated hemoglobin (Hb)
- Deoxygenated Hb is ***paramagnetic*** and has therefore suppressing influence on T_2* weighted MR signal
- More oxygenated Hb is hence expected to result in higher T_2* signal

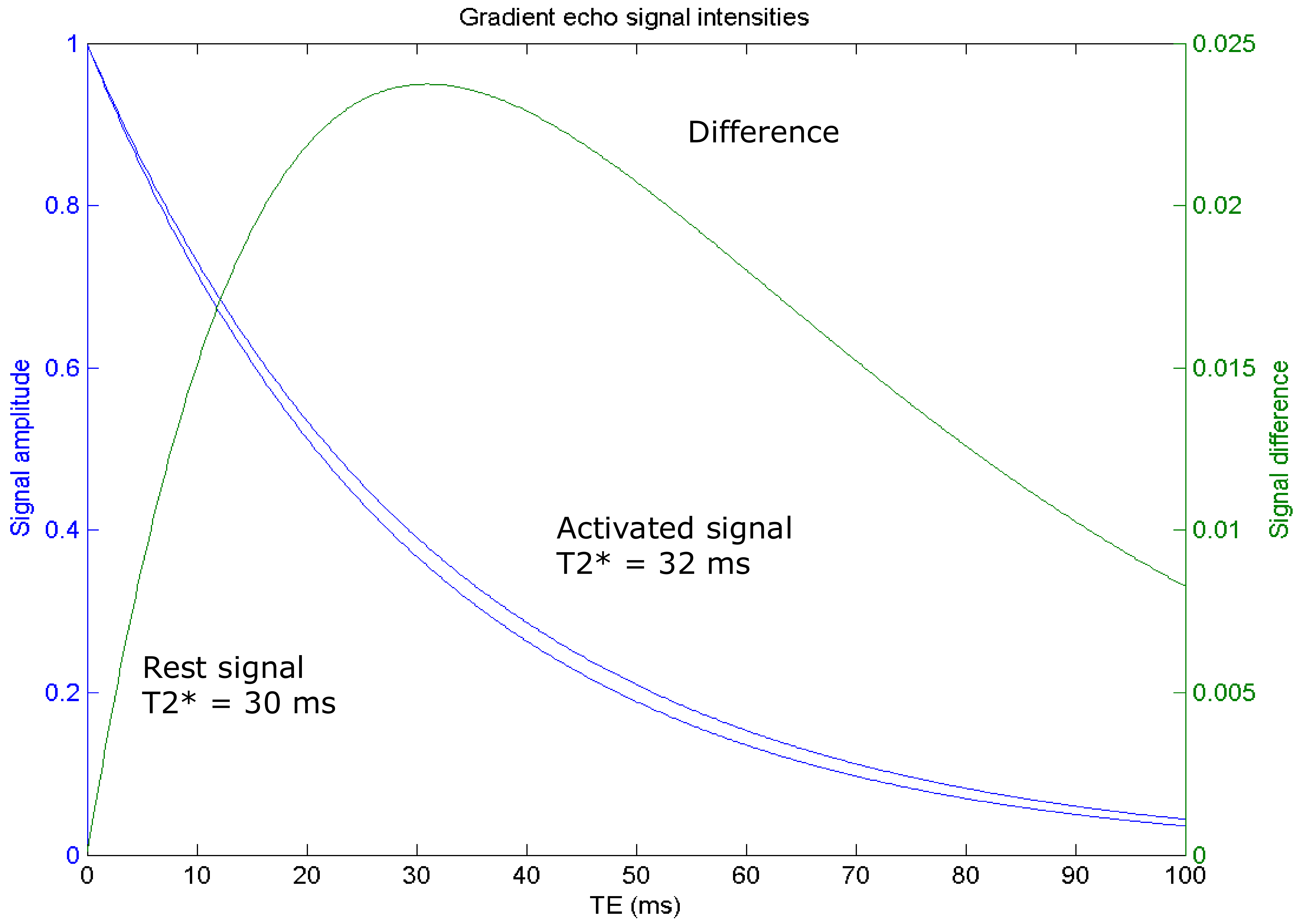
Arterial blood



Venous blood

FUNCTIONAL MAGNETIC RESONANCE IMAGING 3e, Figure 7.4

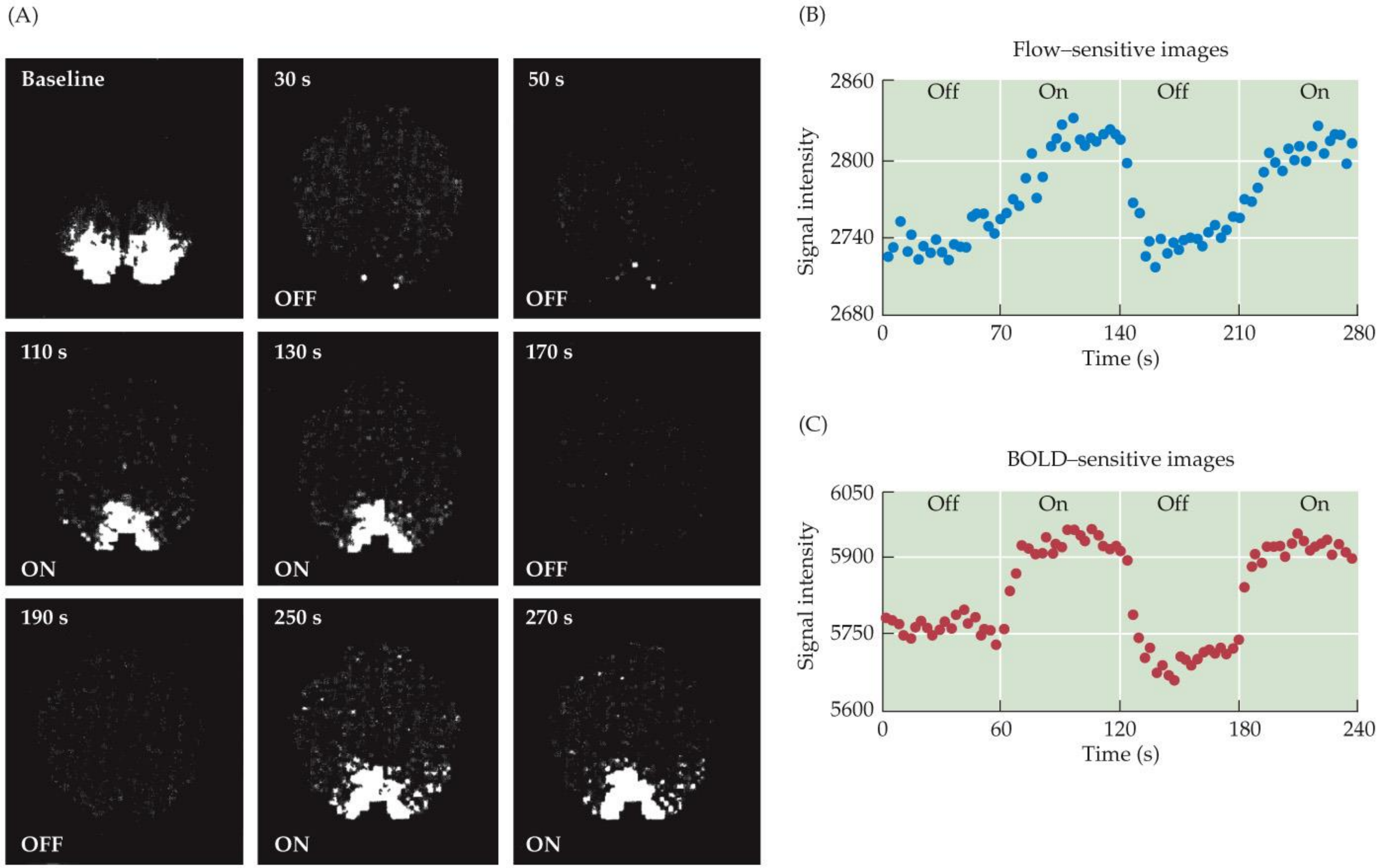
Blood-Oxygenation-Level Dependent (BOLD) signal



Greger Orädd

BOLD signal in blocked visual stimulation

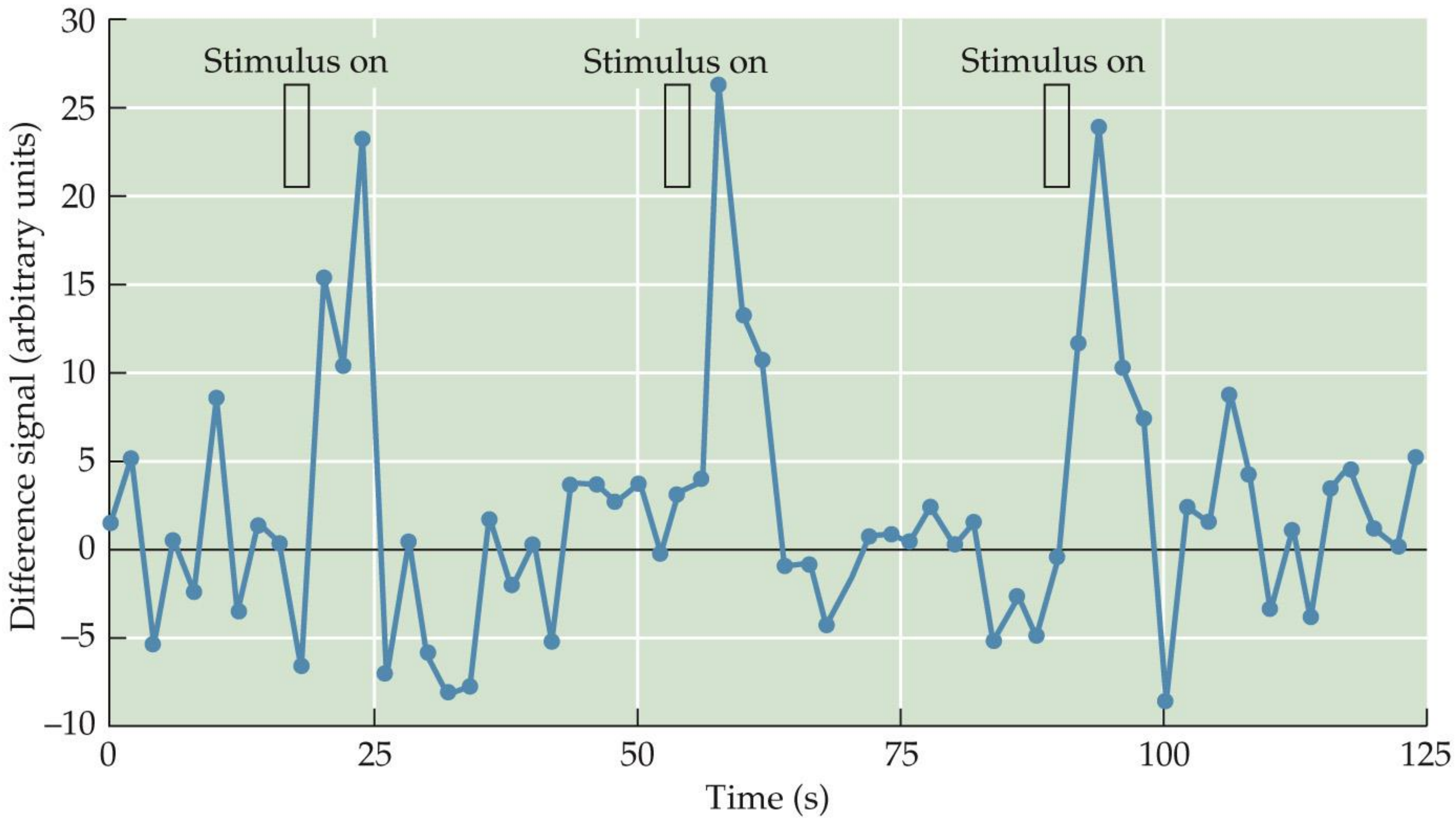
- Kwong et al. (1992) demonstrated flow and BOLD changes using lengthy periods (60 sec) of flickering lights and darkness



FUNCTIONAL MAGNETIC RESONANCE IMAGING 3e, Figure 7.8

BOLD signal related to single visual events

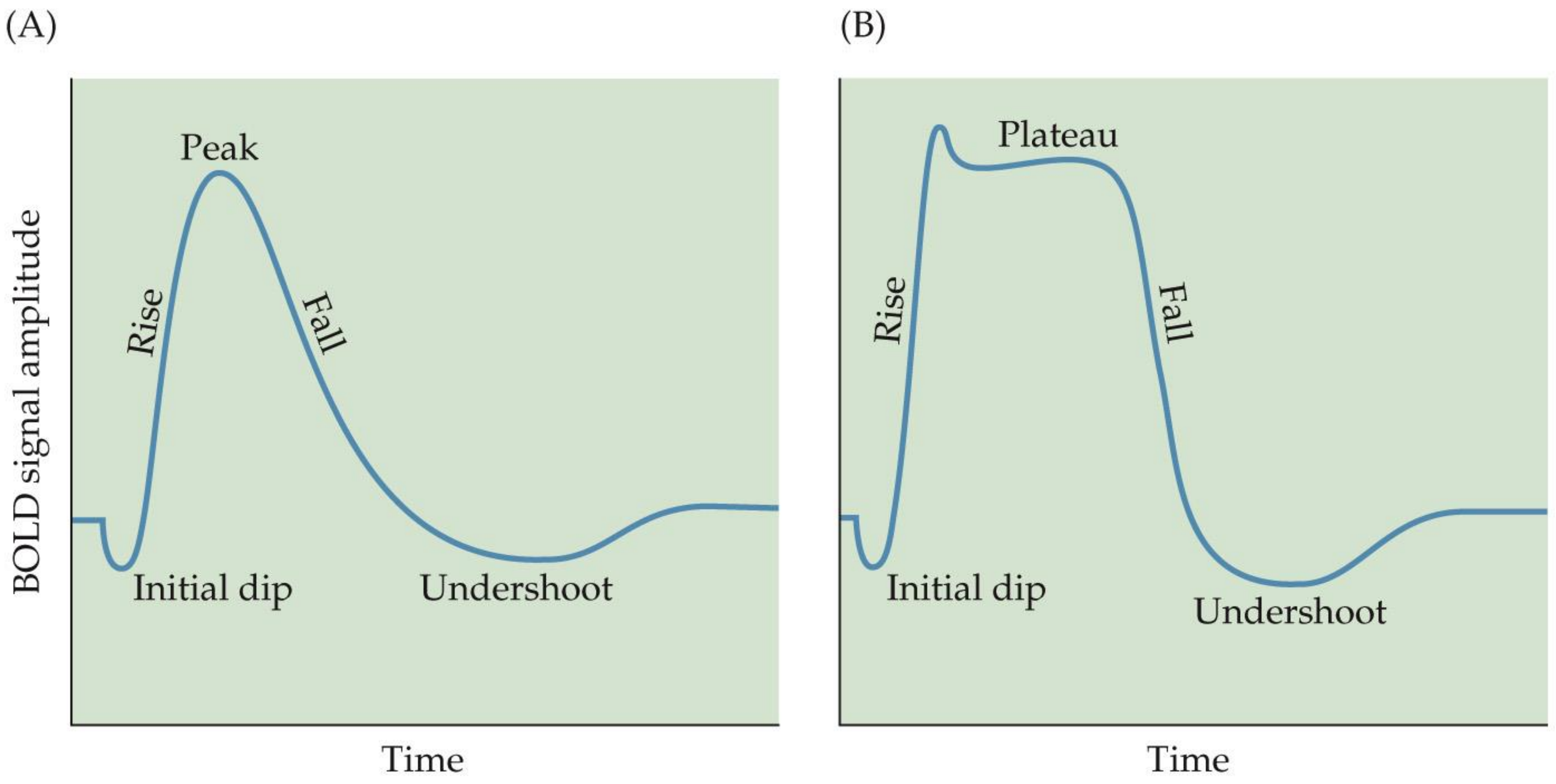
- Blamire et al. (1992) showed significant signal changes in the visual cortex following short stimulations (2 sec)
- Consistent lag between stimulation and peak signal change was observed



FUNCTIONAL MAGNETIC RESONANCE IMAGING 3e, Figure 7.9

BOLD Hemodynamic Response function

- Properties of the stimulus influence the shape of the hemodynamic response:
  - Short-duration event results in brief elevation of signal (A)
  - Block of multiple consecutive events result in sustained response



FUNCTIONAL MAGNETIC RESONANCE IMAGING 3e, Figure 7.10