Physiological imaging with special focus on electromagnetic brain mapping

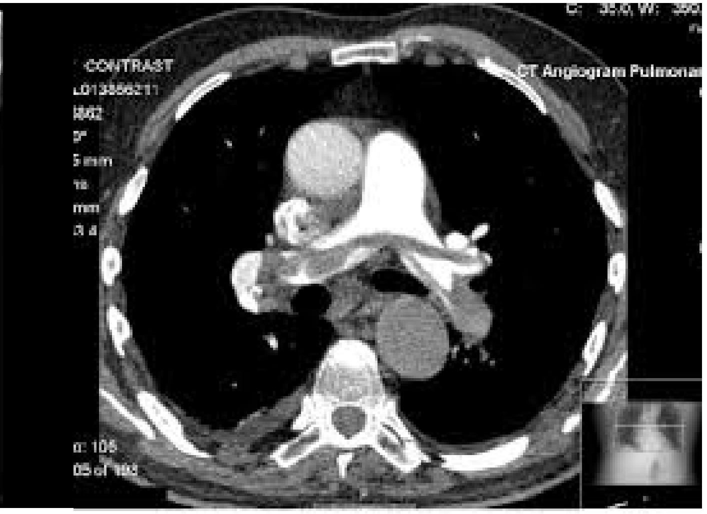
9.1.2024

Learning objectives

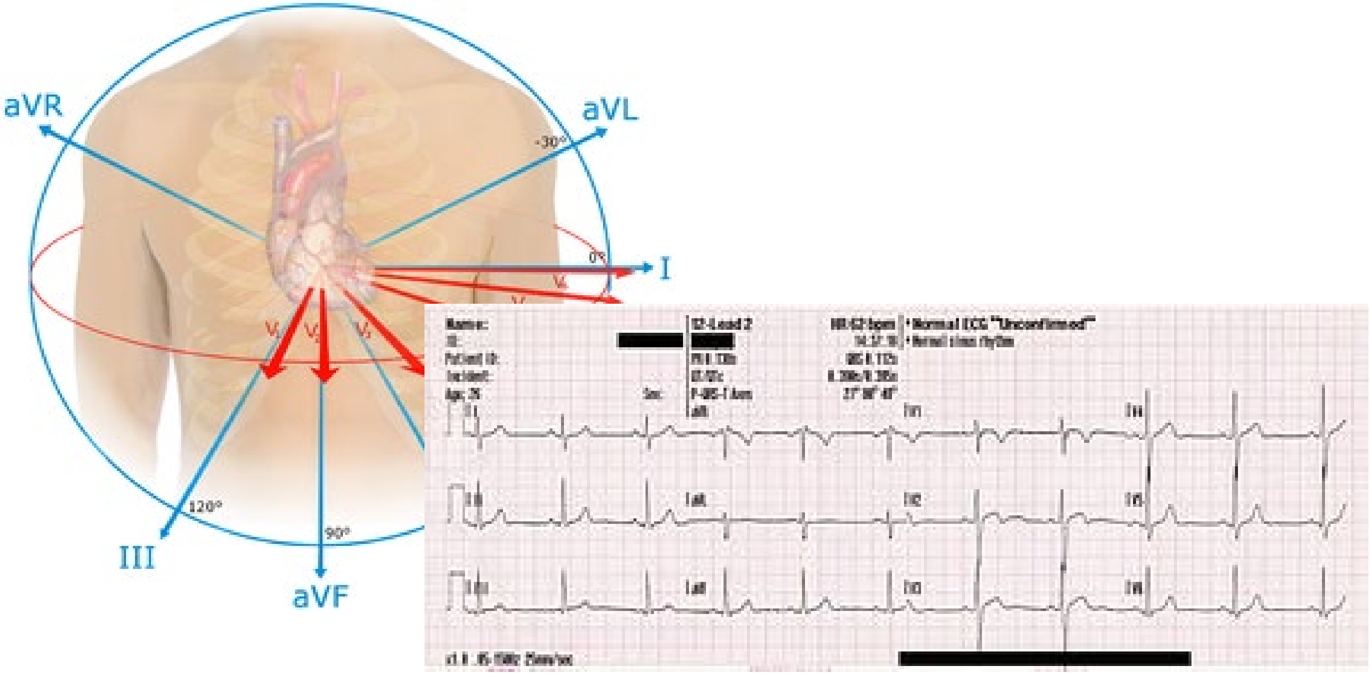
- Recognize the most used imaging methods in physiological research and their pros and cons
- Understand the principles in electromagnetic brain imaging
  - Electroencephalography, EEG
  - Magnetoencephalography, MEG
  - Transcranial magnetic stimulation, TMS

Imaging: Increasing role in studying physiological functions in health and disease

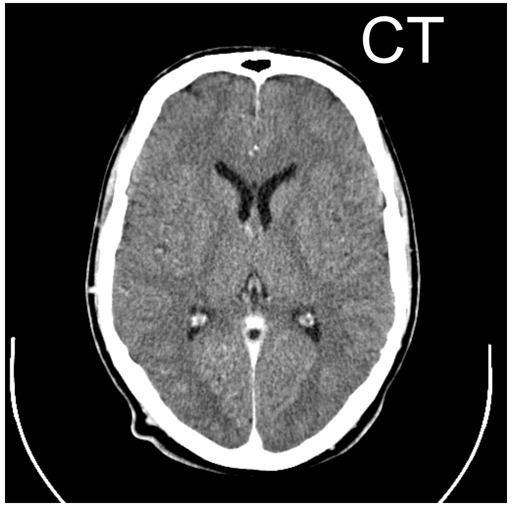
Imaging of body, limbs, and brain
e.g., x-rays, computerized tomography, magnetic resonance imaging

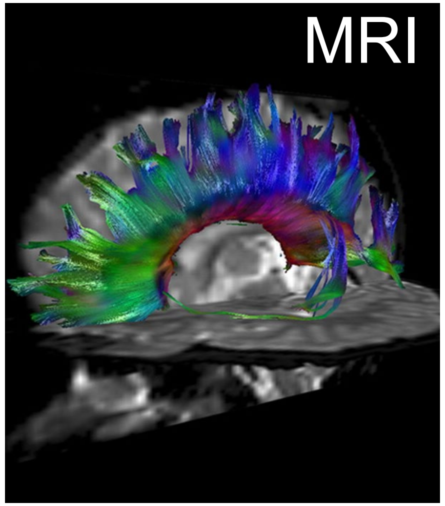


Addressing of electrical functions of the body
e.g., electrocardiography (ECG), electroencephalography (EEG), electromyography (EMG)



Both **structural** and **functional** imaging are needed in clinical diagnostics





http://thebrain.mcgill.ca Lee et al. 2005

Computerized tomography (CT)
Magnetic resonance imaging (MRI)

Computerized tomography (CT)

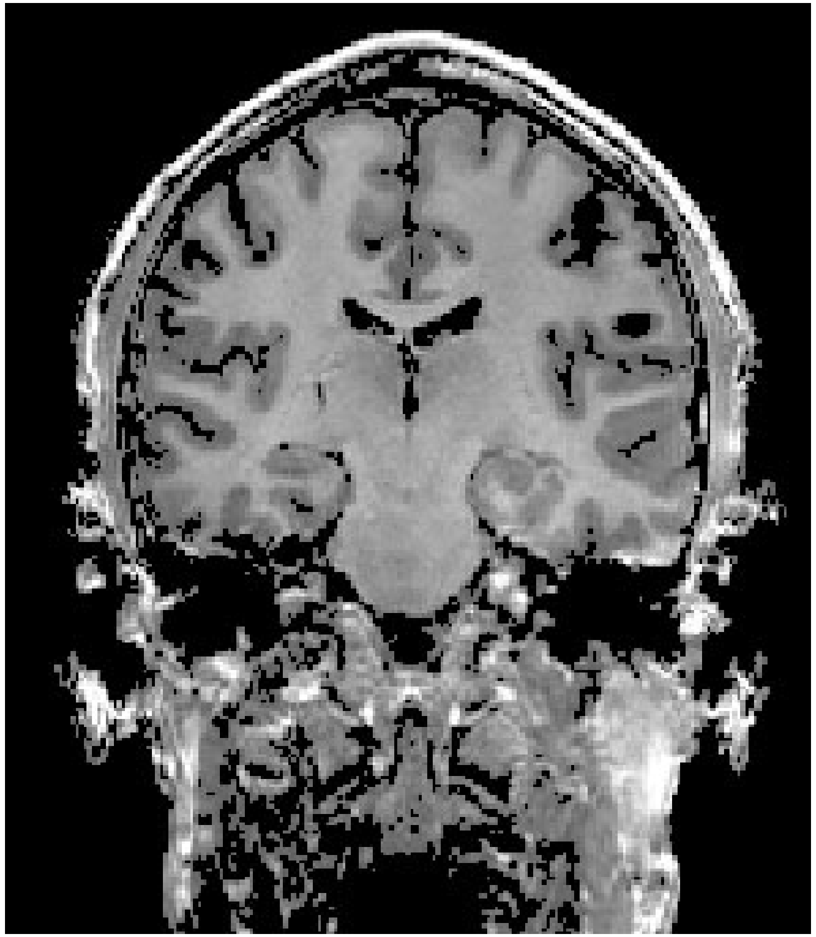
- Based on x-rays
- 3D images with high resolution
- Brain, intestines, lungs

+ Widely available, fast, inexpensive

- Ionizing radiation
- Limited sensitivity, *e.g.,* in many neurological disorders

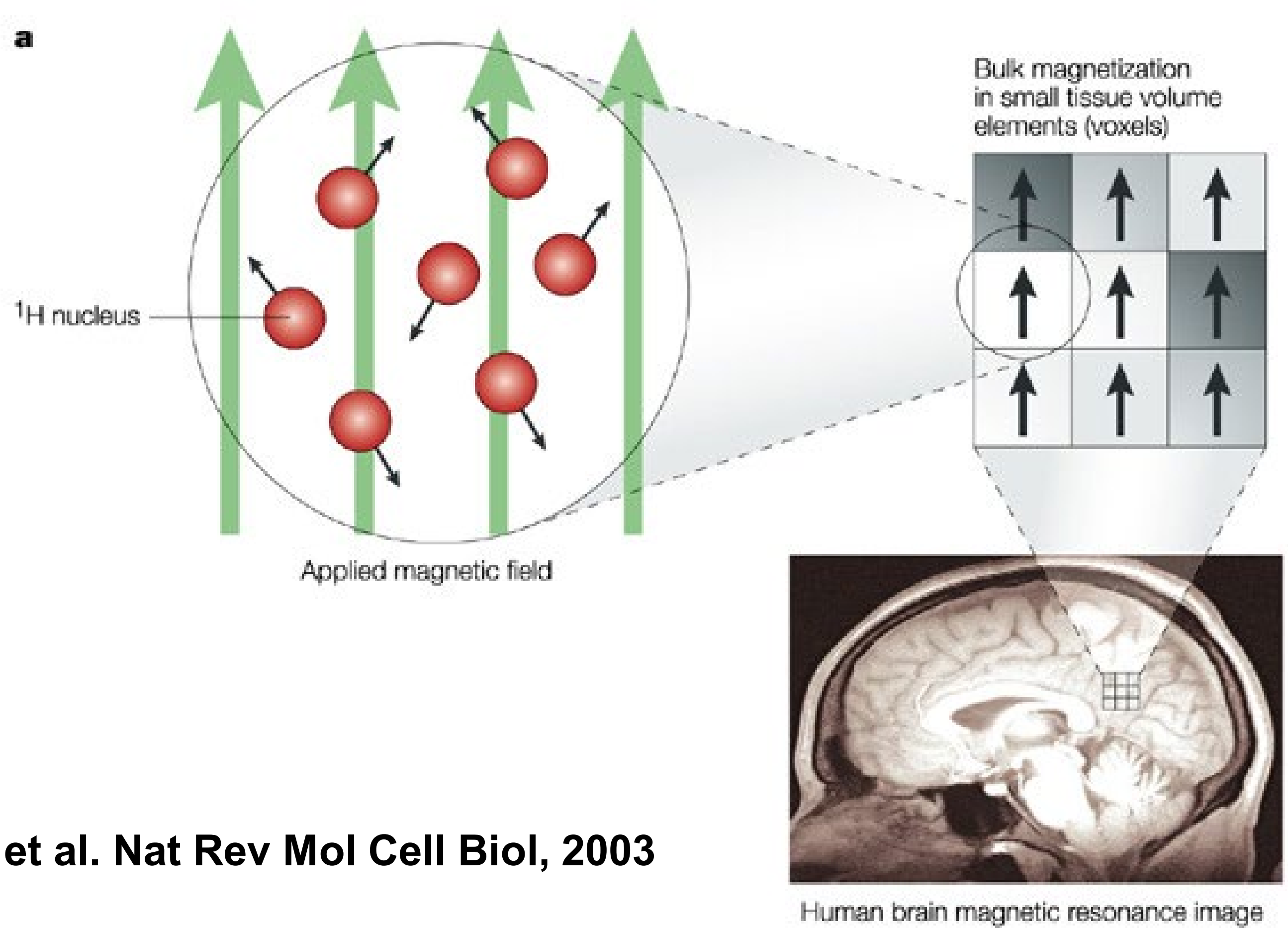
Magnetic resonance imaging (MRI)

Based on nuclear magnetic resonance

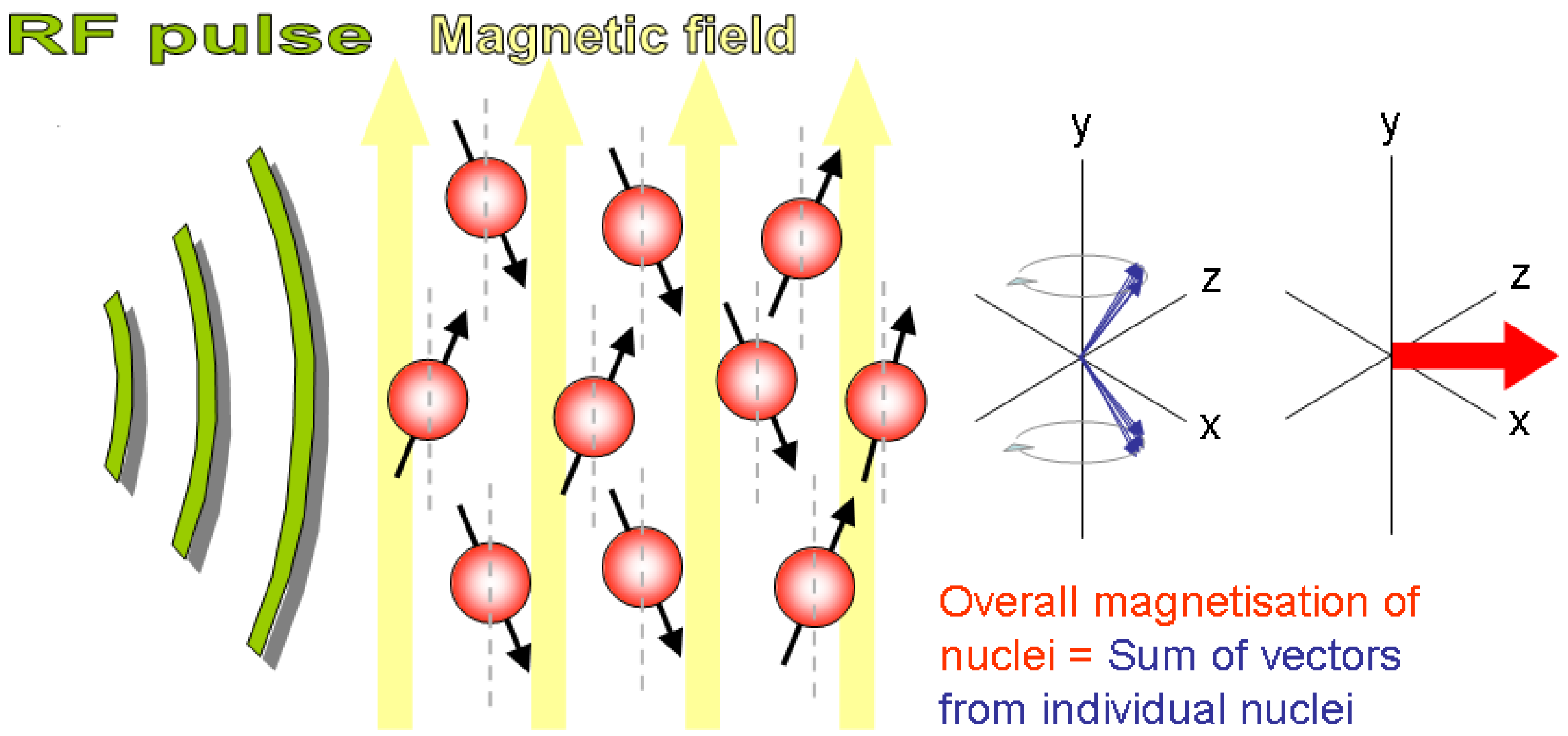


Magnetic resonance imaging (MRI)

- In external magnetic field $\mathbf{B_0}$, hydrogen nuclei align along $\mathbf{B_0}$



Jakobs et al. Nat Rev Mol Cell Biol, 2003

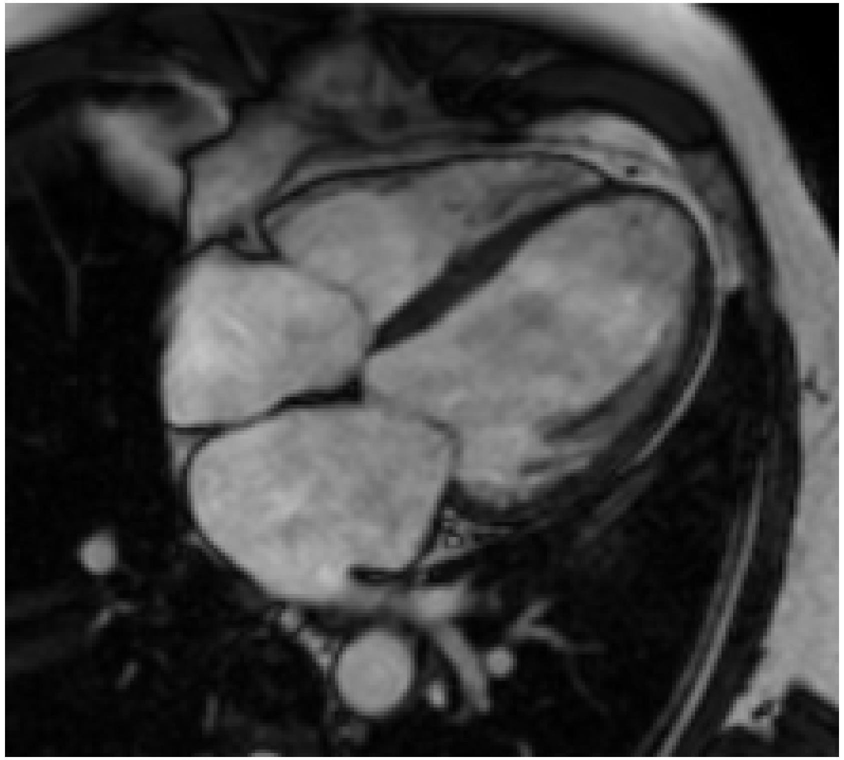


http://physiology-physics.blogspot.com/2010/06/understanding-basic-principles-of.html

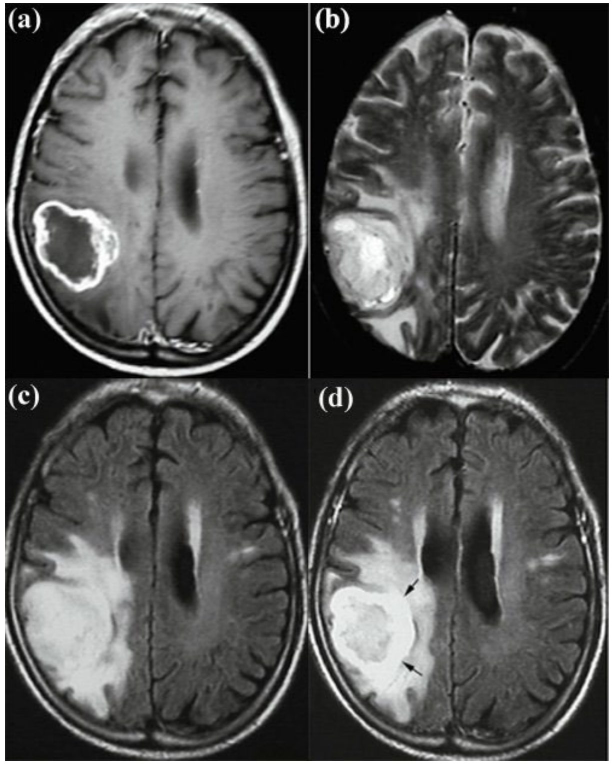
- RF pulse perpendicular to $\mathbf{B_0}$ is applied
- After the RF pulse, different tissues return to equilibrium at different rates → image contrast

https://www.youtube.com/watch?v=Ok9ILIYzmaY

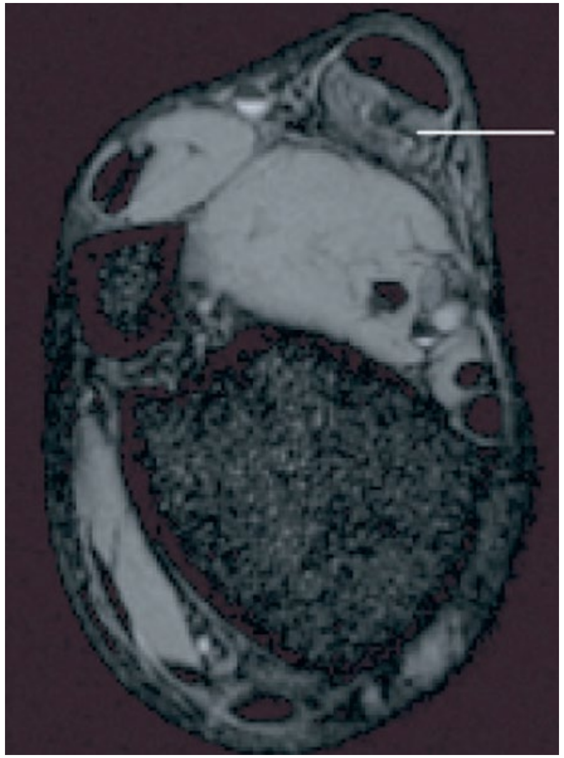
Applications of high-contrast and radiation-free MRI will continue to increase



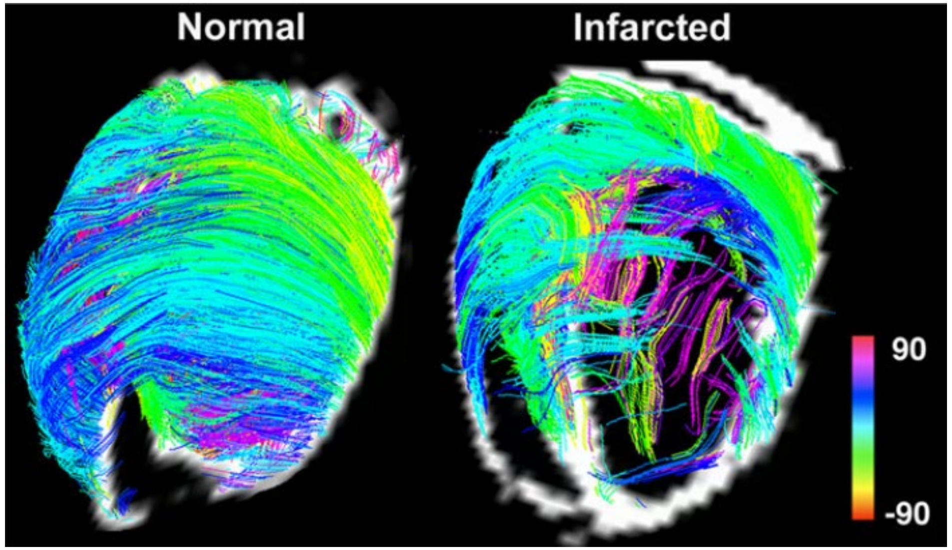
Heart



Brain



Muscles and ligaments

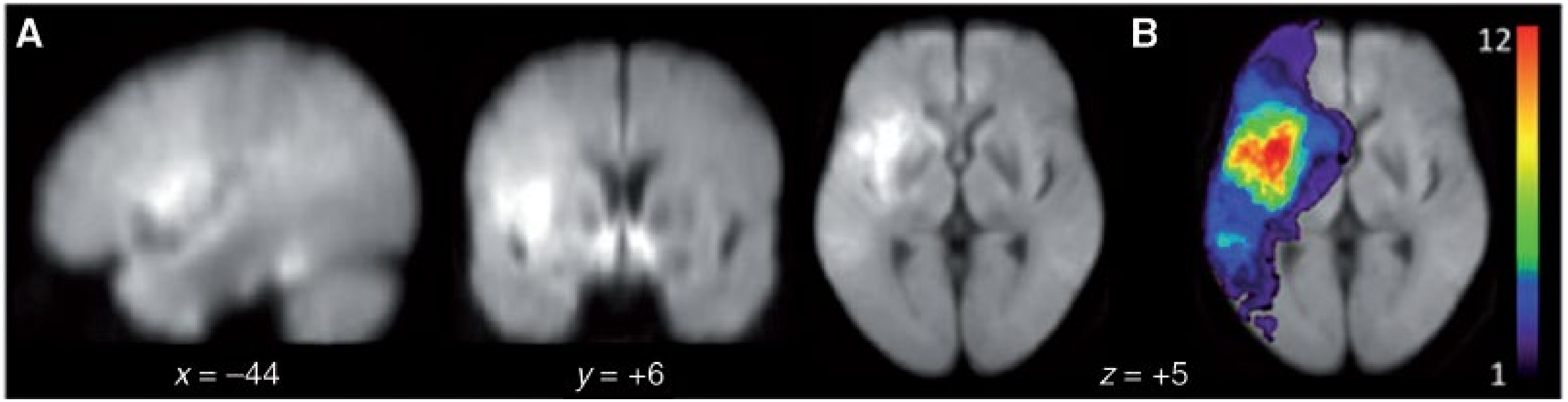


Sydän: Mekkaoui ym. NMR in Biomedicine 2015

Tractography

Visualization of nerve tracts by diffusion MRI

Diffusion weighted imaging



Tissues with cellular swelling exhibit lower diffusion

+ diagnosis of acute stroke

Ultrasound

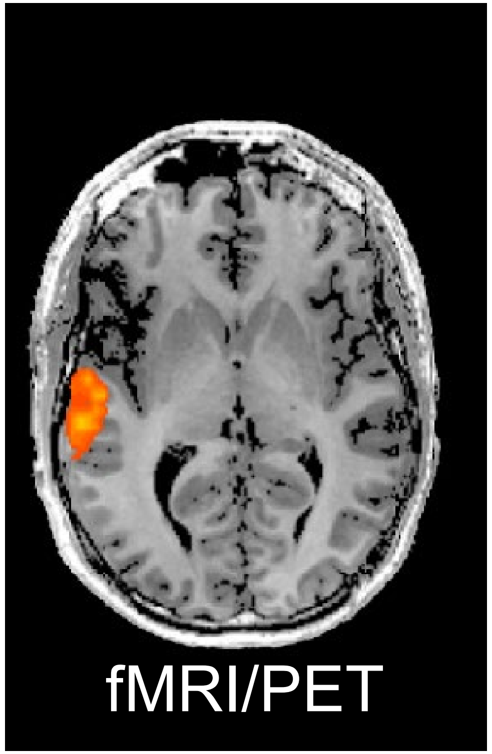
- Ultrasound (> 20 kHz, typically 1-30 MHz) is reflected on the border surface between tissues with different densities

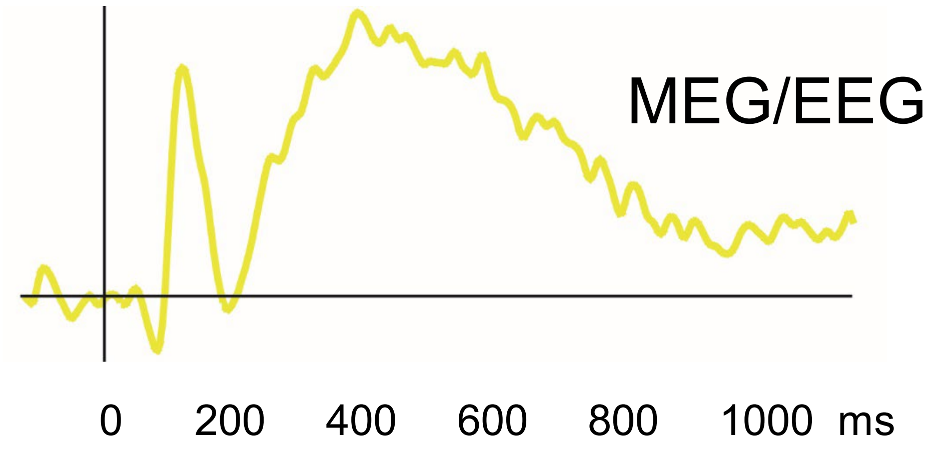
- Heart, inner organs, fetus

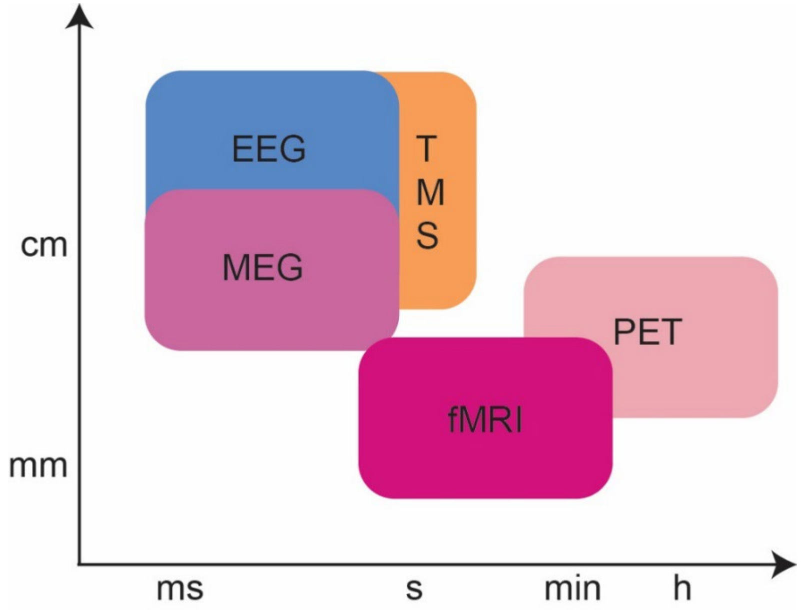
+ Widely available
+ Safe
- Restricted use in many medical indications

Wikipedia

Functional imaging

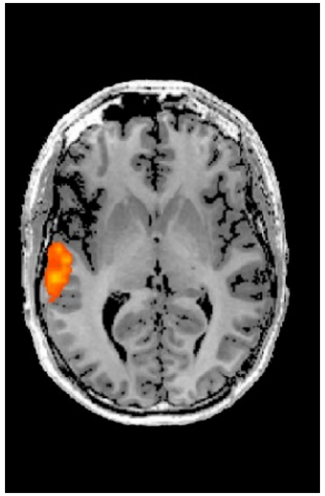




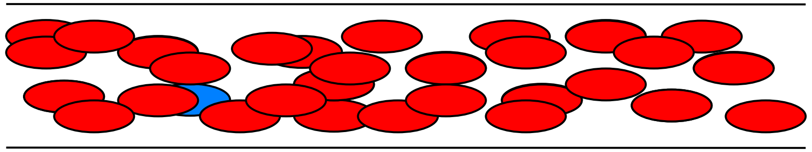


Functional MRI (fMRI), positron emission tomography (PET), electroencephalography (EEG), magnetoencephalography (MEG), transcranial magnetic stimulation (TMS)

Functional magnetic resonance imaging (fMRI)



- Based on different magnetic properties of oxygenated and deoxygenated hemoglobin



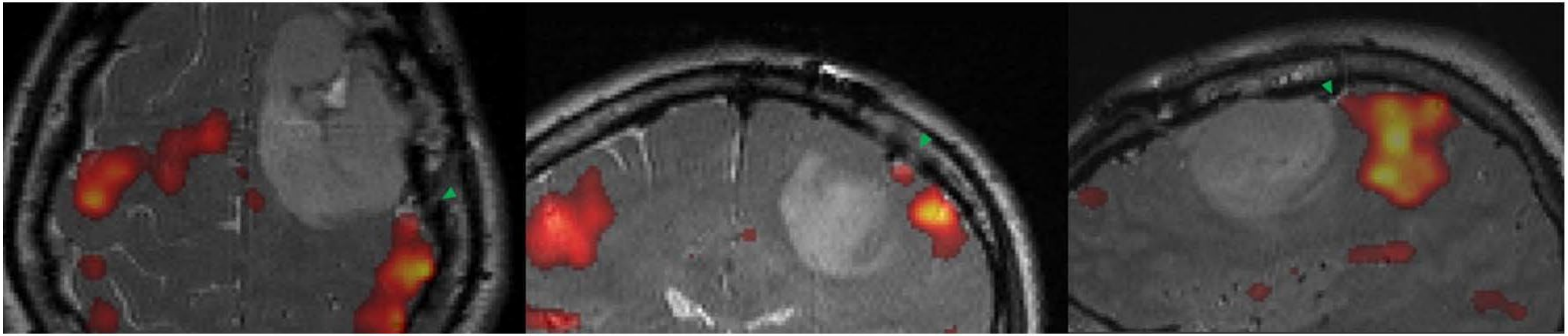
Hb with/without oxygen

Blood-oxygenation-level-dependent (BOLD) signal

- Neural activation → flow of oxygen-rich blood (diamagnetic) in the area

+ Widely available
+ Excellent spatial resolution (< mm)
- Reflects changes in blood flow → poor temporal resolution (seconds)

Functional magnetic resonance imaging (fMRI)



Silva et al. 2018

- Established role in presurgical mapping (tumors, drug-resistant epilepsy)

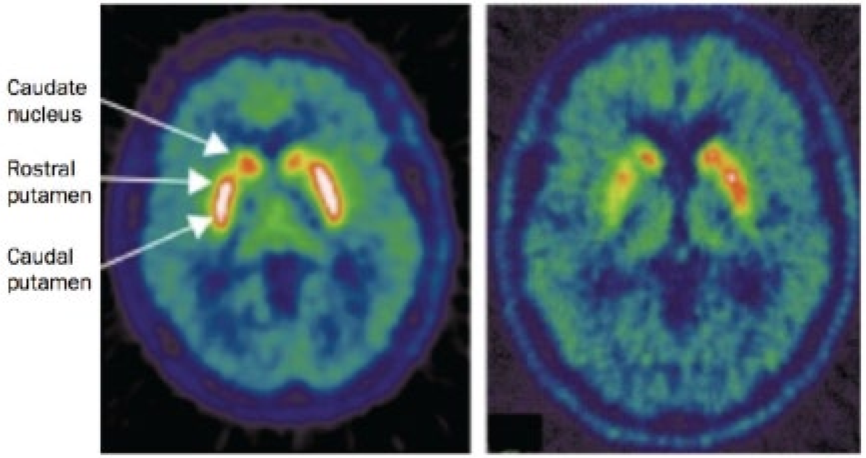
Positron-emission-tomography (PET)

- Radioactive isotope (typically fluorodeoxyglucose) injected into the subject

- Tracer molecule decays (2 min – 2 hrs) in the activated area of high energy consumption

- Tracer decay (gamma radiation) is detected by the scanner

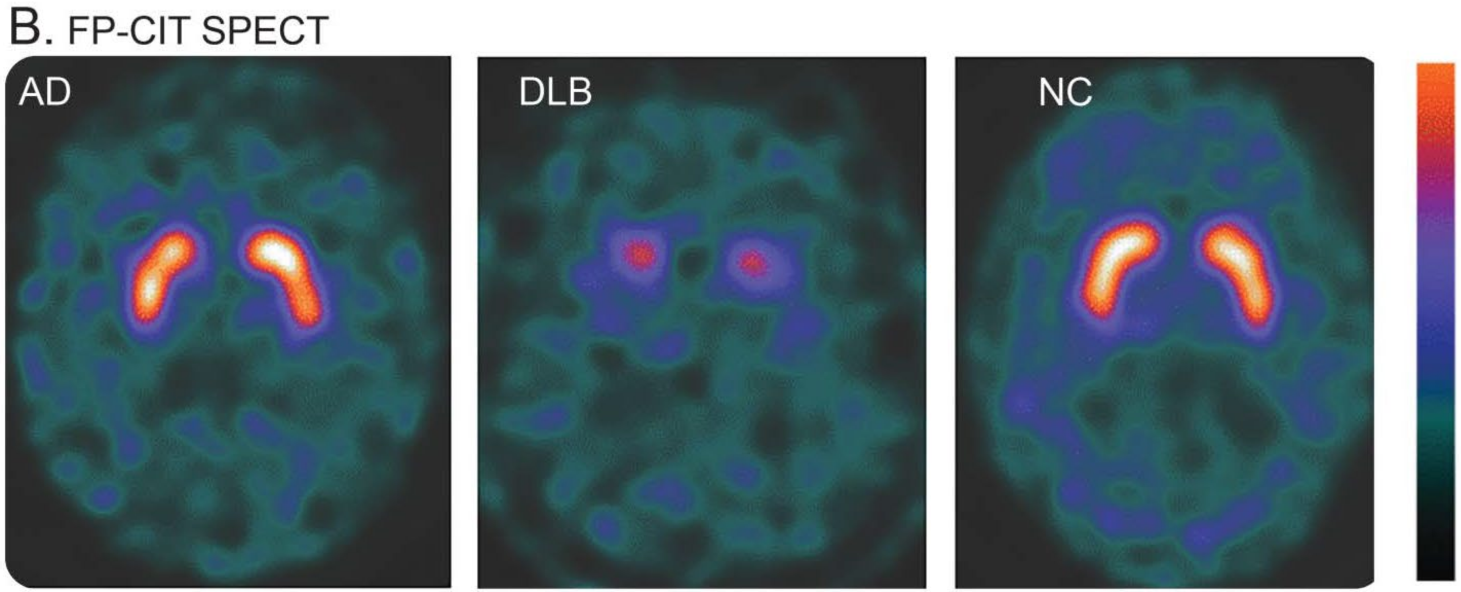
+ Good spatial resolution (but worse than MRI or CT)
- Poor temporal resolution (minutes - hrs)
- Ionizing radiation



Loane and Politis, 2011

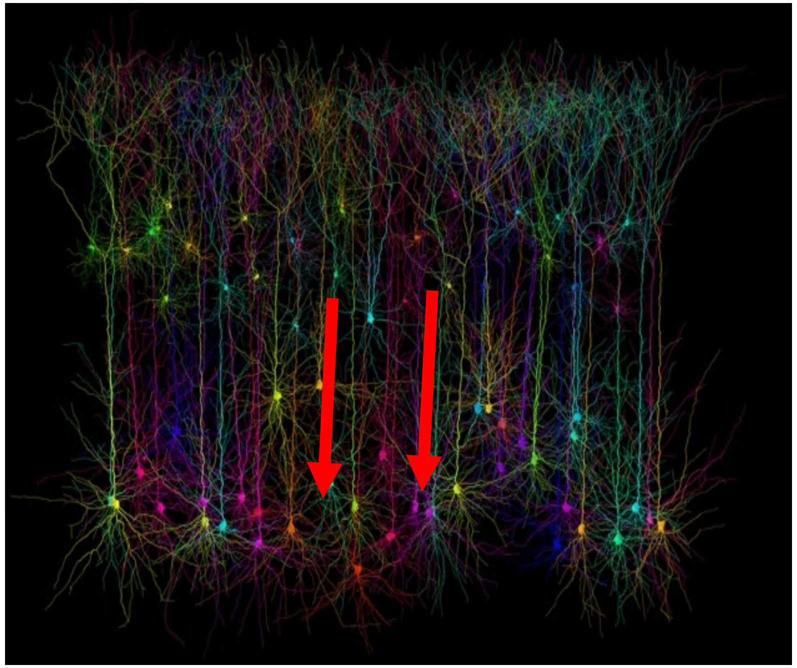
PET

Cancer, neurological diseases (memory disorders, Parkinson's disease)

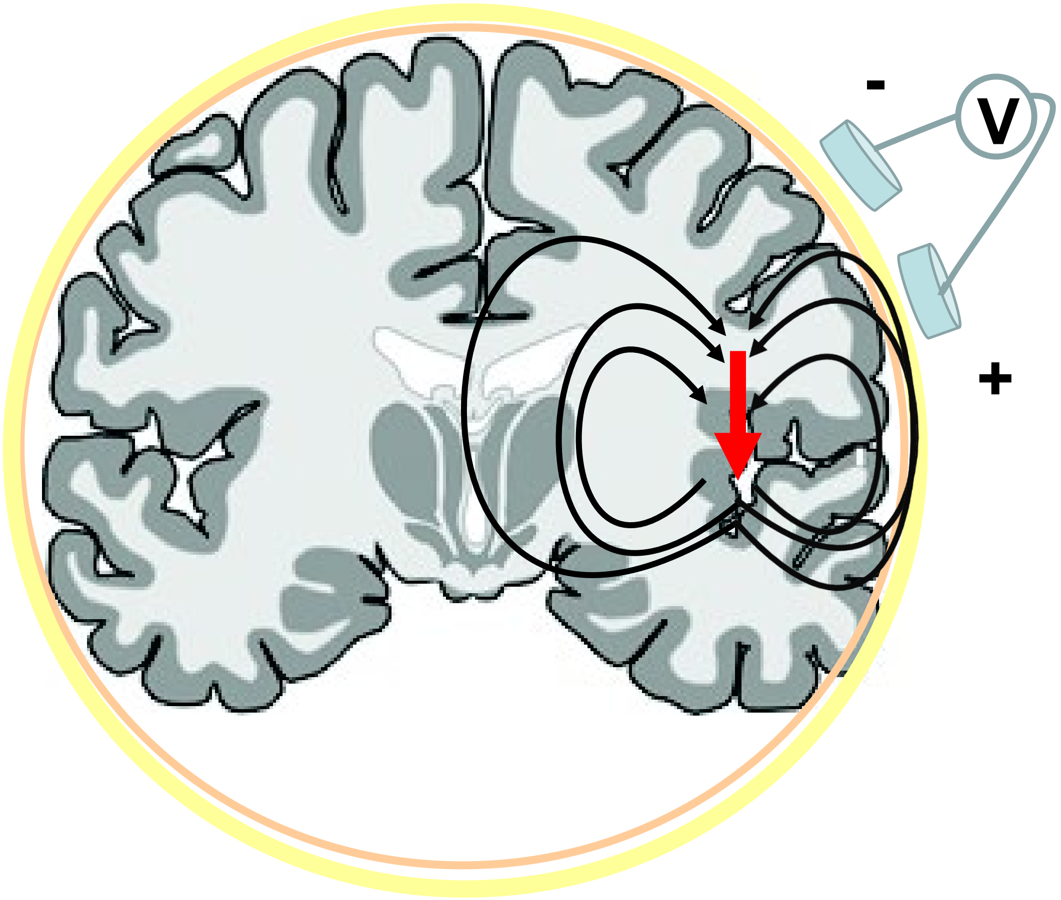


McKeith et al. 2017

Electroencephalography (EEG): Principle

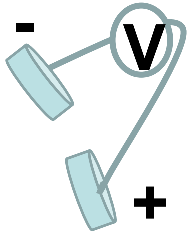


Häusser & Cuntz



EEG: Safe, inexpensive, widely available

Hans Berger, 1929

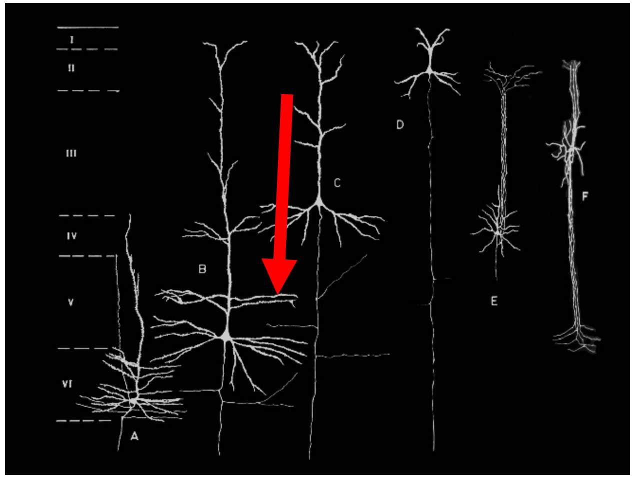


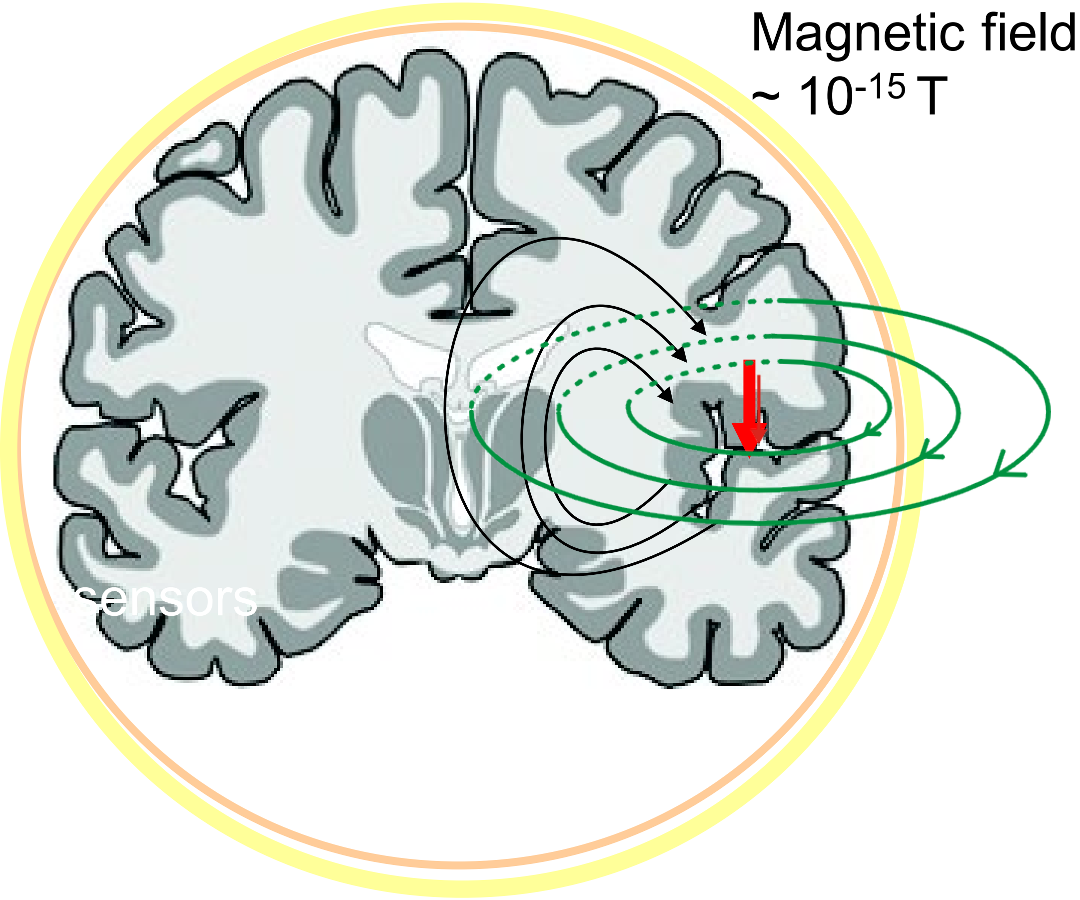
Now

Frequency distribution? Spikes or other pathological waveforms?

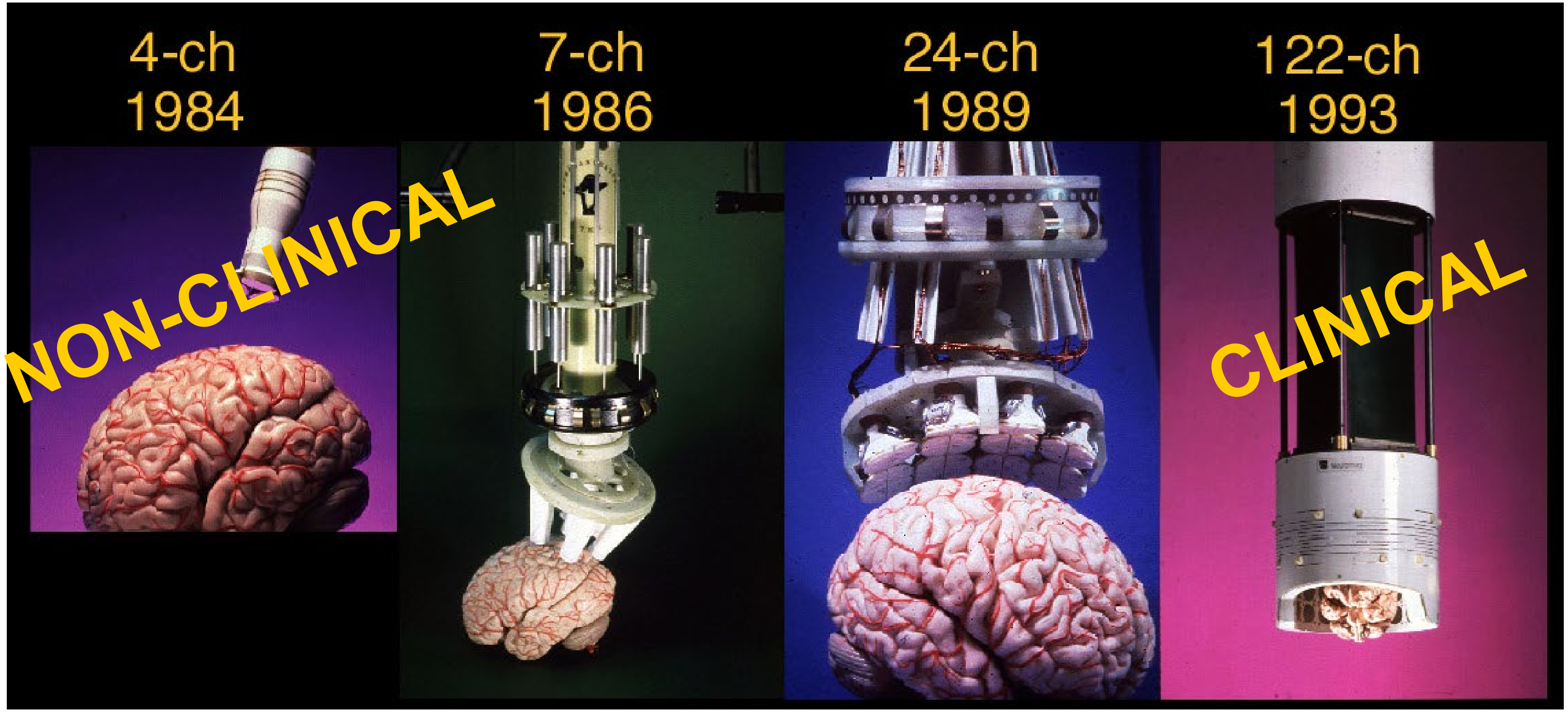
Diagnostics of diseases in central nevous system: **Epilepsy,** infections, sleep disorders, monitoring the depth of anesthesia

Magnetoencephalography (MEG): Principle



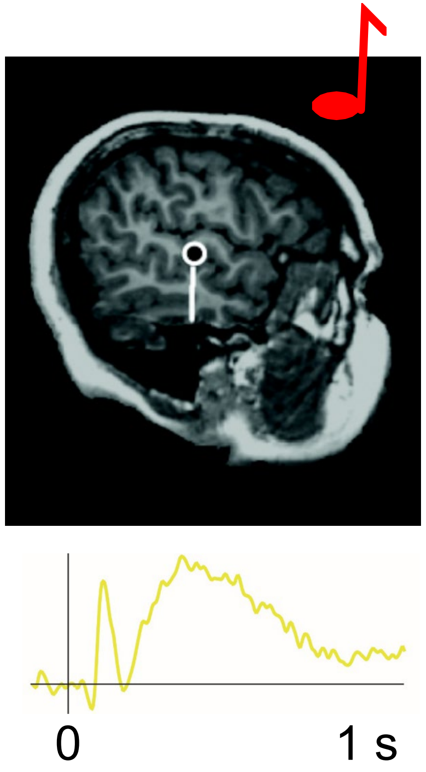


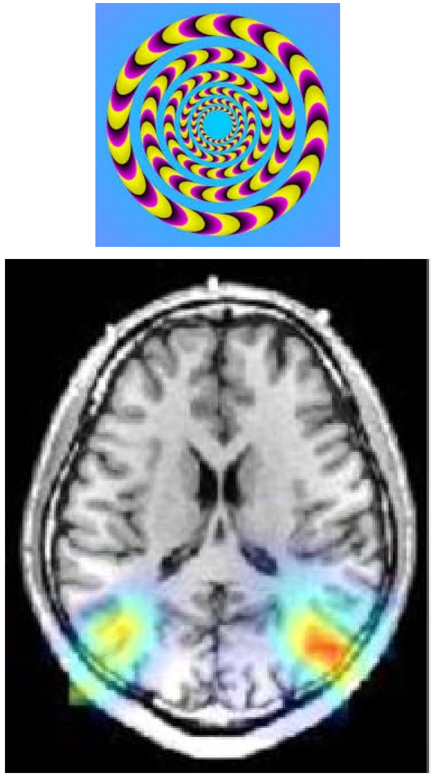
MEG development in Helsinki Univ Technology

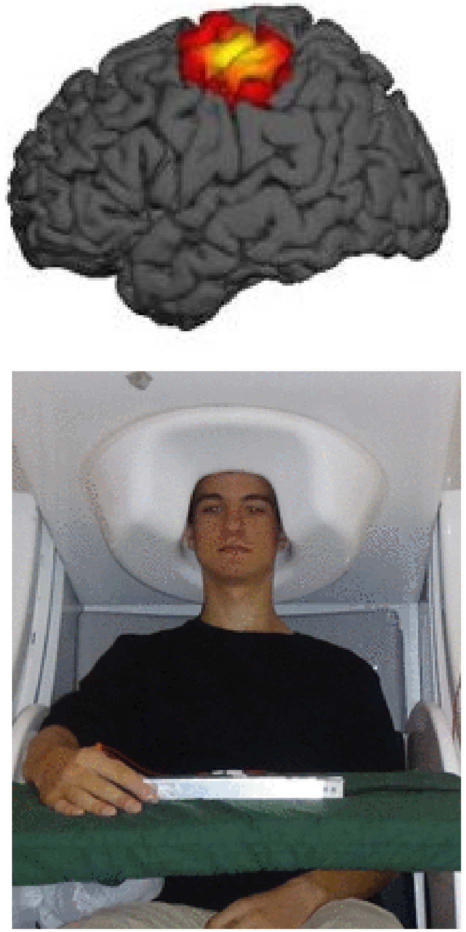


Mapping physiological functions in healthy subjects are the basis for understanding impaired functions in disease

E.g., mapping of sensory cortices
(auditory, visual, somatomotor)

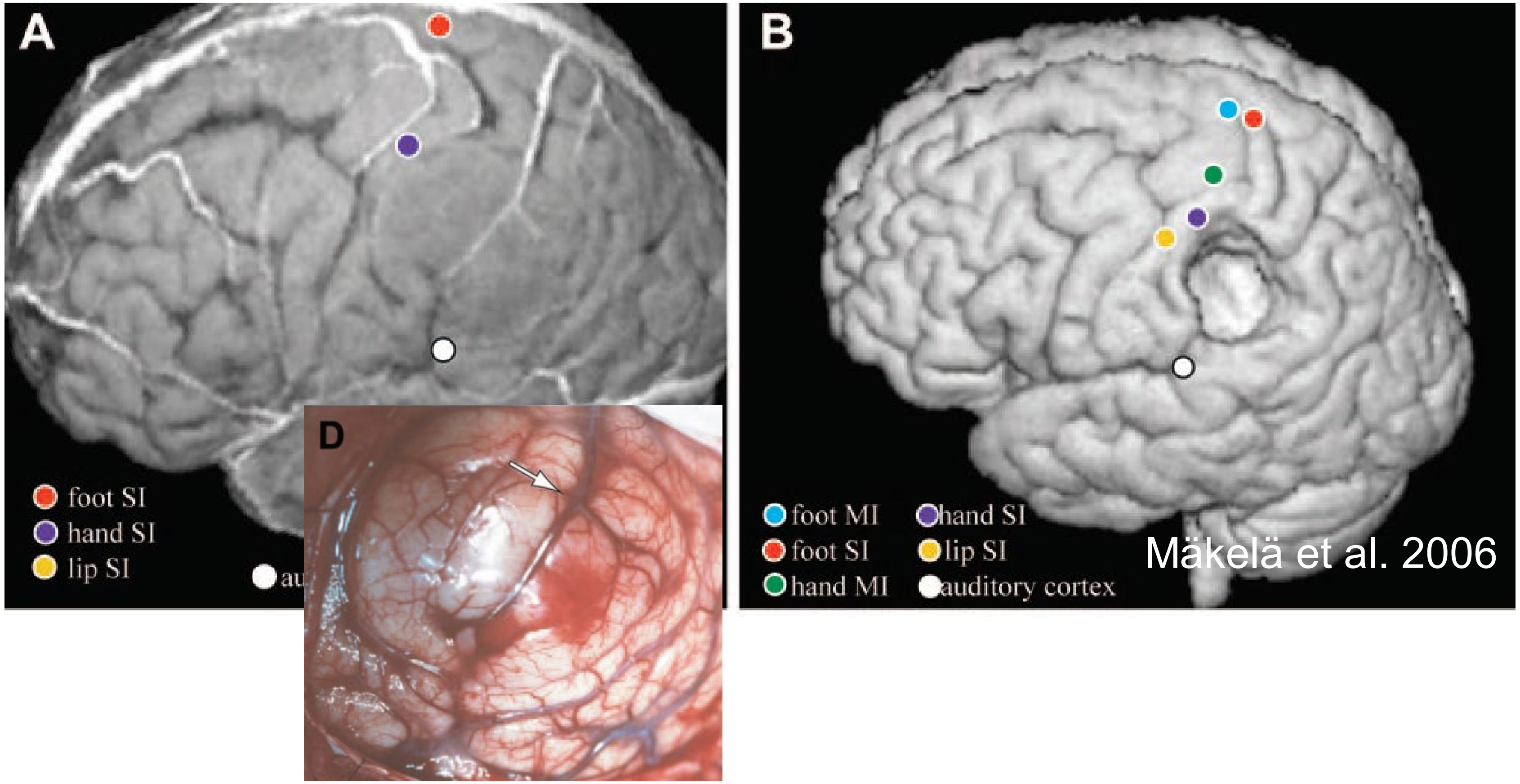






”Roadmaps” for neurosurgeons

Localization of individually most important functional areas (here auditory and somatomotor cortex)



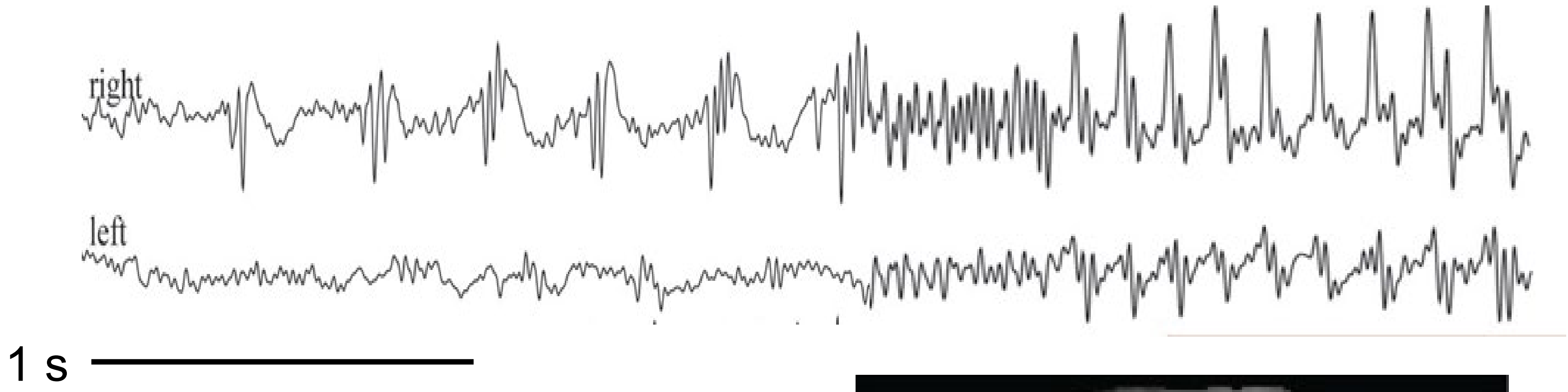
Mäkelä et al. 2006

MEG: established role in presurgical evaluation of **epilepsy**

>30% of epilepsy patients have seizures despite optimal antiepileptic medication

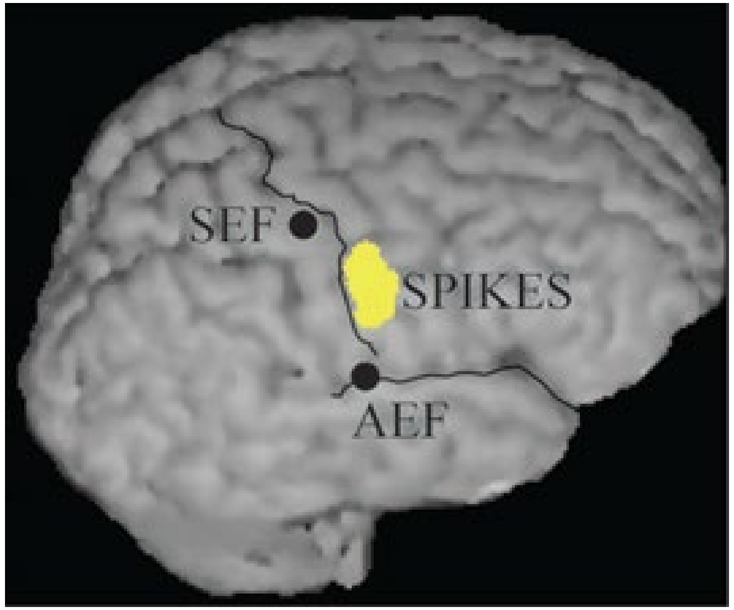
Epilepsy surgery underused, although ¾ patients get >50% seizure reduction (Mohan et al. 2018)

MEG **helps in locating** the focus of pathological activity in epilepsy

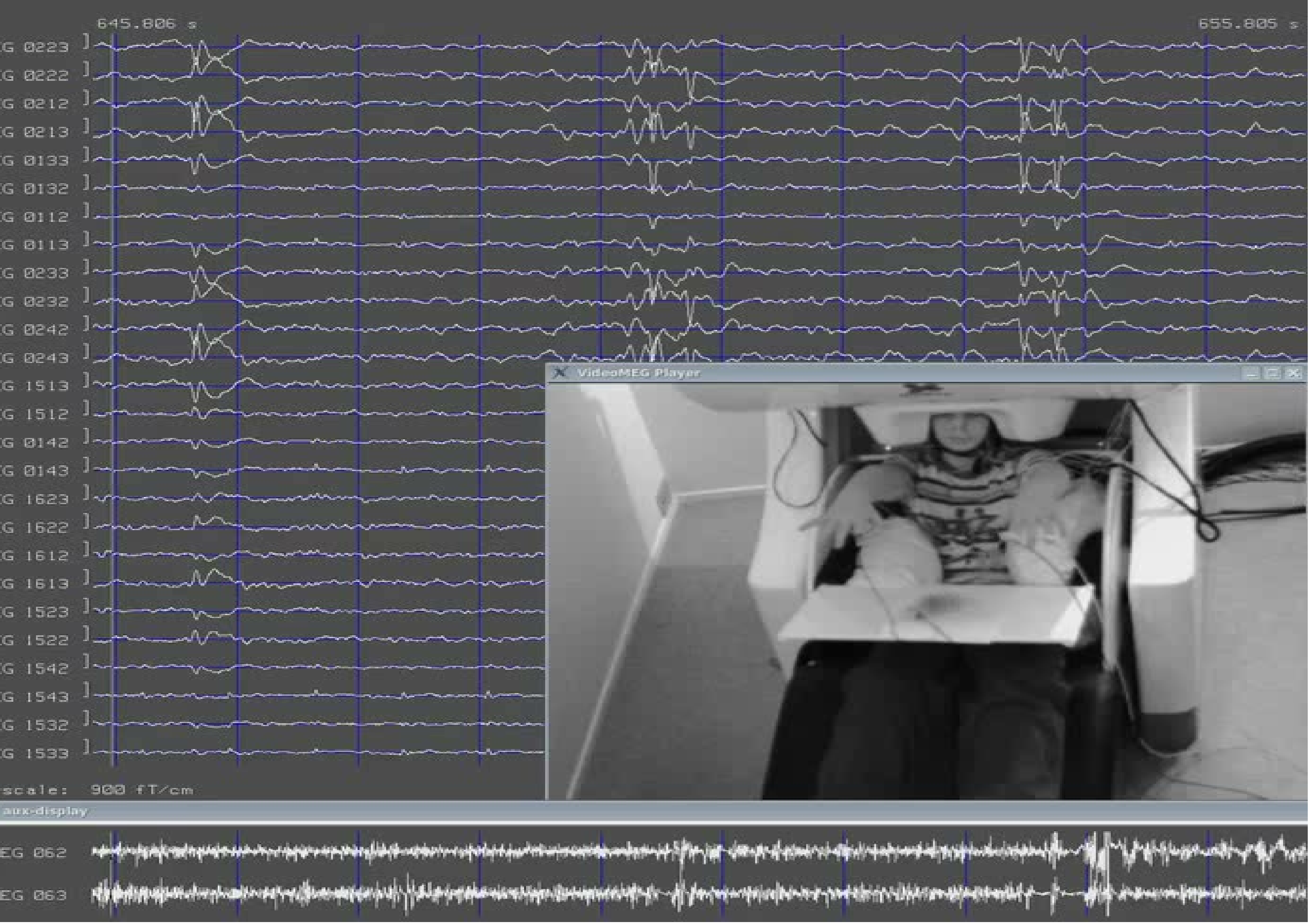


Surgeon needs to know where the epileptic seizure starts from

Single or multiple foci, their precise locations, their temporal activation orders?



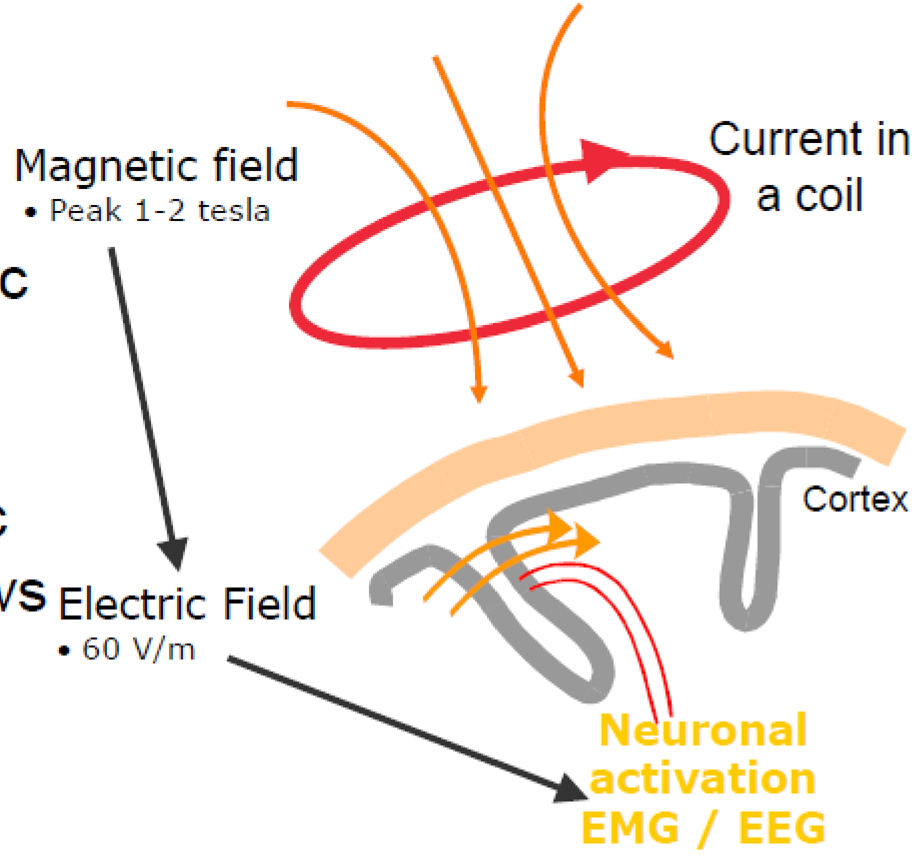
Modified from Forss et al. 1999



Courtesy of J. Mäkelä

Transcranial magnetic stimulation (TMS)

- Non-invasive tool for stimulation of cortical cells by strong magnetic field pulses
- Time-varying magnetic field induces an electric field, thus a current flows in the tissue



Courtesy of J. Ruohonen

TMS

- Disturbing ongoing neuronal activity → Measurable behavioural and/or electrophysiological consequences

- Therapeutic purposes, *e.g.,* depression, pain, rehabilitation after spinal cord injury, mapping of functional areas before surgery

Video example:

TMS SPEECH MAPPING

Short samples of:

1: baseline naming of objects

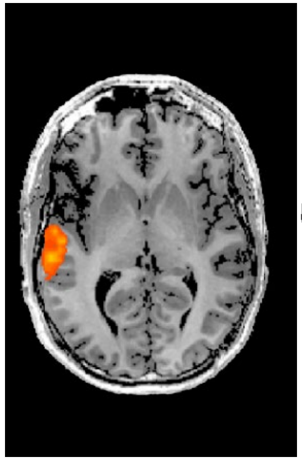
2: object naming

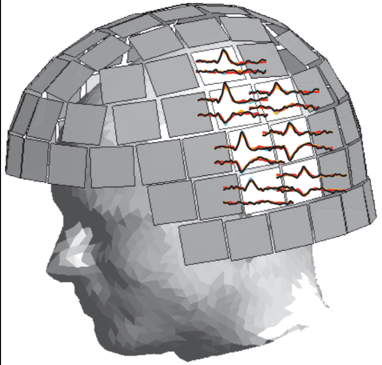
3: baseline naming of actions

4: action naming

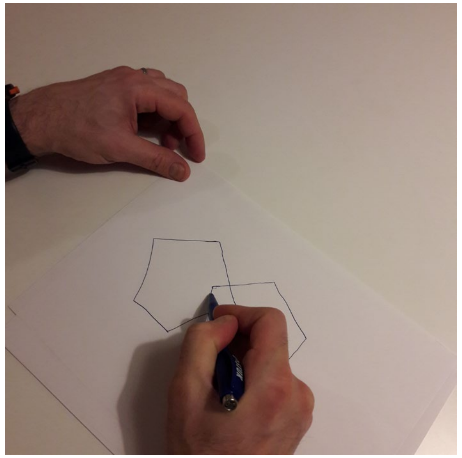
Future of physiological research: How to best combine all available information?

Structural and functional imaging

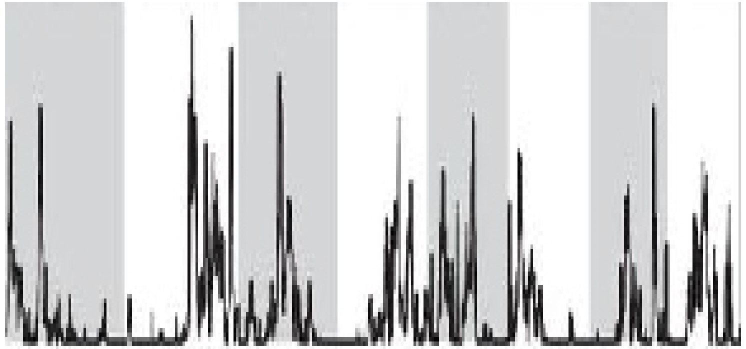




Behaviour



Other clinical information, e.g., genetics



Chromosome #