Physics in Medicine:
Physical Fundamentals of Medical Imaging

Klaus Lehnertz

Content:

- Introduction / overview
- x-ray tomography and Computed Tomography (CT)
- Single Photon Emission Computed Tomography (SPECT)
- Positron Emission Tomography (PET)
- Magnetic Resonance Imaging/Tomography (MRI/MRT)
- functional MRI (fMRI)
- Neuroelectric (EEG) and Neuromagnetic (MEG) Imaging

Literature:

O. Dössel: Bildgebende Verfahren in der Medizin, Springer, 2016

M.A. Fowler: Webb's Physics of Medical Imaging, CRC Press, 2012

H. Morneburg (Hrsg.): Bildgebende Systeme für die medizinische Diagnostik, 3. Aufl. , Publicis MCD Verlag, 1995

P. Bösiger: Kernspin-Tomographie für die medizinische Diagnostik, Teubner

W. Buckel: Supraleitung, VCH Weinheim, 1993
R. Kleiner, W. Buckel: Superconductivity, Wiley-VCH, Berlin, 2015

Niedermeyer's Electroencephalography: Basic Principles, Clinical Applications, and Related Fields. 6ed. Lippincott, 2011

Aims of medical imaging:

- visualization of the body's internal structure

- non-destructive (non-invasive) investigation of structure and function

- diagnosis

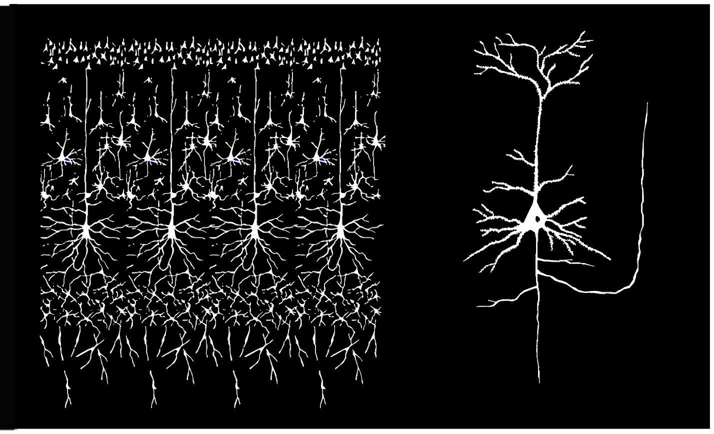
- therapy / therapy planning

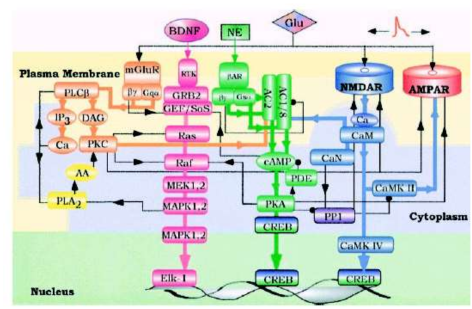
- follow up

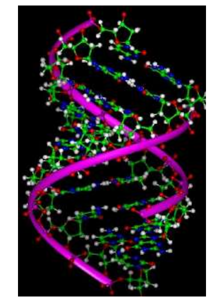
macroscopic
cm

→

microscopic
< nm







anatomy

histology

cytology

molecular
biology

biochemistry

medical imaging is a multi-disciplinary field of research

- physics (matter, energy, radiation, ...)
- mathematics (linear algebra, numerics, statistics)
- life sciences (biology / physiology / medicine ...)
- engineering (implementation)
- computer science (image reconstruction, signal processing)

medical imaging requires interdisciplinarity !!

definition of terms:

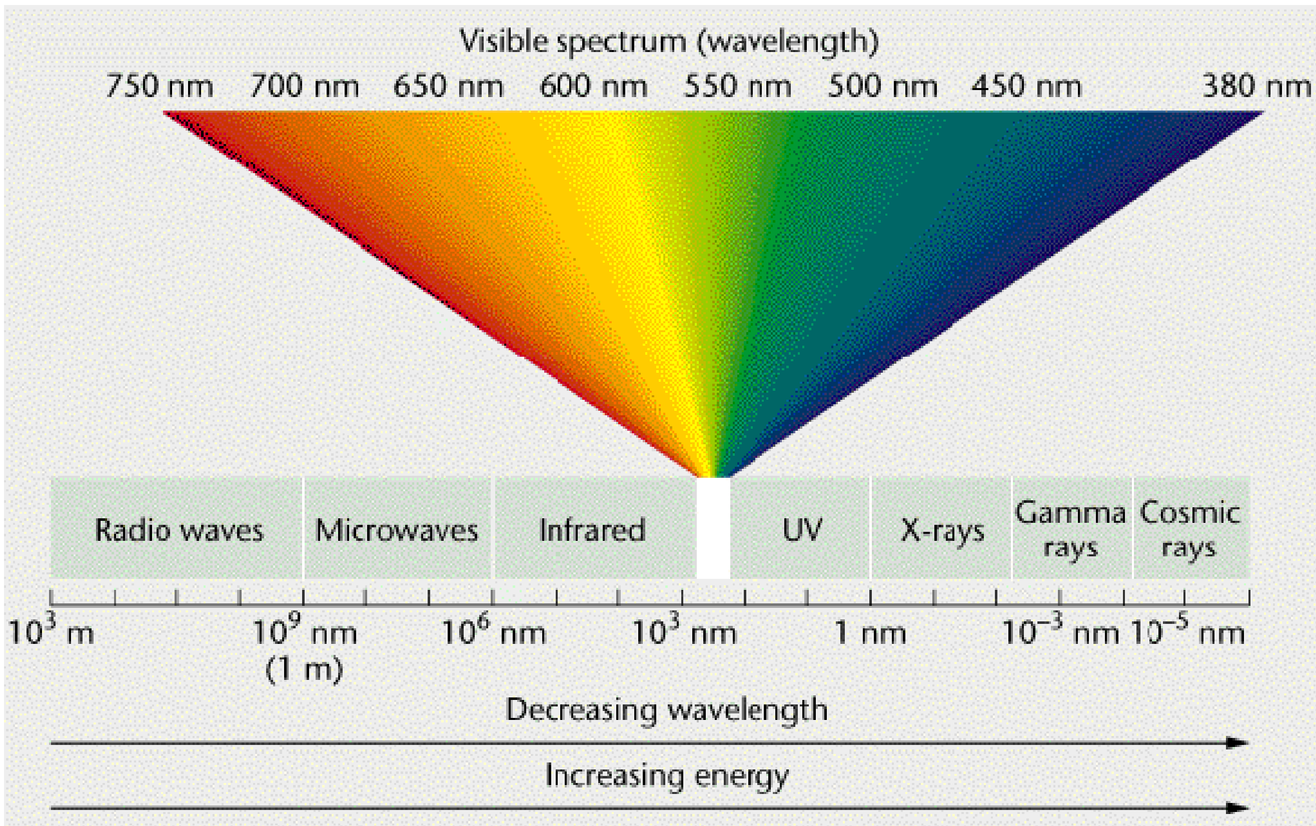
medical imaging:

- techniques to visualize **distributions of physical properties** (e.g. density, conductance, concentration) inside the body

- **Basics**: physics of interactions between energy and matter

- **Forms of energies**: photons, γ, e^+, e^-, EM-field, ultra sound, ...

forms of energies



(Klug & Cummings 1997)

caveat: biocompatibility !!

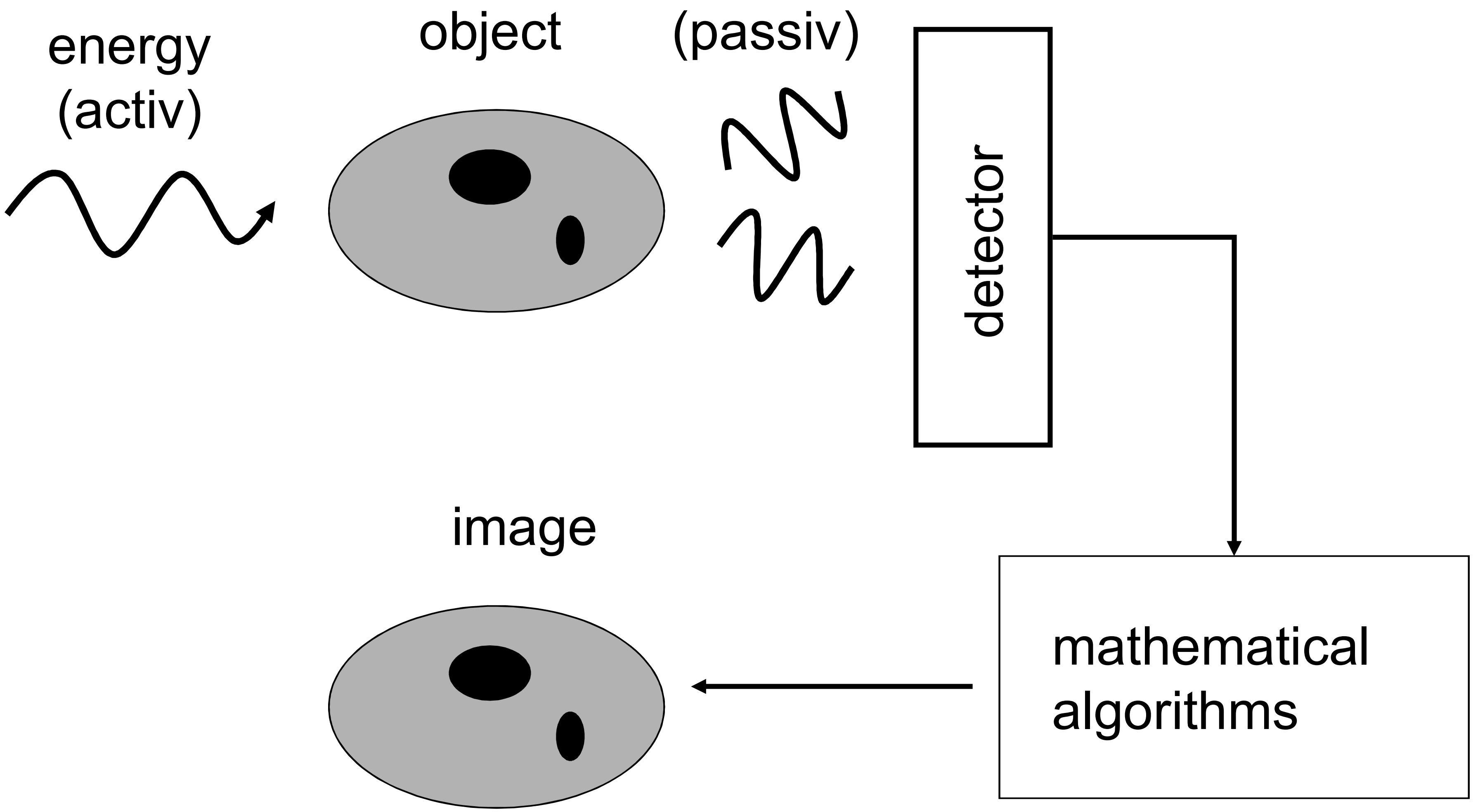
definition of terms:

active imaging:

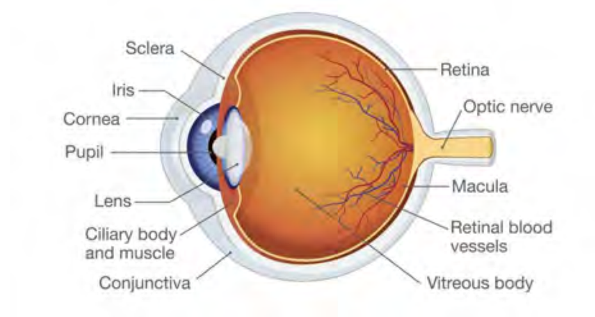
- imaging through exposure of energy
  ("exogenous" signals, e.g. x-rays, EM-fields, ultrasound)
  and recording of outcome of interactions

passive imaging:

- imaging through recording of "endogenous" signals
  (emitted from the body, e.g. EEG, MEG, EKG, MKG)


energy
(activ)
object
(passiv)
detector
image
mathematical
algorithms

eye:



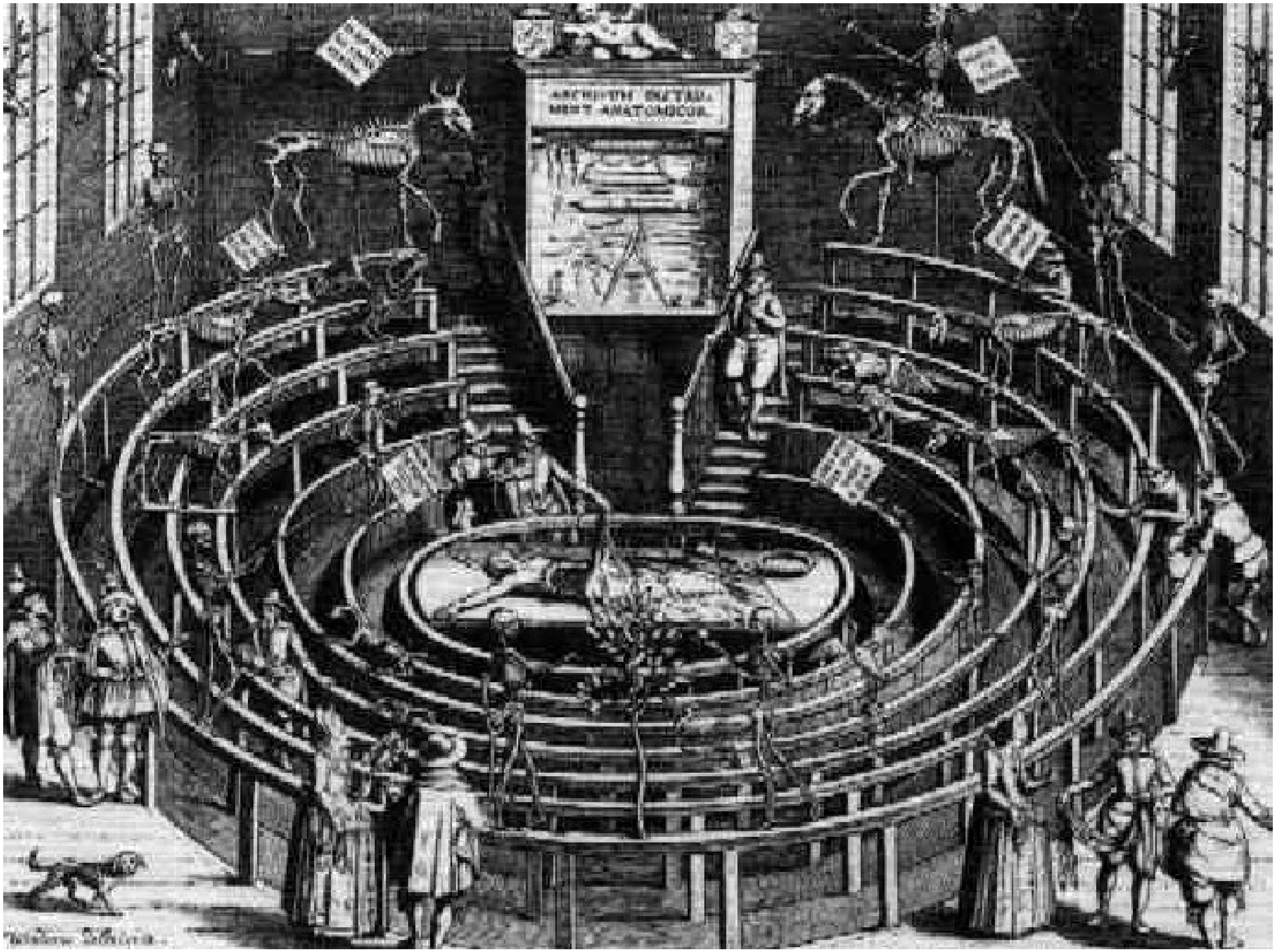
- highly efficient transmitter of information

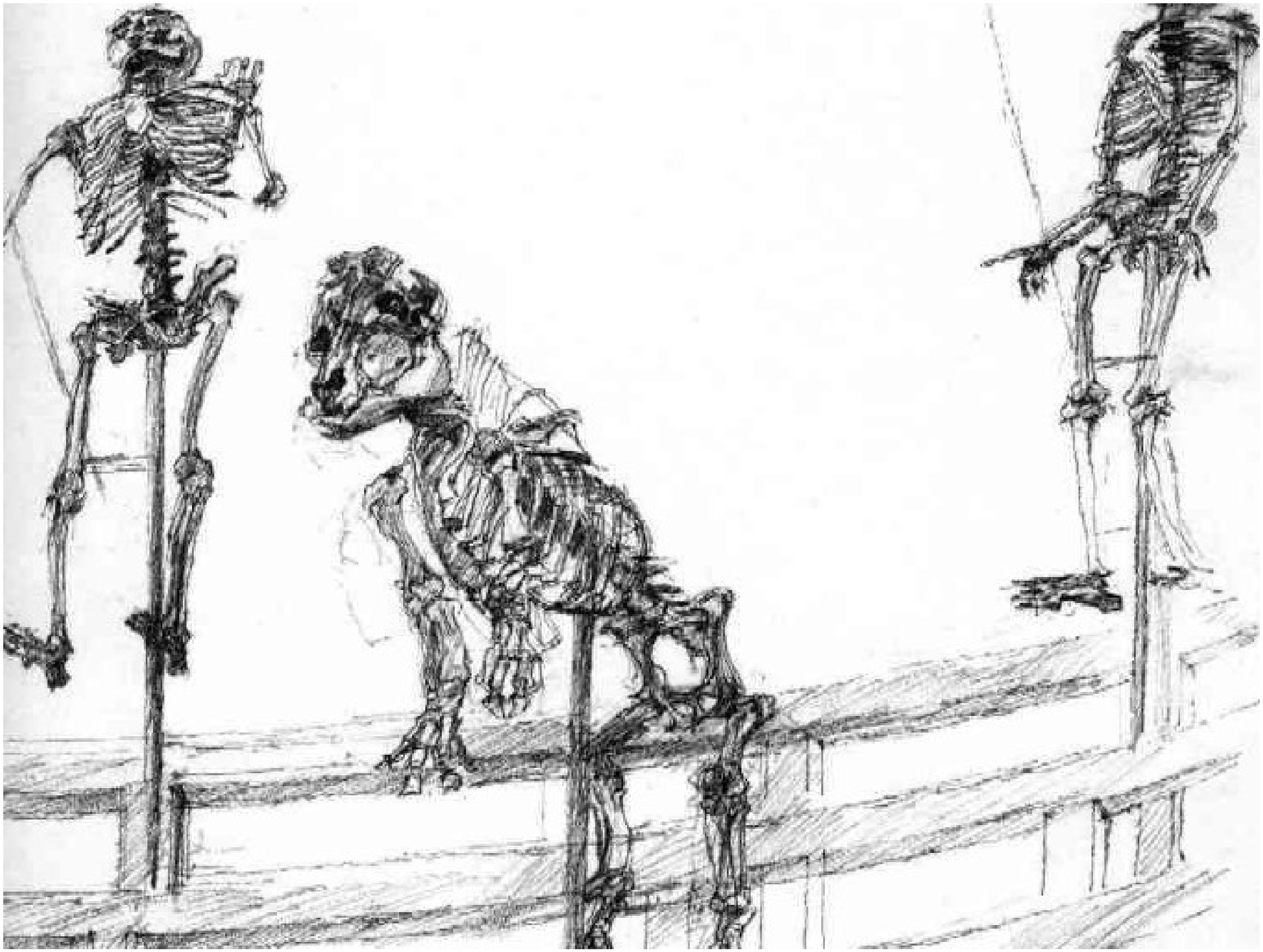
- limited range of wave lengths

- perception of EM-waves (light) ***reflected*** from (or being generated on) the ***surface*** of an object

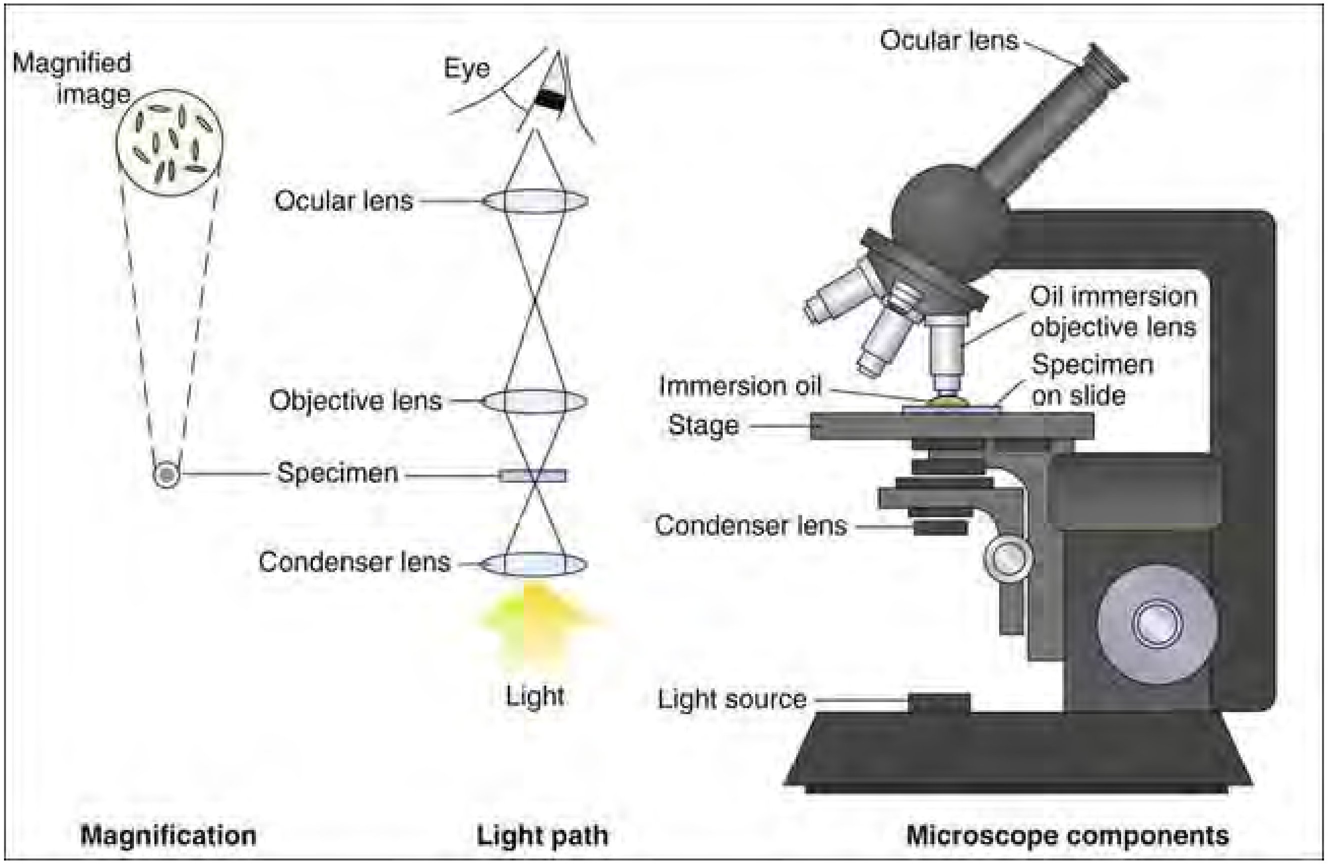
-But: most (animate and inanimate) tissues are lightproof due to thickness

- perception of the body's internal structure requires destruction (artificial generation of new surfaces)

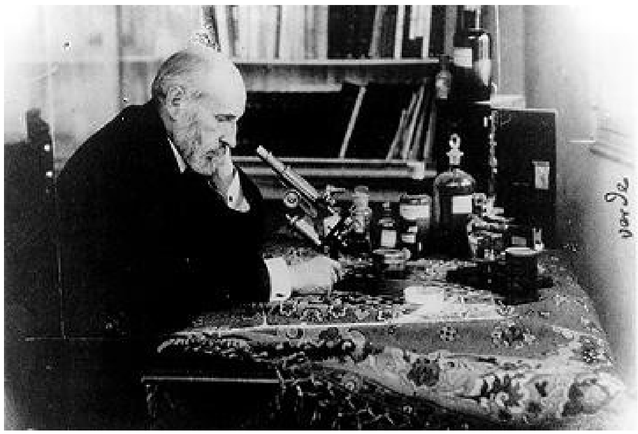




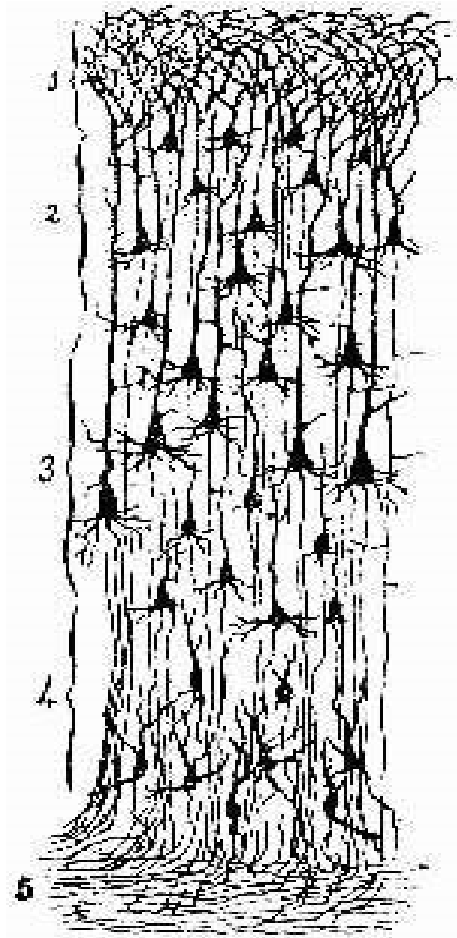
light microscopy (LM)

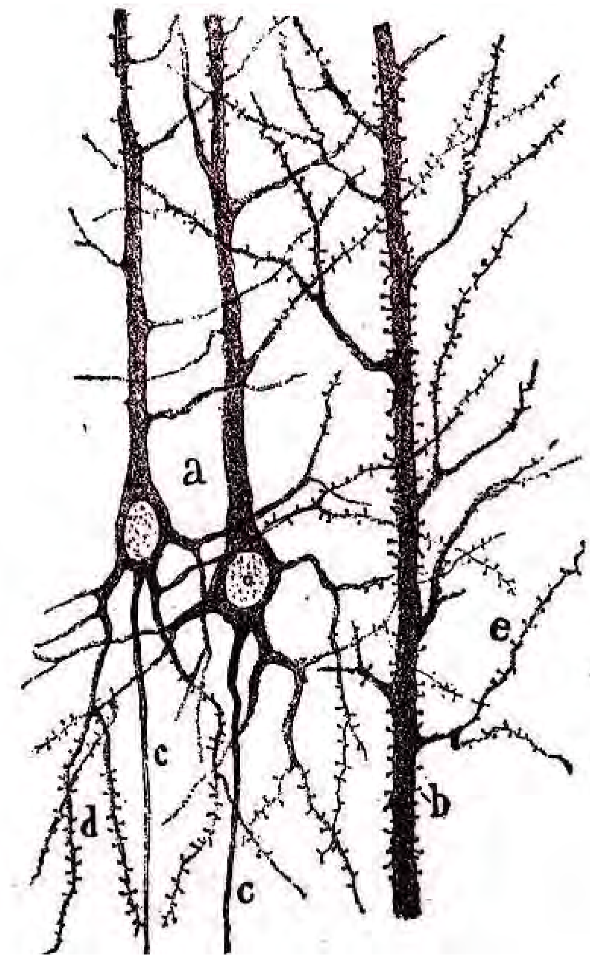


light microscopy (LM)

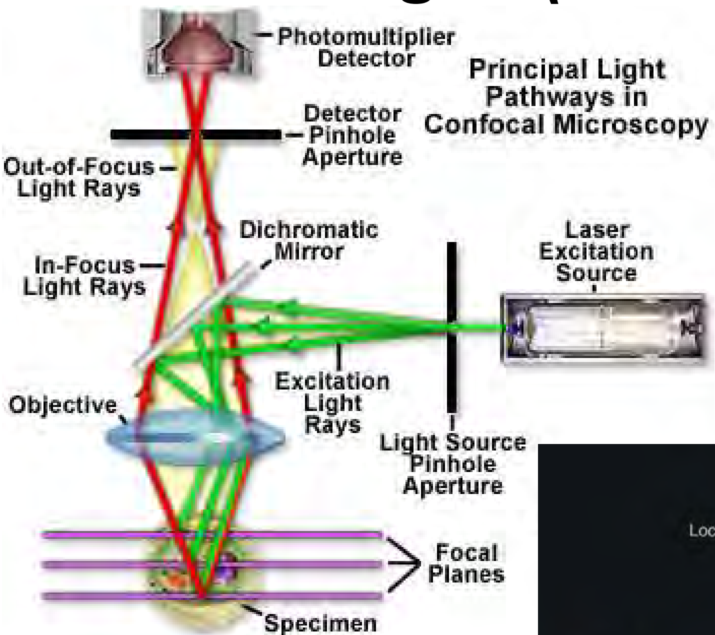


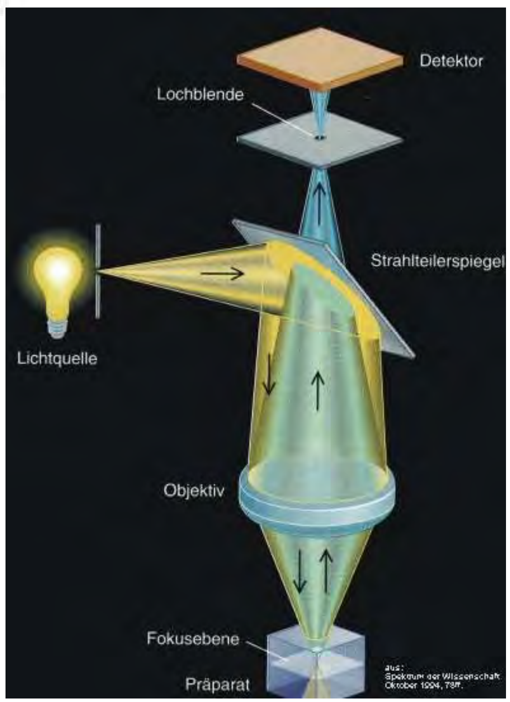
Santiago Ramon y Cajal, 1920

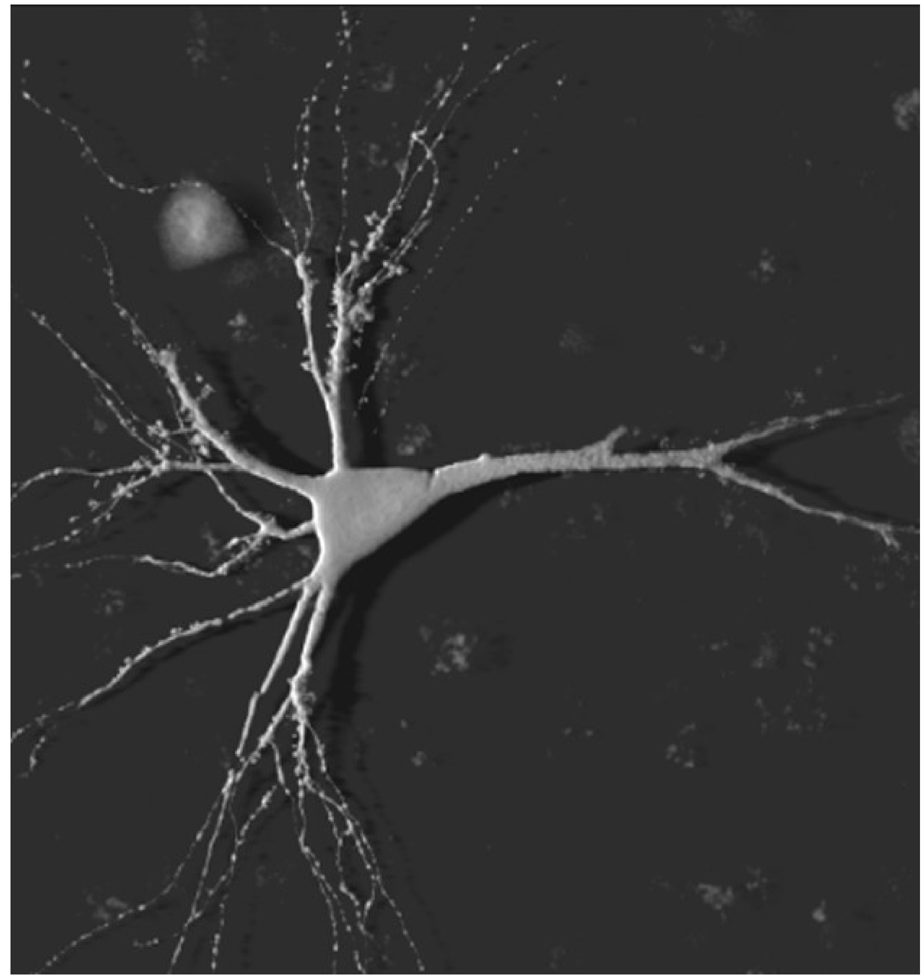




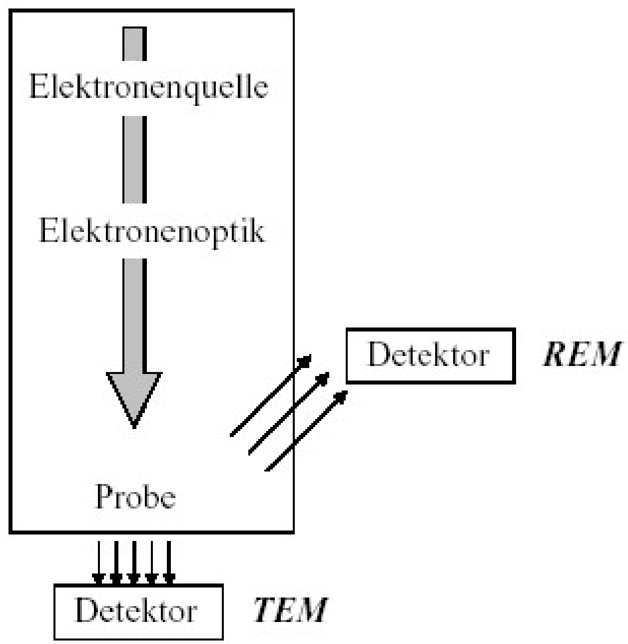
confocal light-(Laser) microscopy



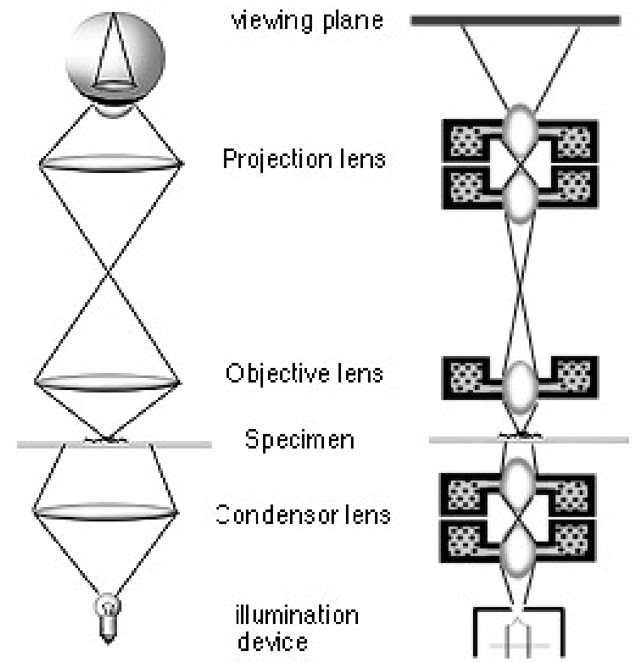


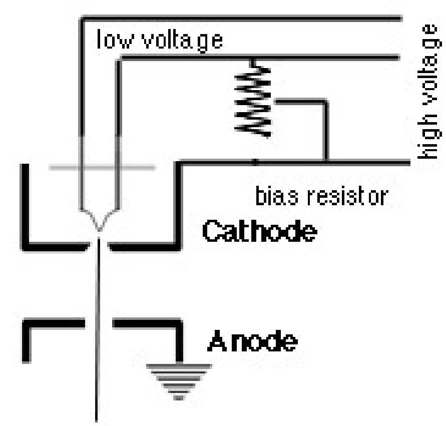


electron microscopy (EM)

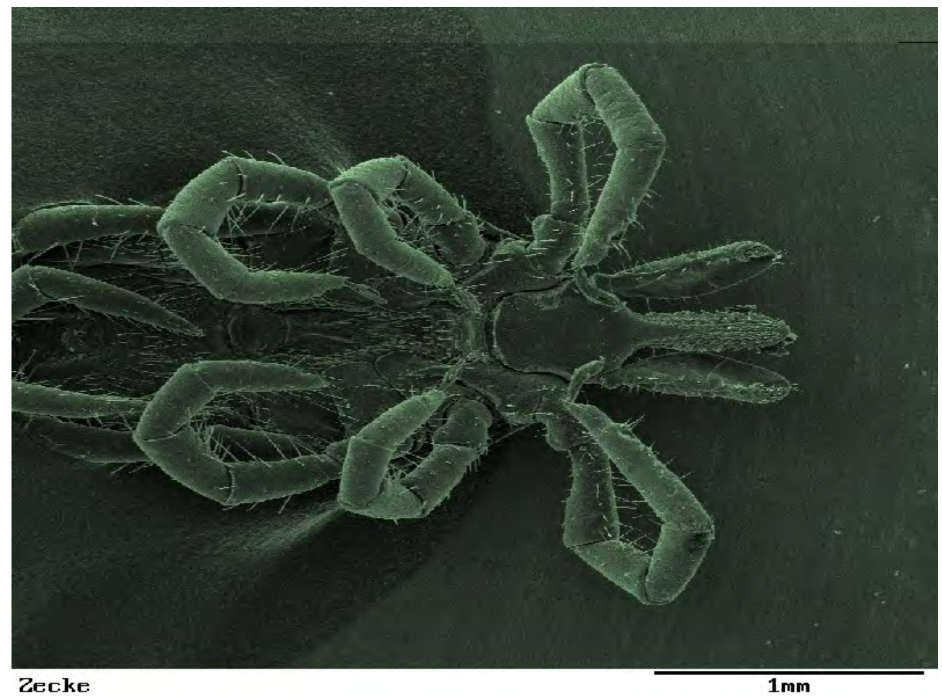


TEM Transmissions-Elektronenmikroskop
REM Raster-Elektronenmikroskop (SEM scanning electron microscopy)

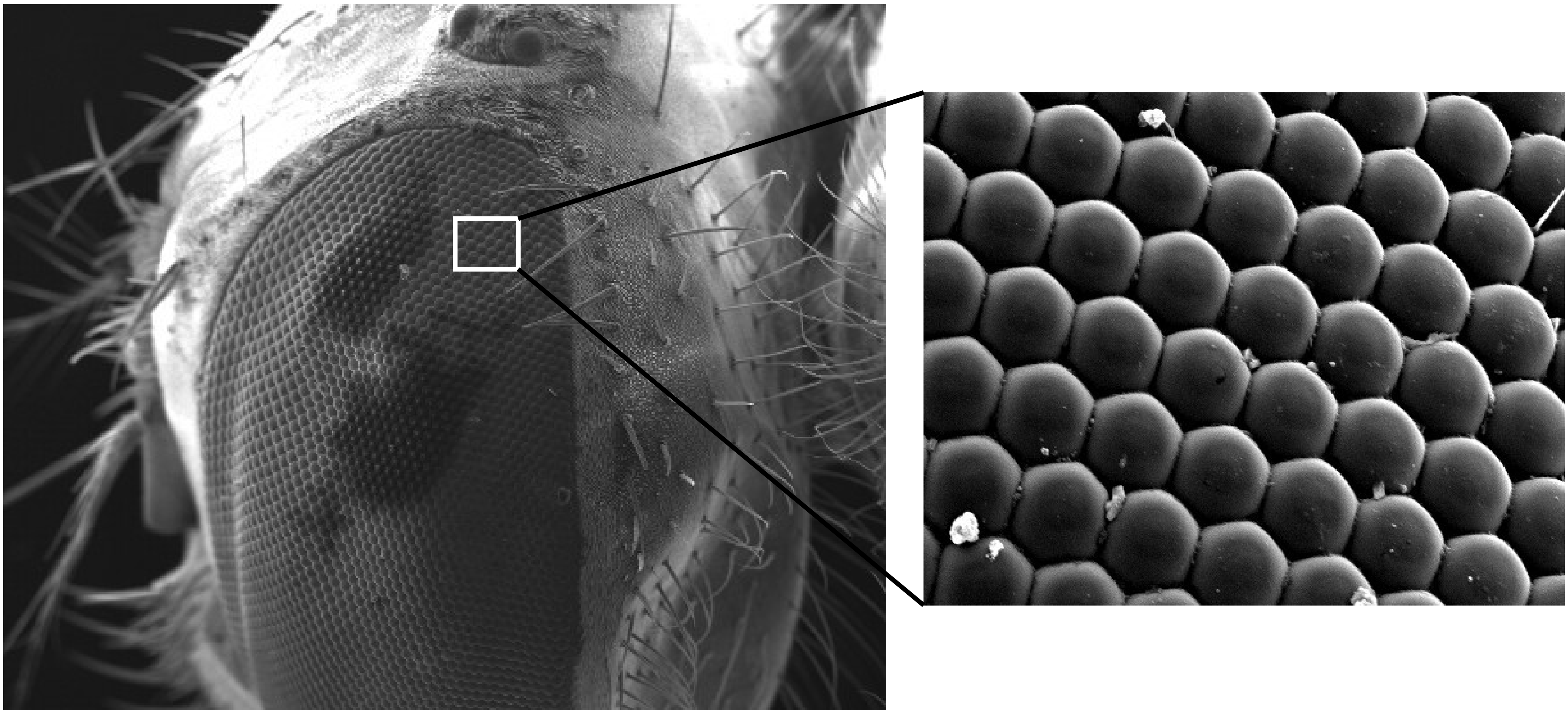




scanning electron microscopy (SEM)



scanning electron microscopy (SEM)



Fliegenauge

atomic force microscopy (AFM)

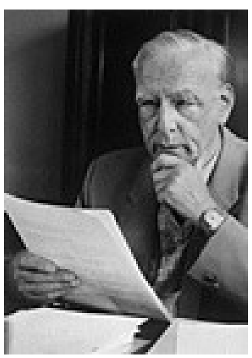
VOLUME 56, NUMBER 9 PHYSICAL REVIEW LETTERS 3 MARCH 1986

Atomic Force Microscope

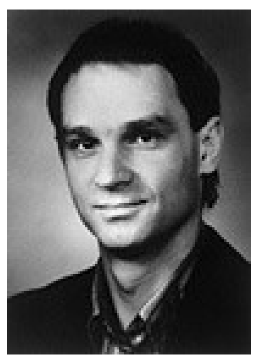
G. Binnig[(a)] and C. F. Quate[(b)]
Edward L. Ginzton Laboratory, Stanford University, Stanford, California 94305
and
Ch. Gerber[(c)]
IBM San Jose Research Laboratory, San Jose, California 95193
(Received 5 December 1985)

The scanning tunneling microscope is proposed as a method to measure forces as small as 10^{-18} N. As one application for this concept, we introduce a new type of microscope capable of investigating surfaces of insulators on an atomic scale. The atomic force microscope is a combination of the principles of the scanning tunneling microscope and the stylus profilometer. It incorporates a probe that does not damage the surface. Our preliminary results *in air* demonstrate a lateral resolution of 30 Å and a vertical resolution less than 1 Å.

The Nobel Prize in Physics 1986

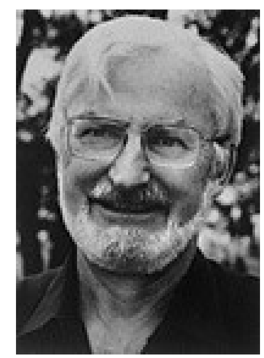


Ernst Ruska
Fritz-Haber-Institut der Max-Planck-Gesellschaft
Berlin
b. 1906
d. 1988
"for his fundamental work in electron optics, and for the design of the first electron microscope"



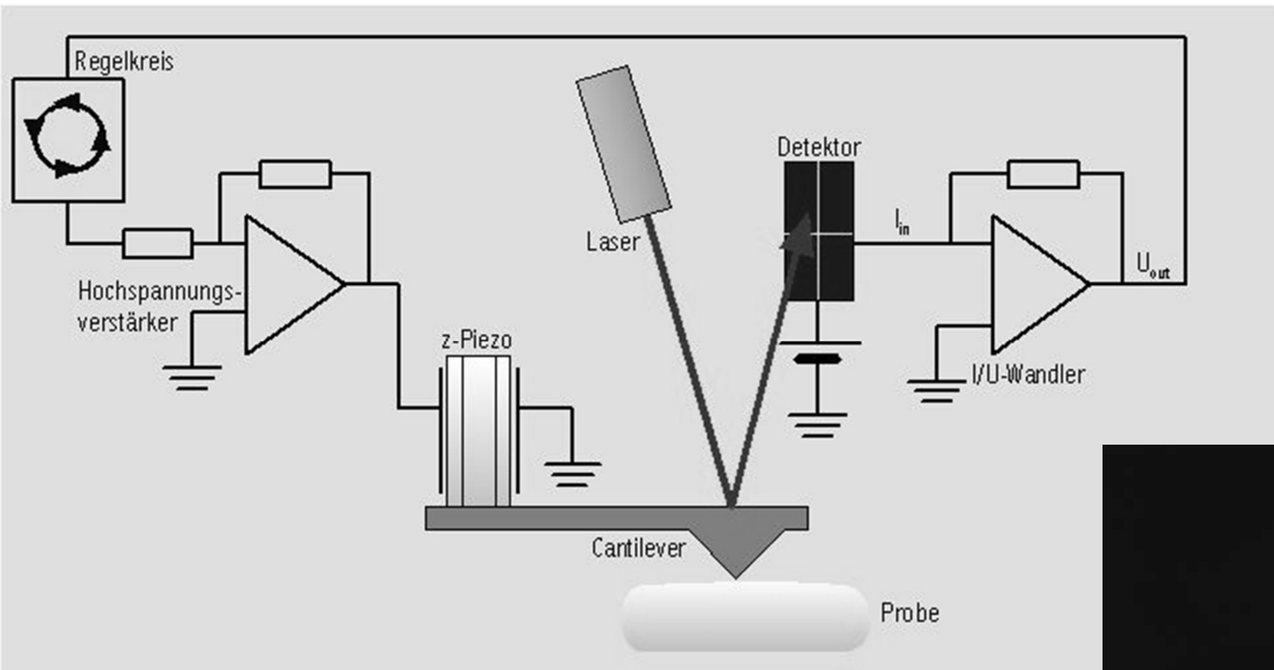
Gerd Binnig
IBM Zurich Research Laboratory Rüschlikon
b. 1947

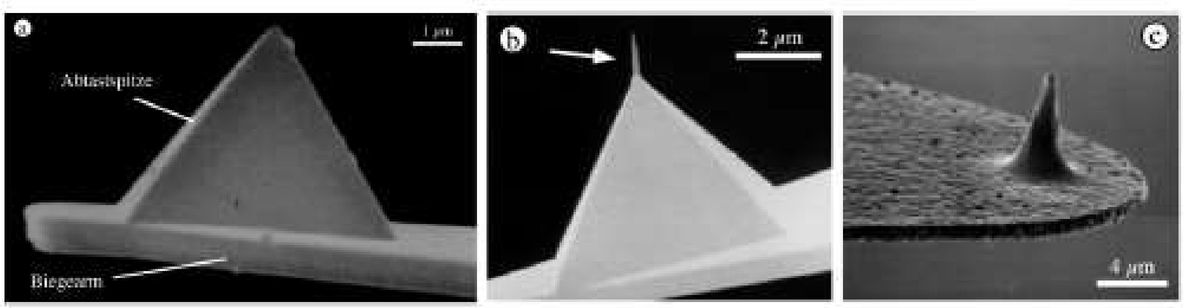
Heinrich Rohrer
IBM Zurich Research Laboratory Rüschlikon
b. 1933

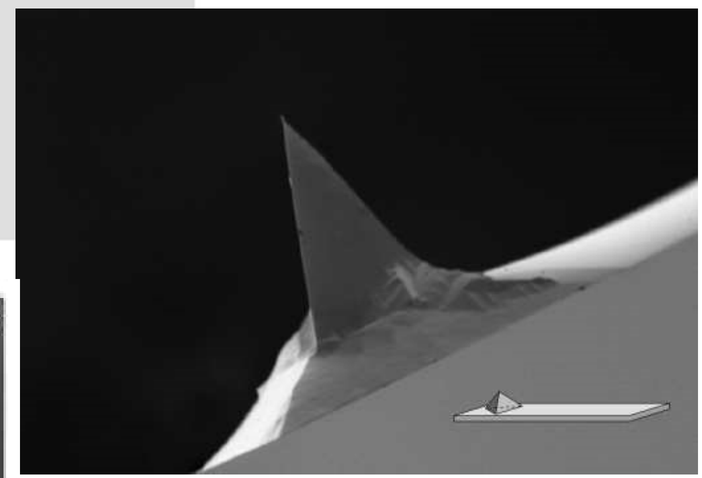


"for their design of the scanning tunneling microscope"

atomic force microscopy (AFM)

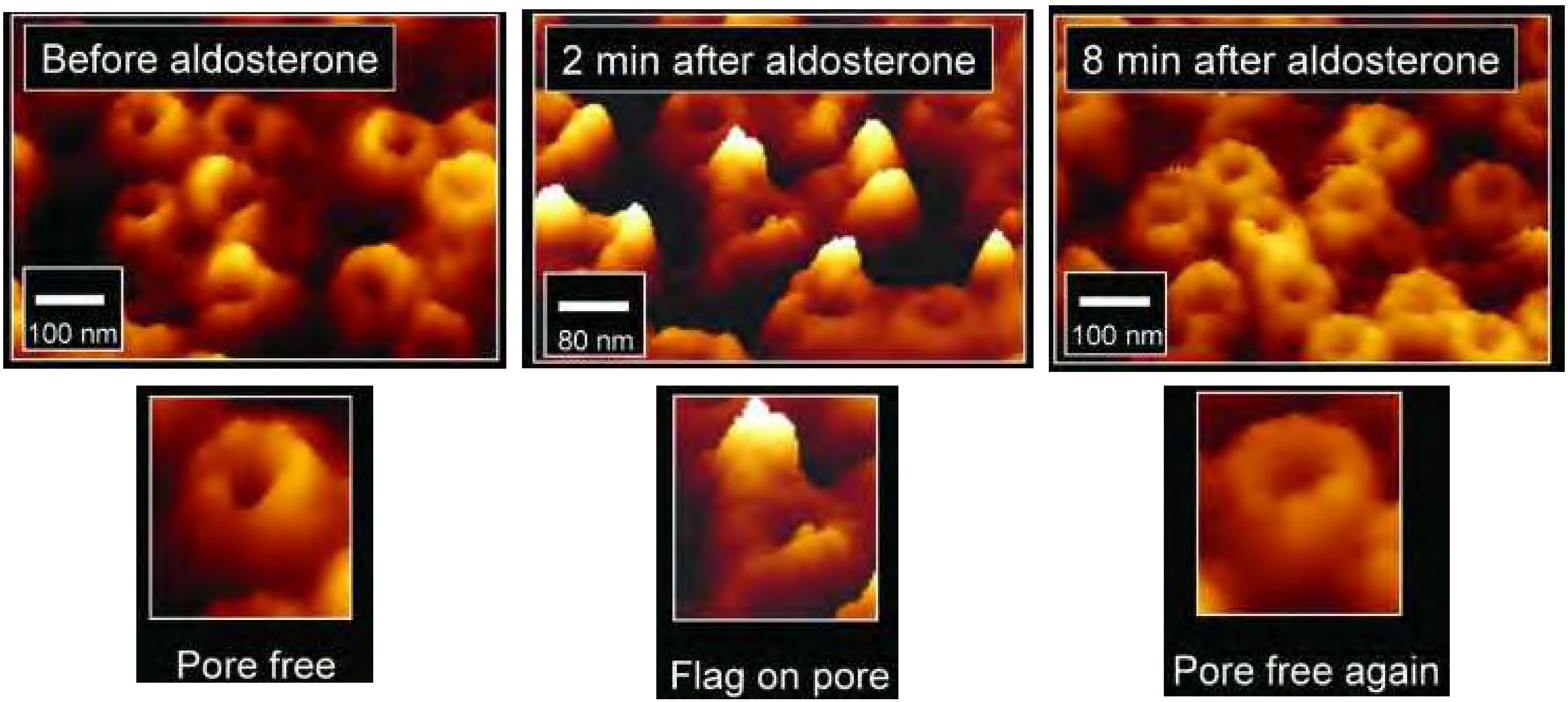






atomic force microscopy (AFM)

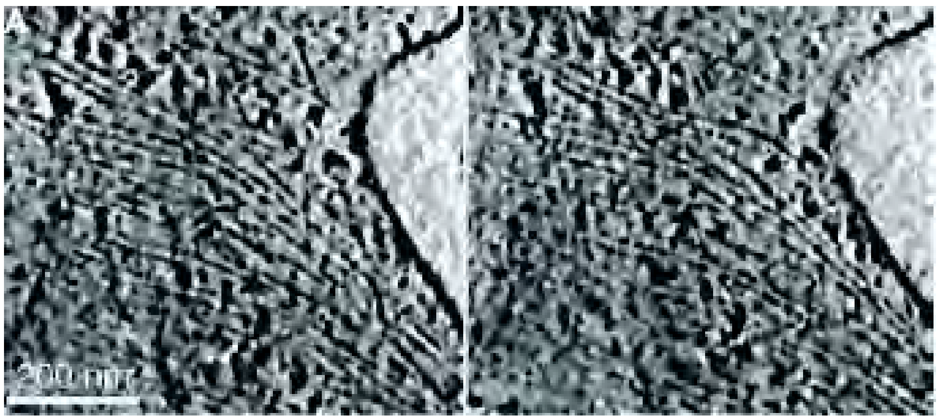
hormone macromolecules entering cell nucleus



Schaefer et al., PNAS 99, 7154, 2002

3D electron tomography

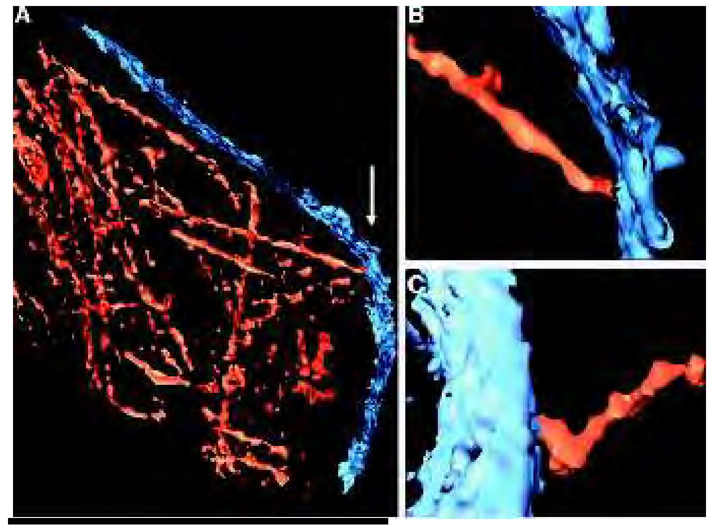
light microscopy



700 nm

actin cyto-sceleton of cells

3D electron tomography



300 nm

resolution: 1.5 - 2 nm

Medalia et al., Science 298, 1209, 2002

Comparison of microscopic techniques

technique	resolution	skin depth	interaction	environment
optical (photons)	~0.3 – 1 µm	<1 µm @10^3X	Light EM wave	air, gas, vacuum, fluid
SEM	0.2 nm	high, but requires thin probes	E-,H-field e^- scattering e^- diffraction	vacuum
AFM	lateral ~ 1 nm depth 0.1 nm	0.1 nm	atomic forces (van der Waals, covalent, ionic) friction, electrostatic + magn. forces	vacuum, air, gas, fluid

Aims of medical imaging:

- visualization of the body's internal structure

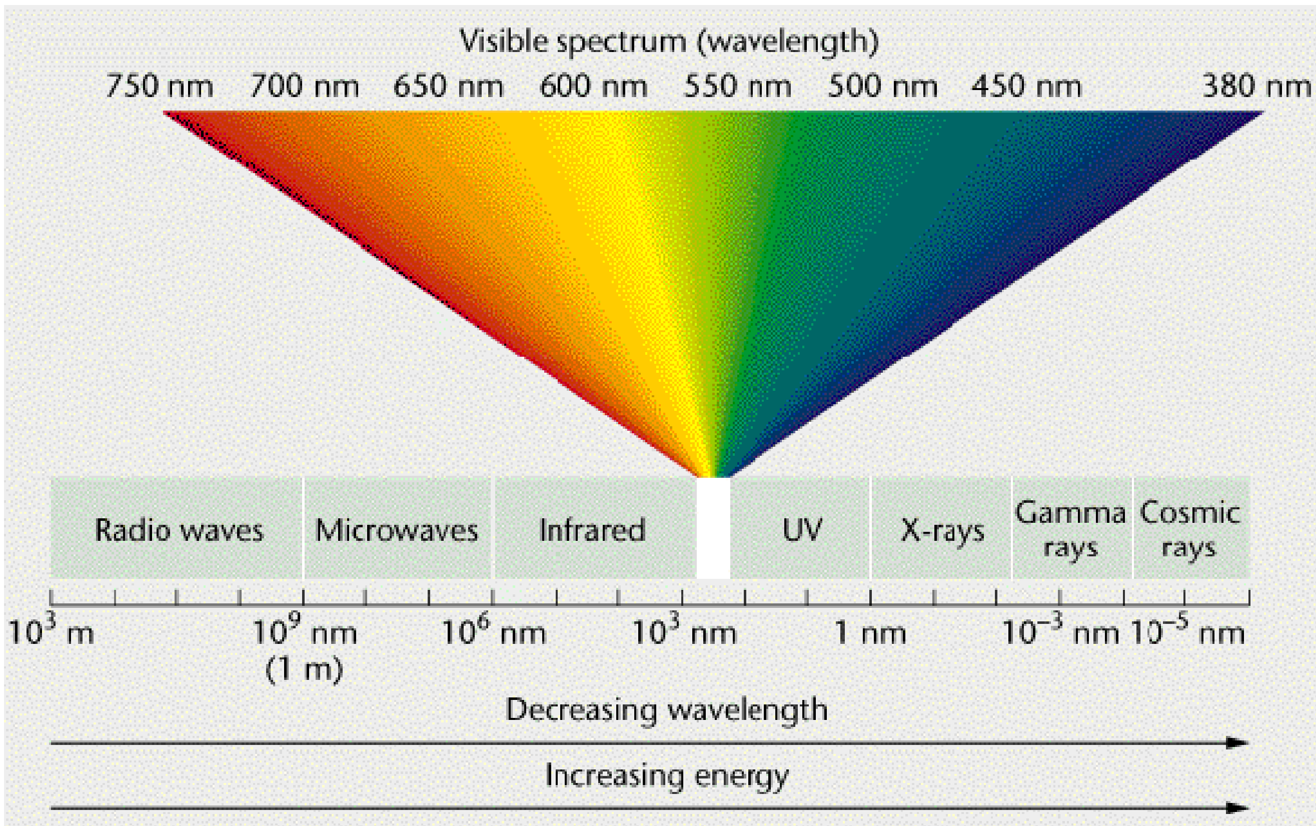
LM, SEM, AFM inapplicable

- non-destructive (non-invasive) investigation of structure and function

LM, SEM, AFM inapplicable

- diagnosis
- therapy / therapy planning
- follow up

forms of energies



(Klug & Cummings 1997)

caveat: biocompatibility !!

Signals of imaging techniques for medical diagnosis

endogenous signals				exogenous signals					
Bio- elec-tricity	Bio- magne-tism	infrared imaging	impedance imaging	X-rays CT	PET	SPECT	Scinti-graphy	Magnetic Nuclear Resonance	US CT
EKG EEG ECoG EMG ENG	MKG MEG	IRI	IMPI	image plate image ampl. detectors synchronton-radiation	Positron Emission Tomogr.	Single Photon Emission Computed Tomogr.		MRS MR-Angio. fMRI	Sono-graphy
E-field	H-field	IR	Z	μ	γ (511 keV)	γ	γ	e.m. HF	sound
function / (morphology)				morphology		metabolism			function / morphology

Bioelectricity / Biomagnetism

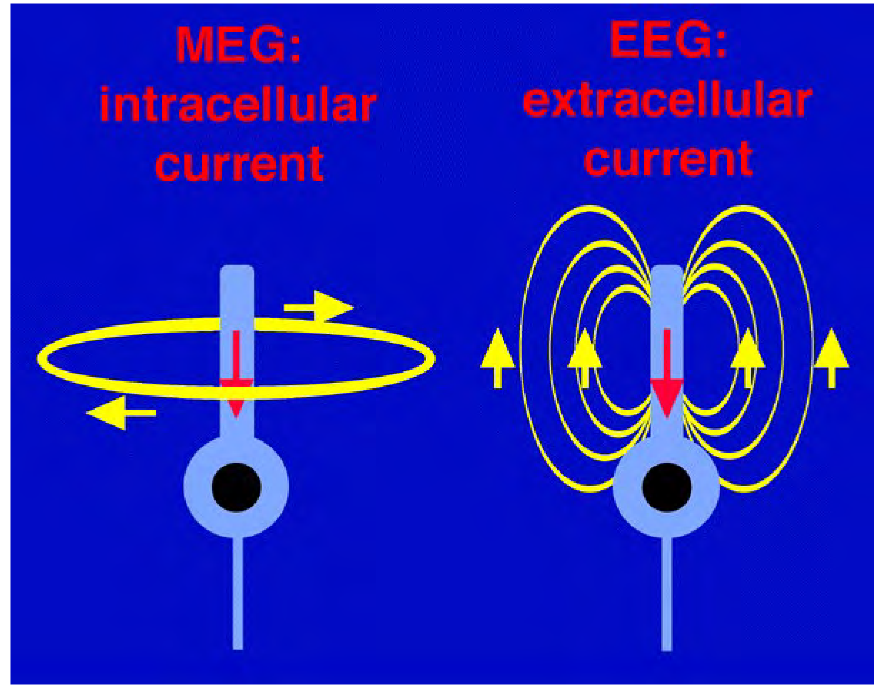
- Electric / Magnetic Source Imaging:

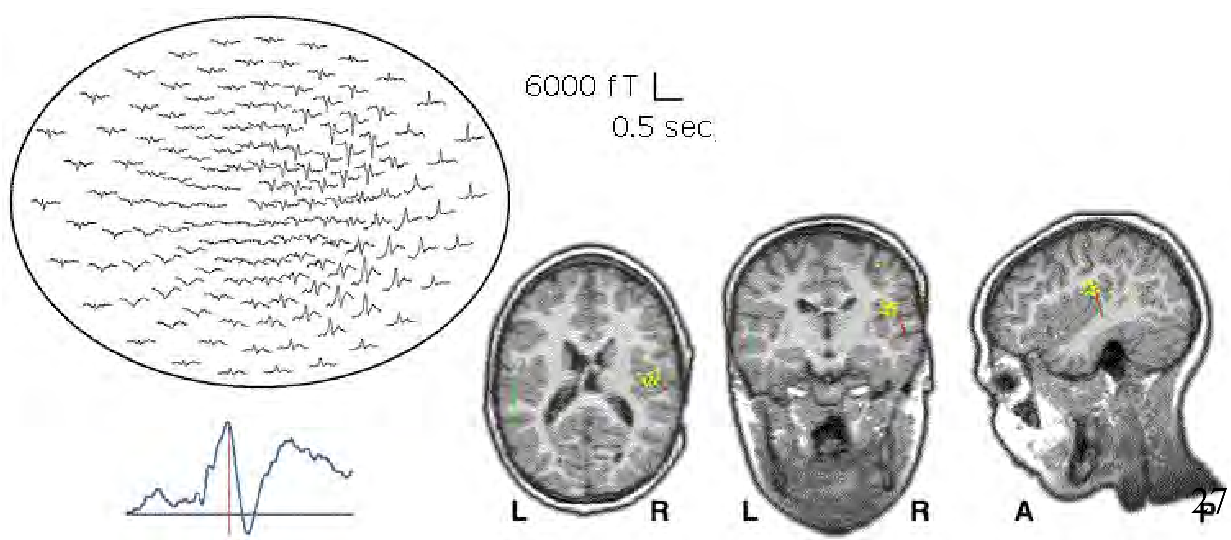
- Information exchange
  (neurons, cells, muscle fibres)
  -> current flow -> magnetic field
  (nV – mV) (fT – mT)

- sensitive sensors/amplifier
  E-field: electrodes
  H-field: SQUID

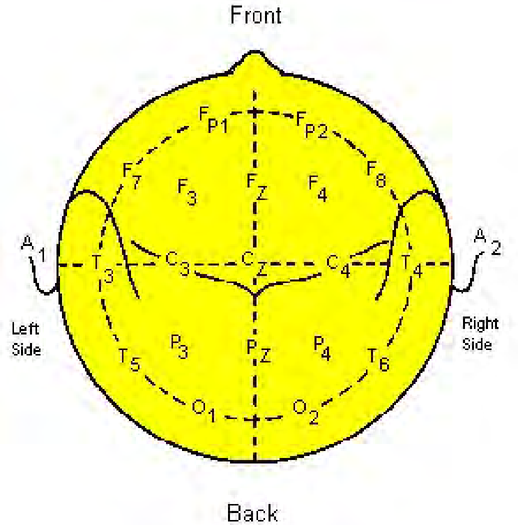
- source-/volume-conductor models
  inverse problem!

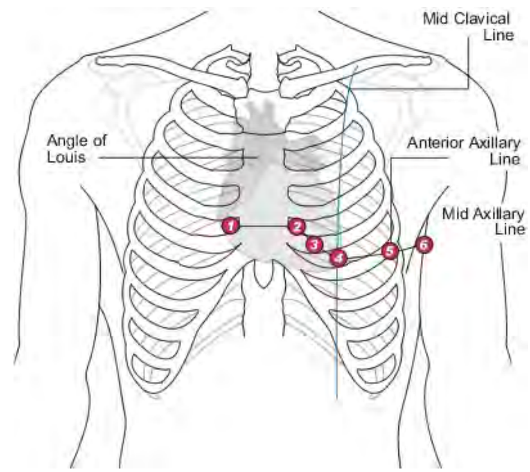
- fusion with CT/MRI

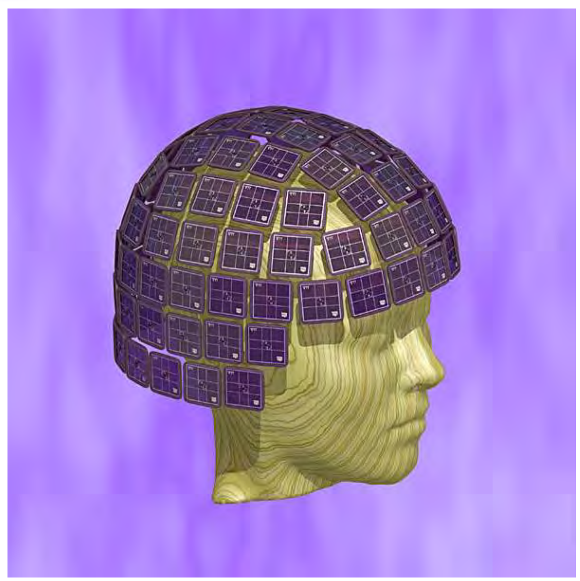


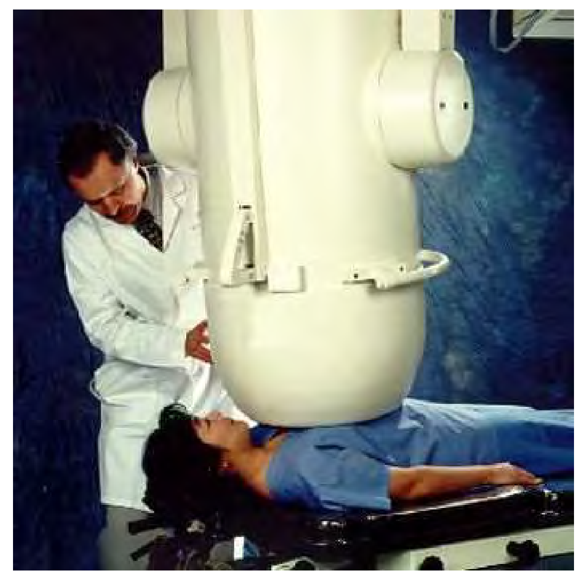


Bioelectricity / Biomagnetism



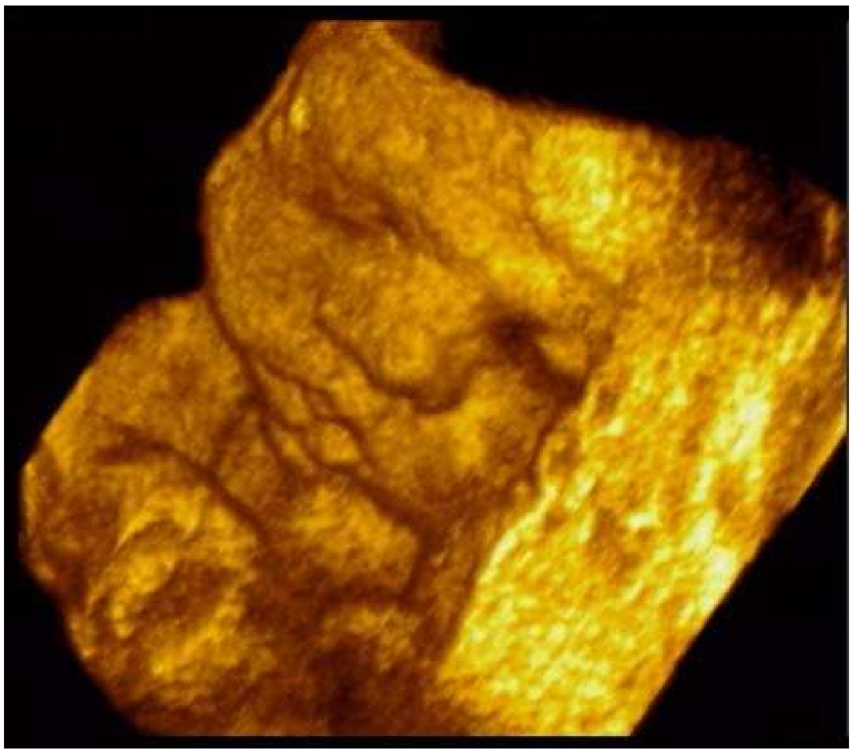


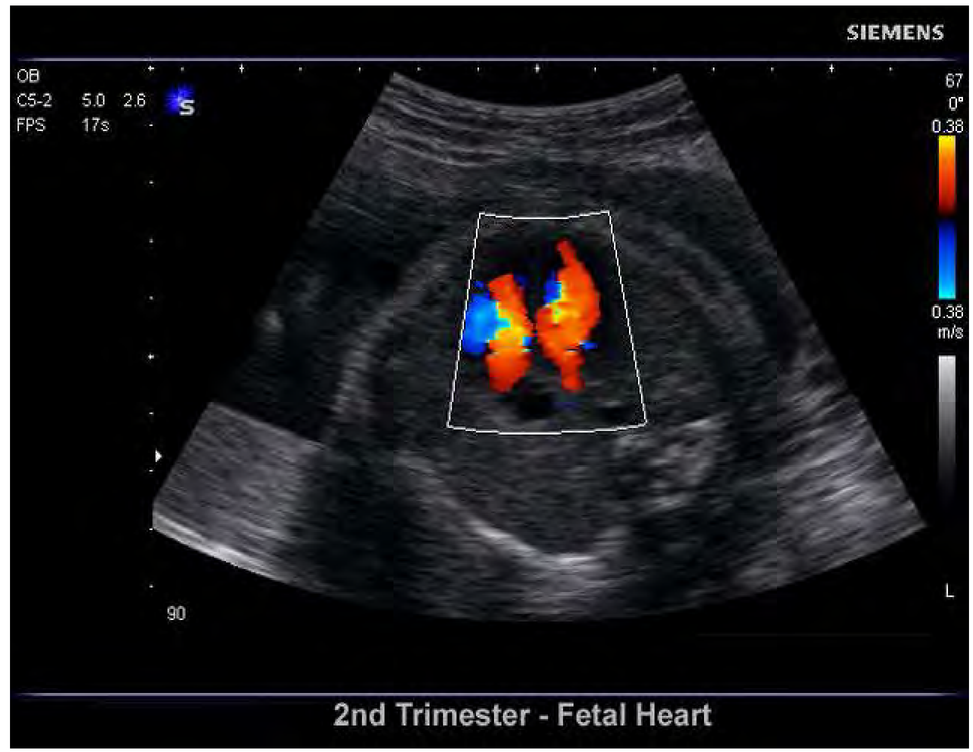




ultrasound (US):

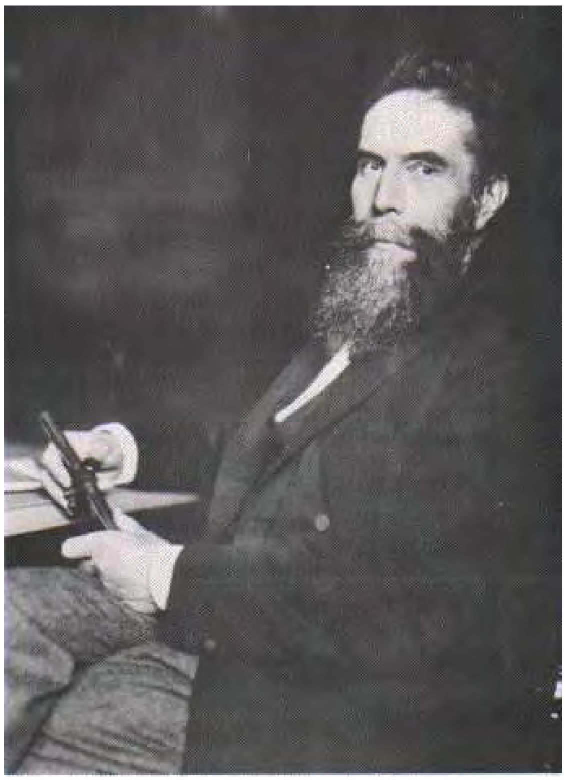
- reflection of US from (acoustic) surface (e.g. boundary of organ)
- degree of reflection depends on acoustic properties of tissues (a few % of sound energy for soft tissue)
- scattering of US on small objects; speckle noise





x-ray imaging

attenuation of x-rays in different tissues of the body

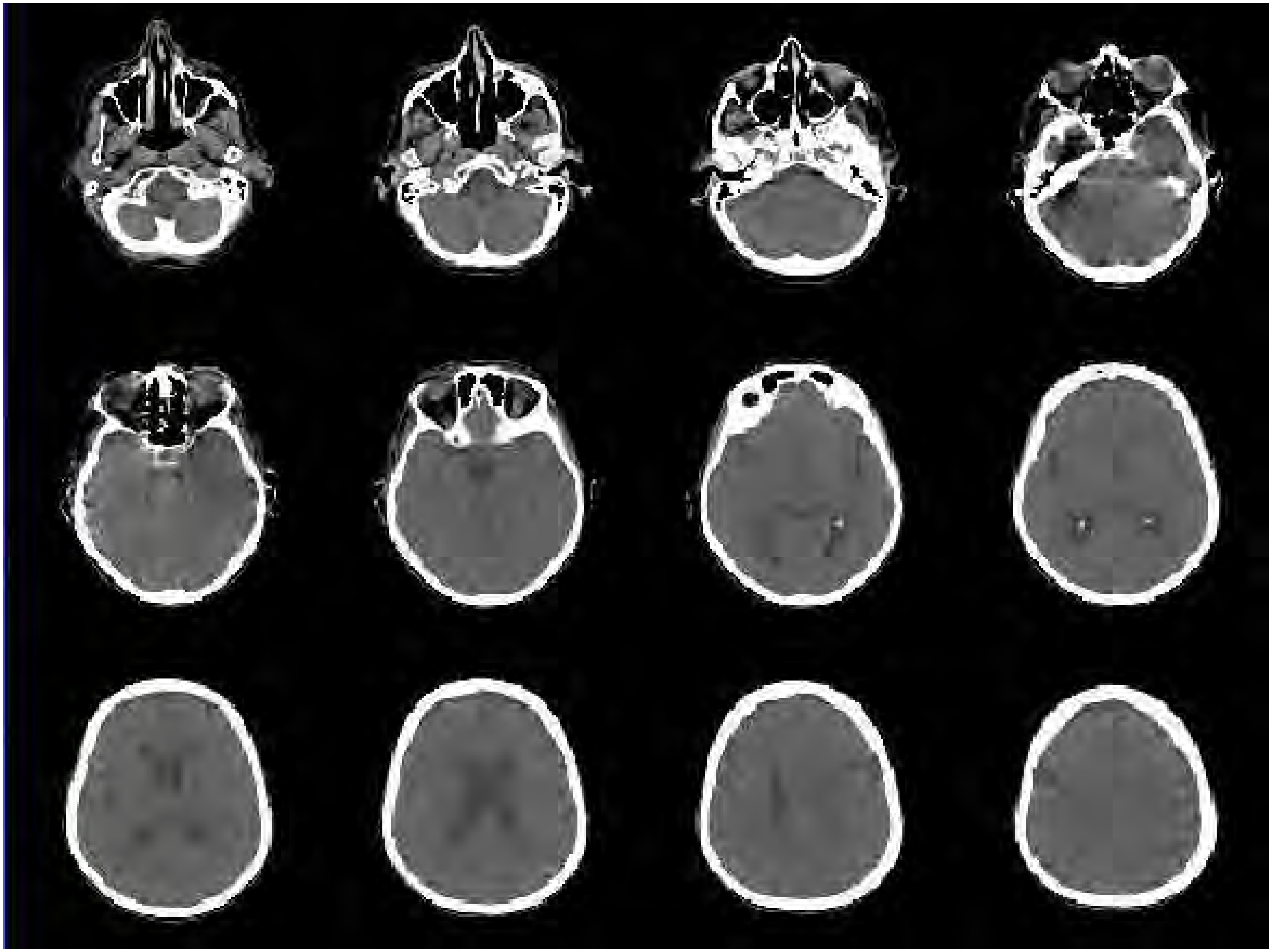


Wilhelm Conrad Röntgen
discovery of x-rays
on 8. November 1895
Nobel Physics prize: 1901

x-ray image of
Mrs. Röntgen's hand
(22. December 1895)

modern x-ray image

x-ray CT:

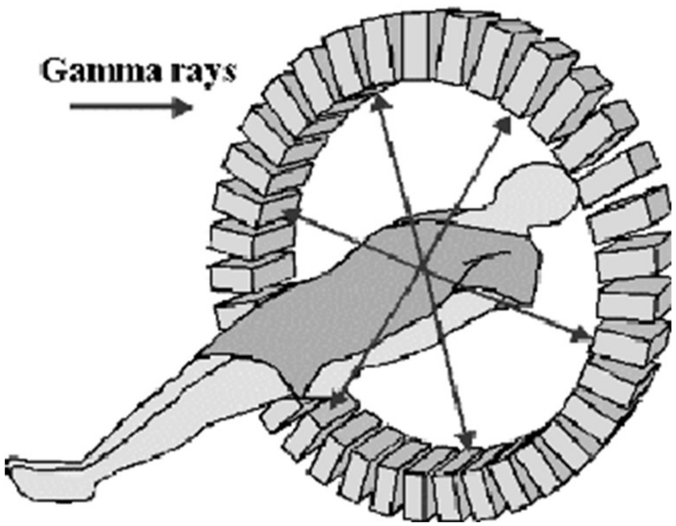


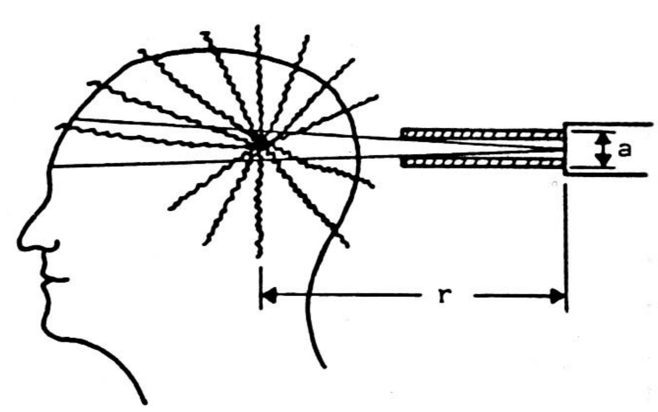
x-ray CT:

nuclear medical imaging techniques (PET/SPECT)

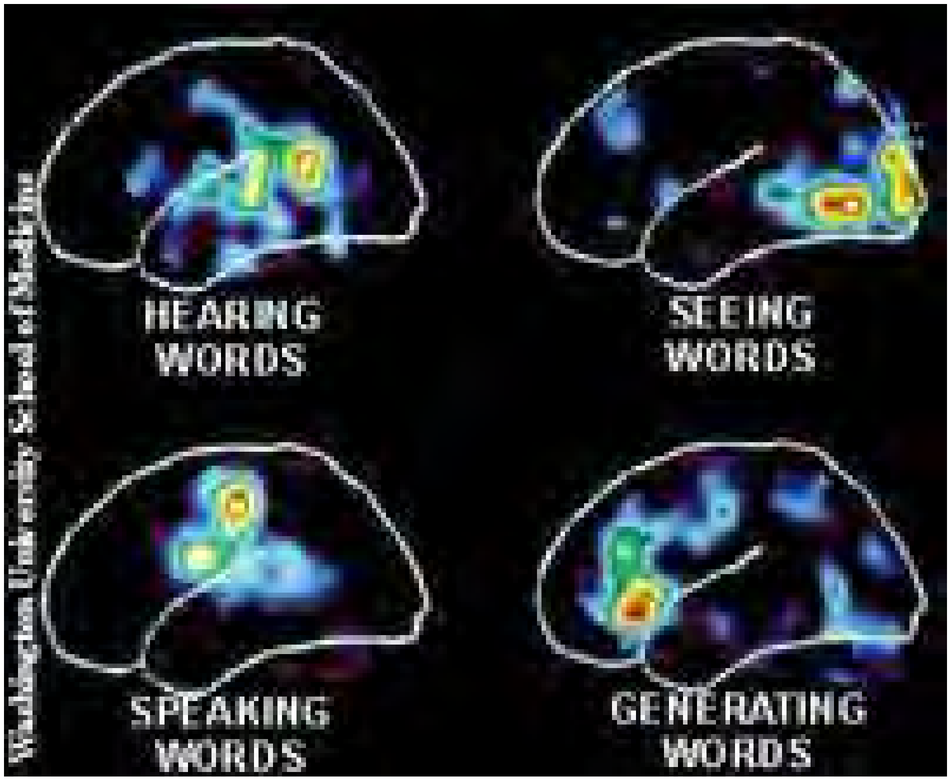
- *Positron Emission Tomography* (PET): radioactive labeling of biological substance with positron emitter (C-11, N-13, O-15, F-18) e.g. O-15 water, F-18 deoxyglucose
- *Single Photon Emission Computed Tomography* (SPECT): radionuclide, γ-emitter

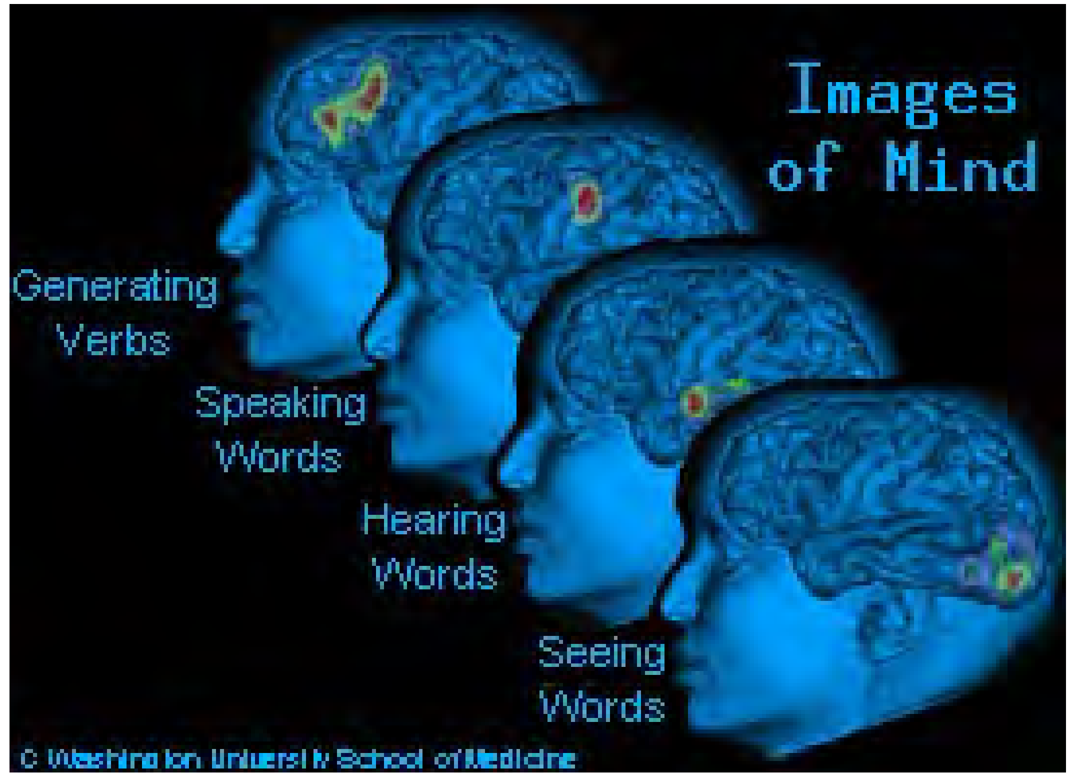
- introduce tracer into body
- distribution pattern depending on function of targeted organ(s) and recording time
- measurement of radiation emitted from the body



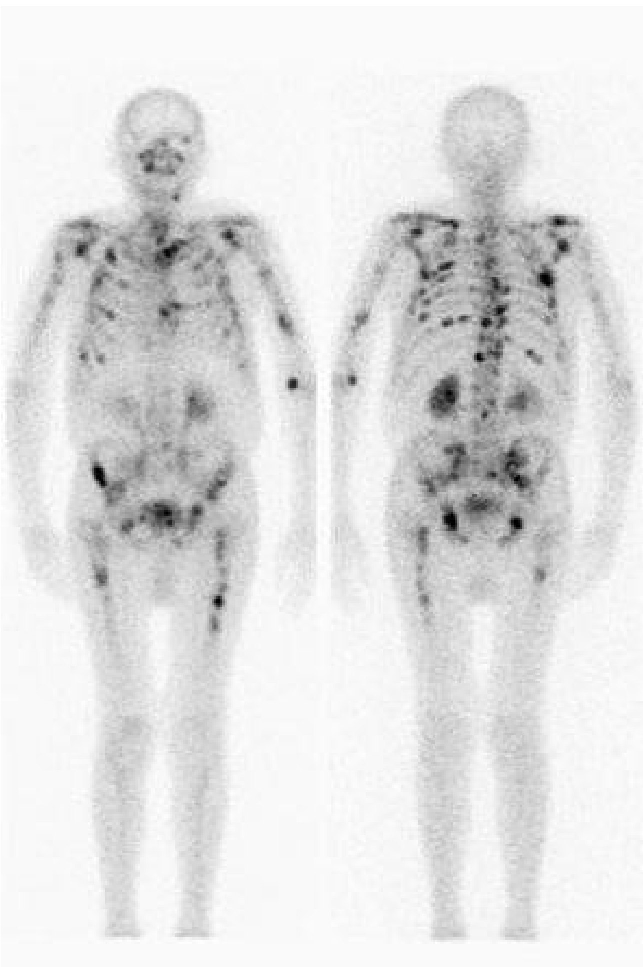


nuclear medical imaging techniques (PET)

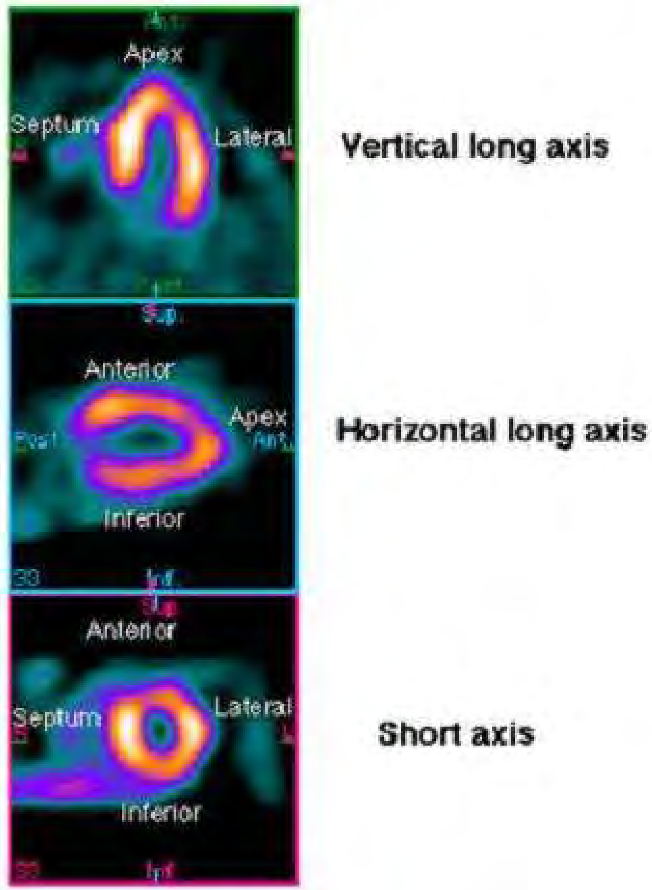




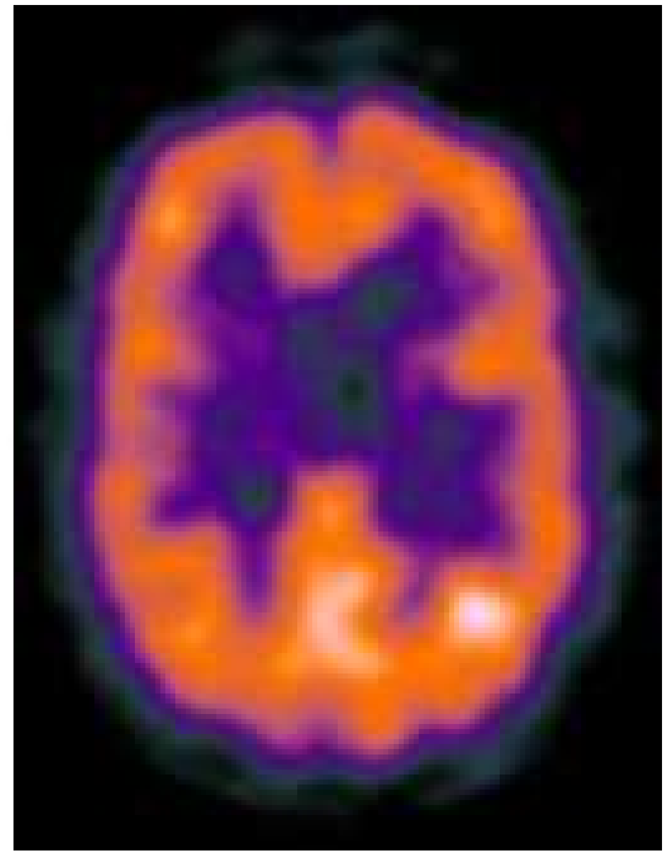
nuclear medical imaging techniques (SPECT)



whole body
bone neoplasm (tumor)



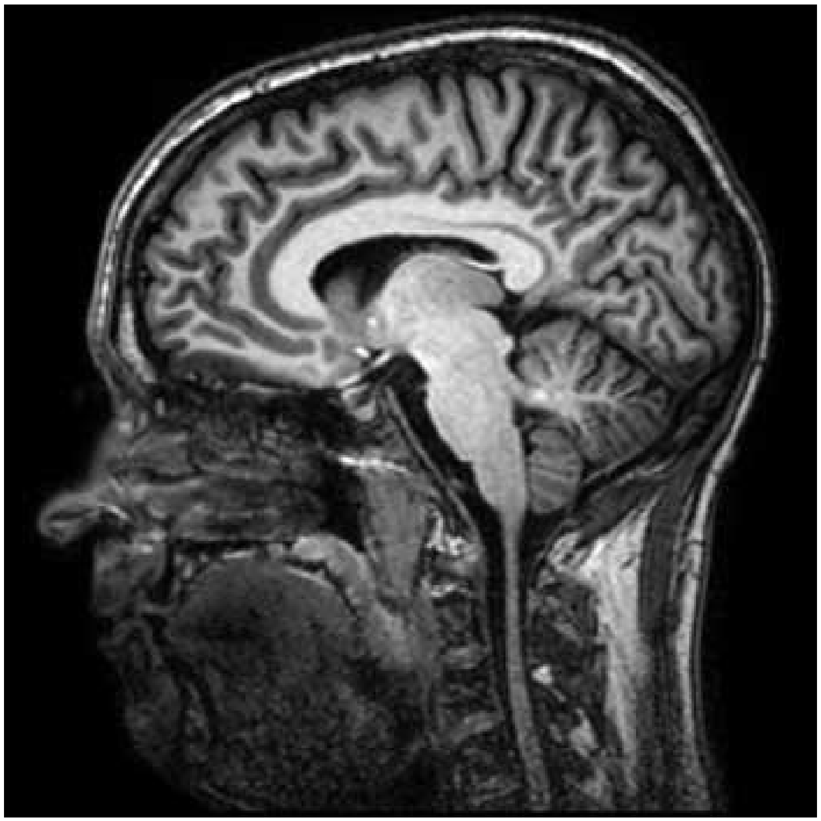
heart
functioning



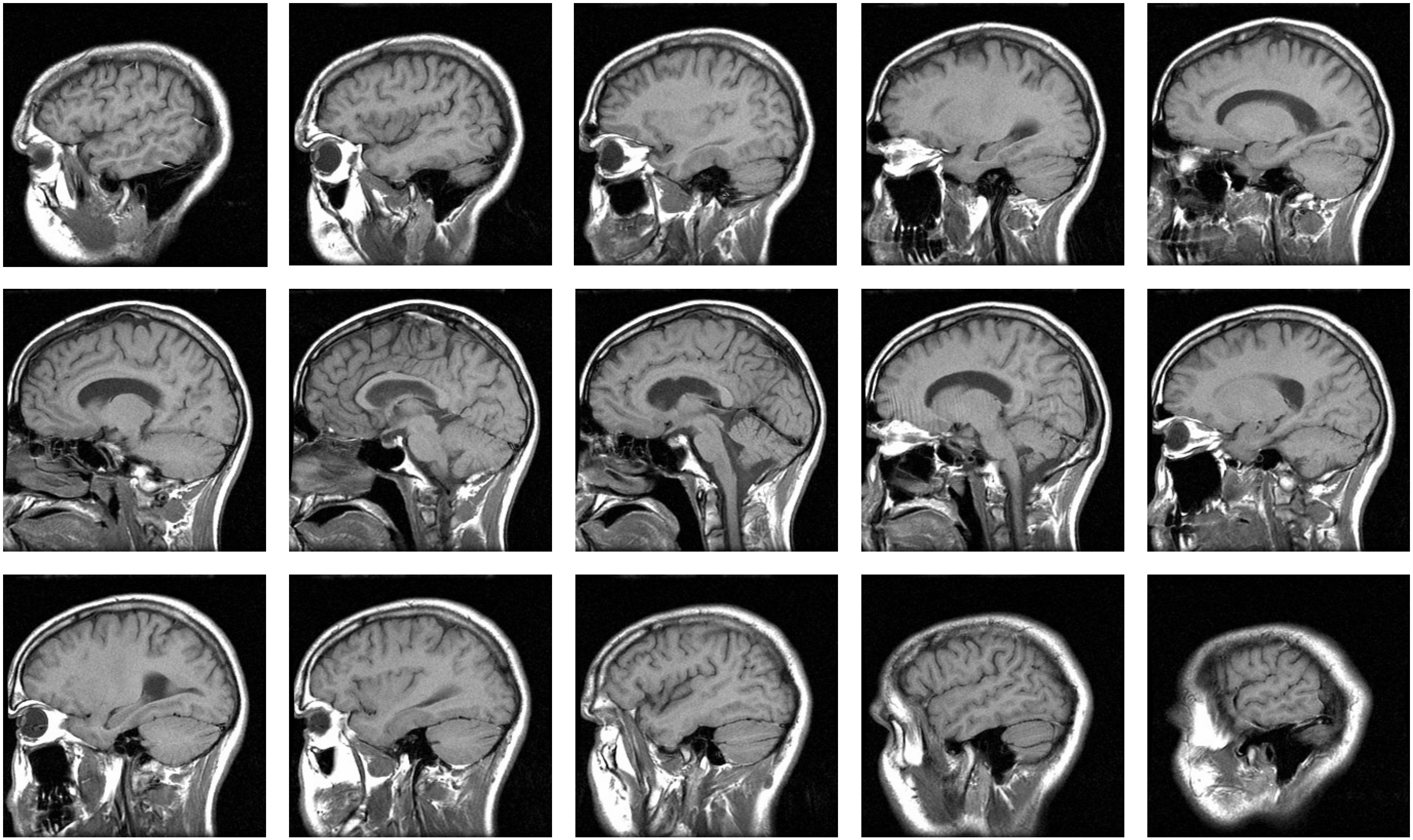
brain

Magnetic Resonance Imaging (MRI)

- based on nuclear magnetic resonance (NMR)
- distribution of different relaxation time of hydrogen nuclei and of proton density due to chemical changes or due to changes in concentration

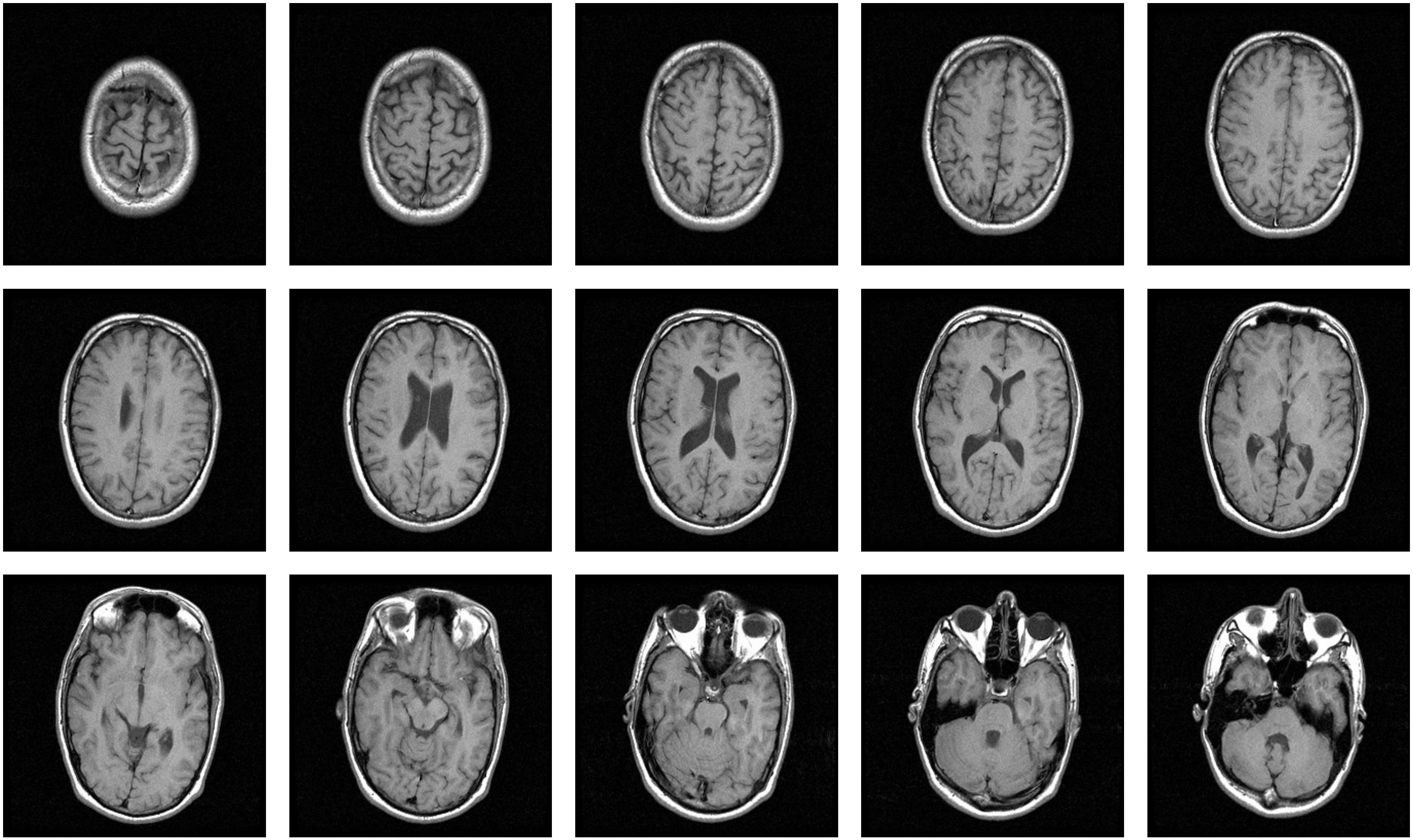


Magnetic Resonance Imaging (MRI)



brain; sagittal Multislice T1

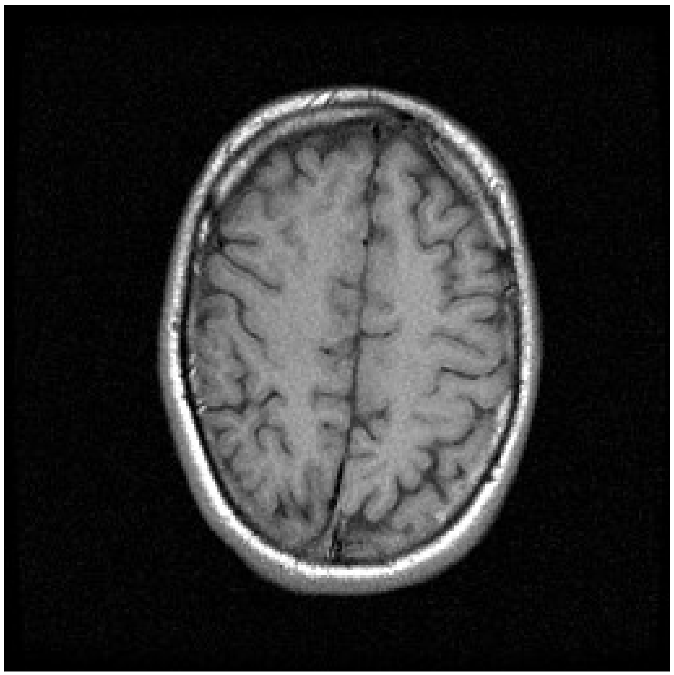
Magnetic Resonance Imaging (MRI)



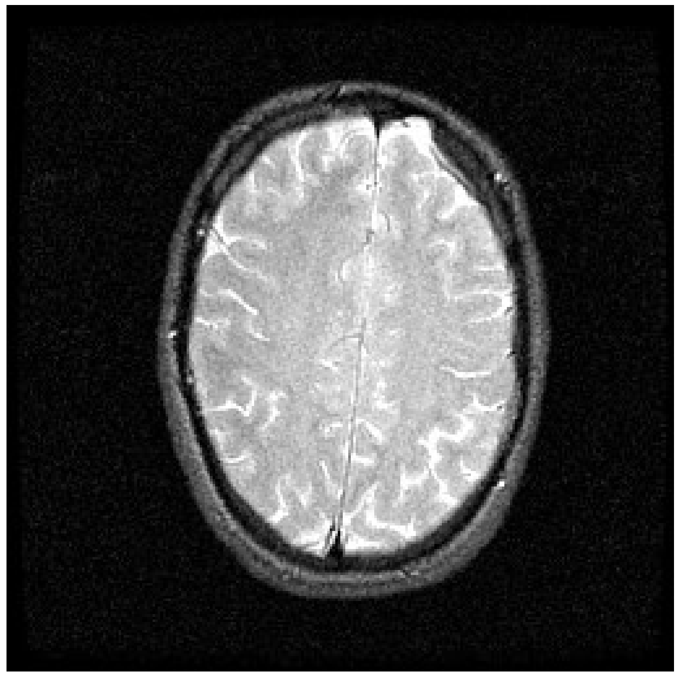
brain; axial Multislice T1

Magnetic Resonance Imaging (MRI)

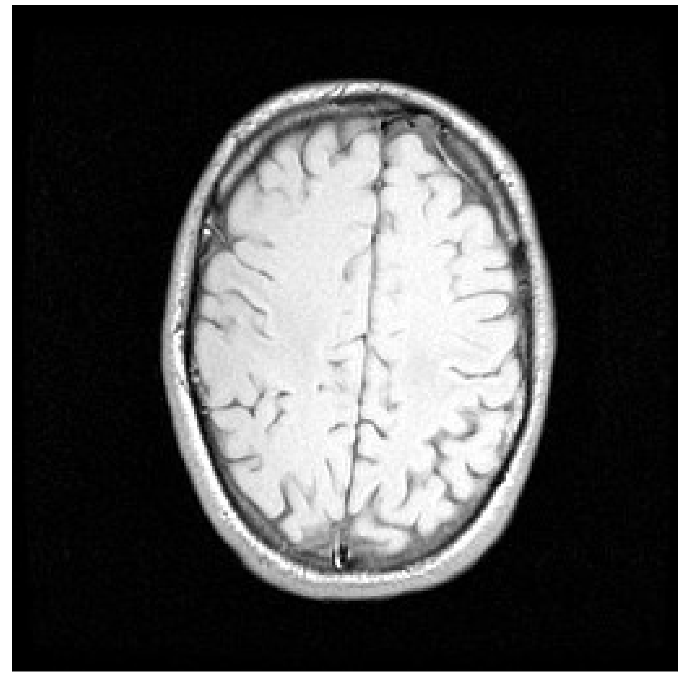
T1 contrast



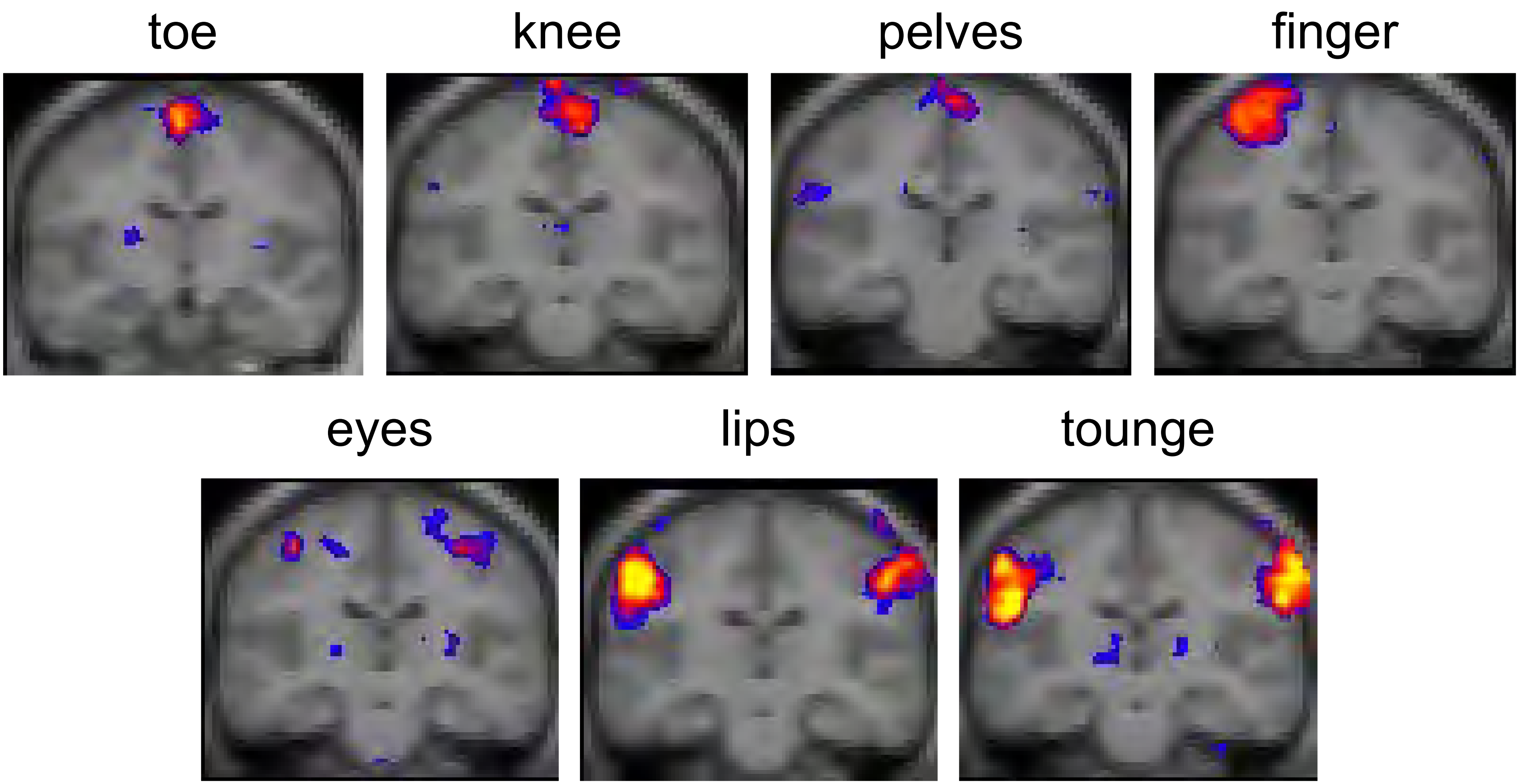
T2 contrast



proton density

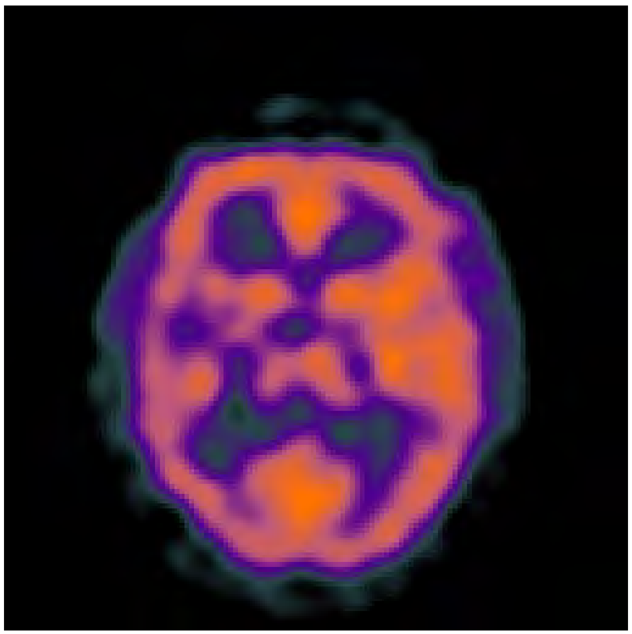


functional Magnetic Resonance Imaging (fMRI)



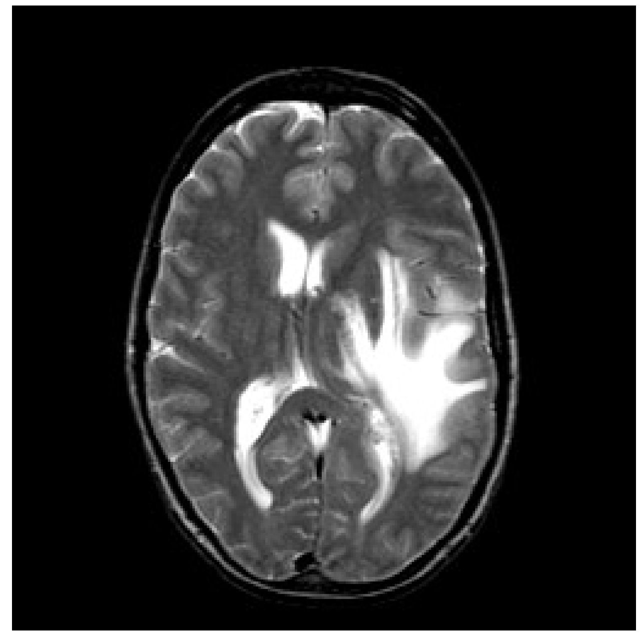
comparison of imaging techniques

PET



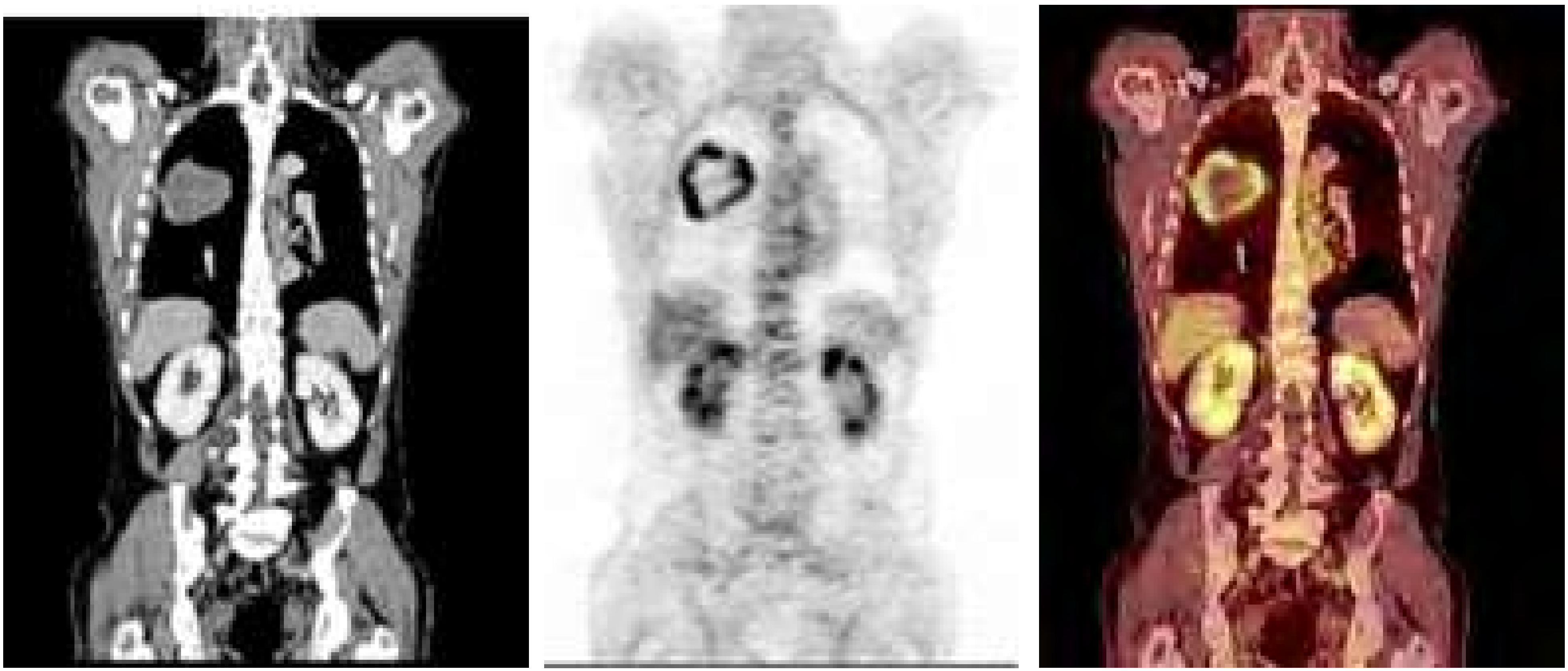
CT

MRI

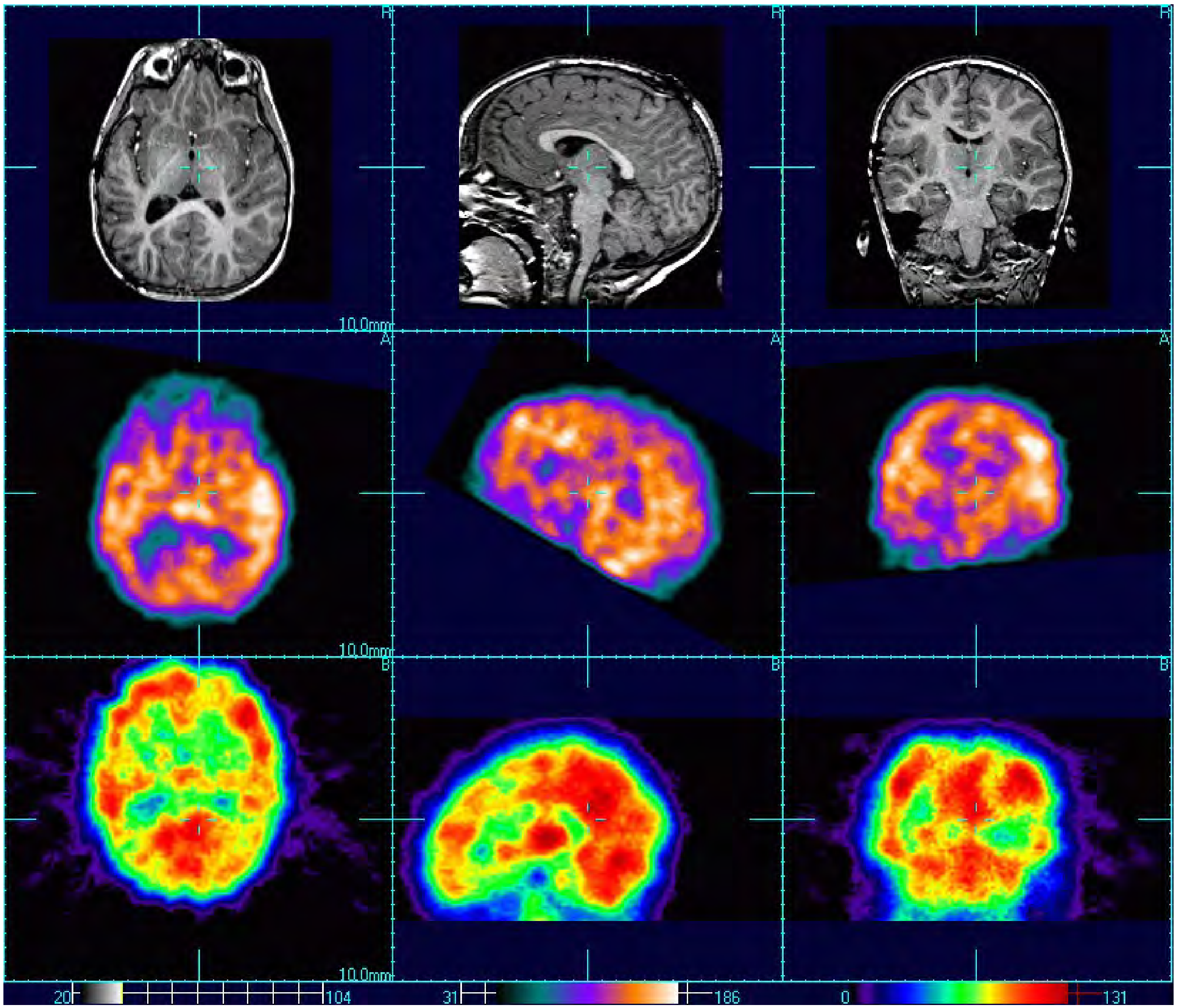


fusion of imaging techniques

CT PET CT-PET overlay



fusion of imaging techniques

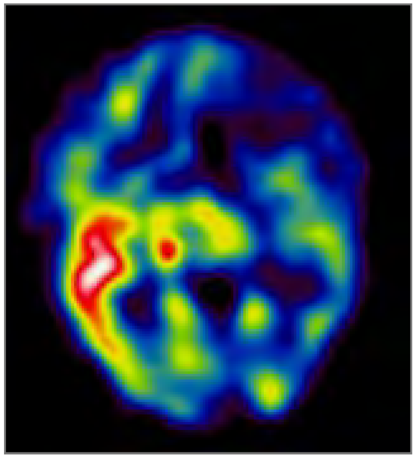


MRI

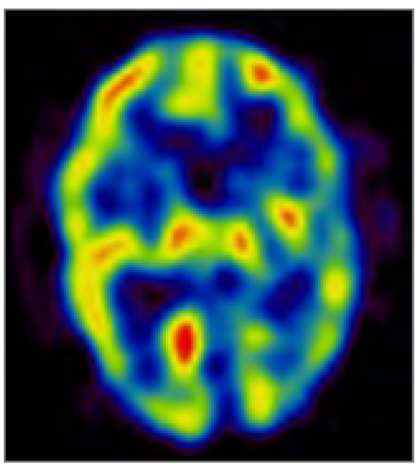
SPECT
(A-scan)

SPECT
(B-scan)

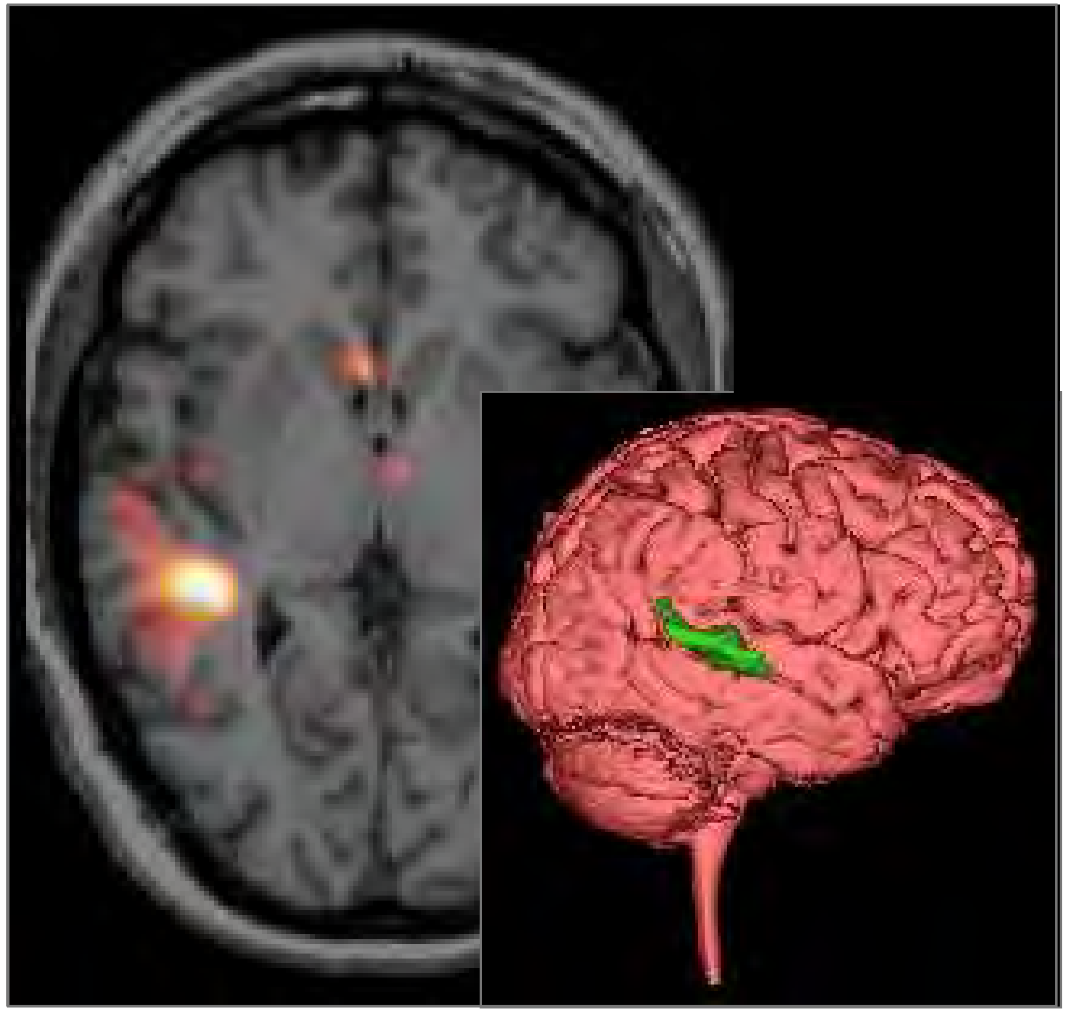
fusion of imaging techniques



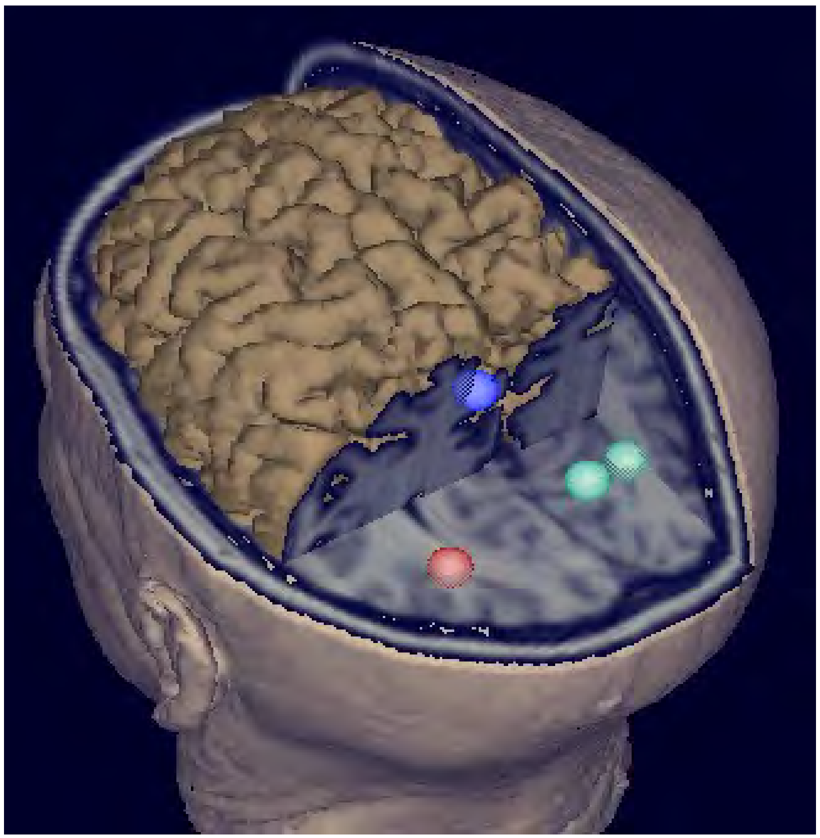
ictal SPECT

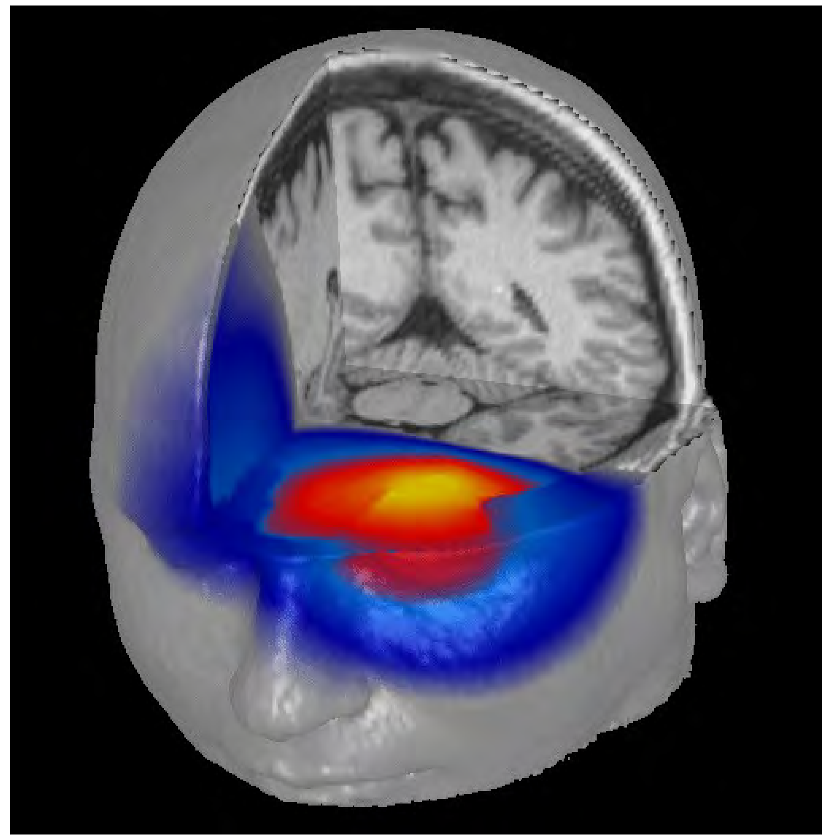


interictal SPECT



fusion of imaging techniques
MSI and MRI

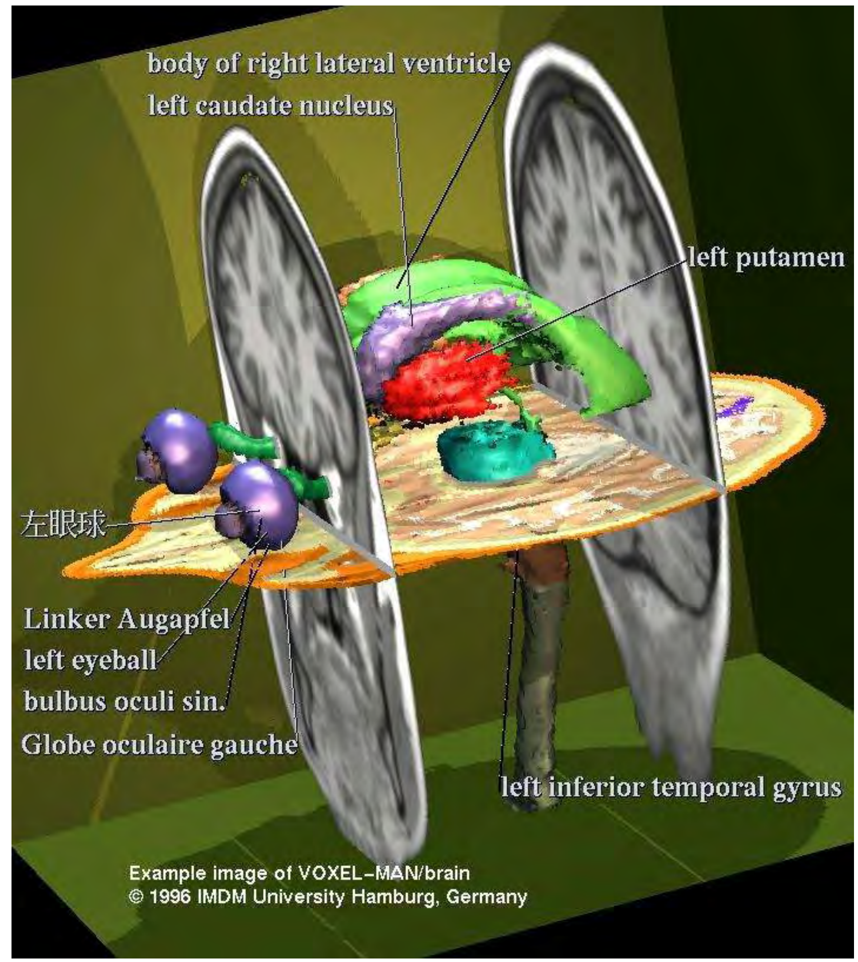




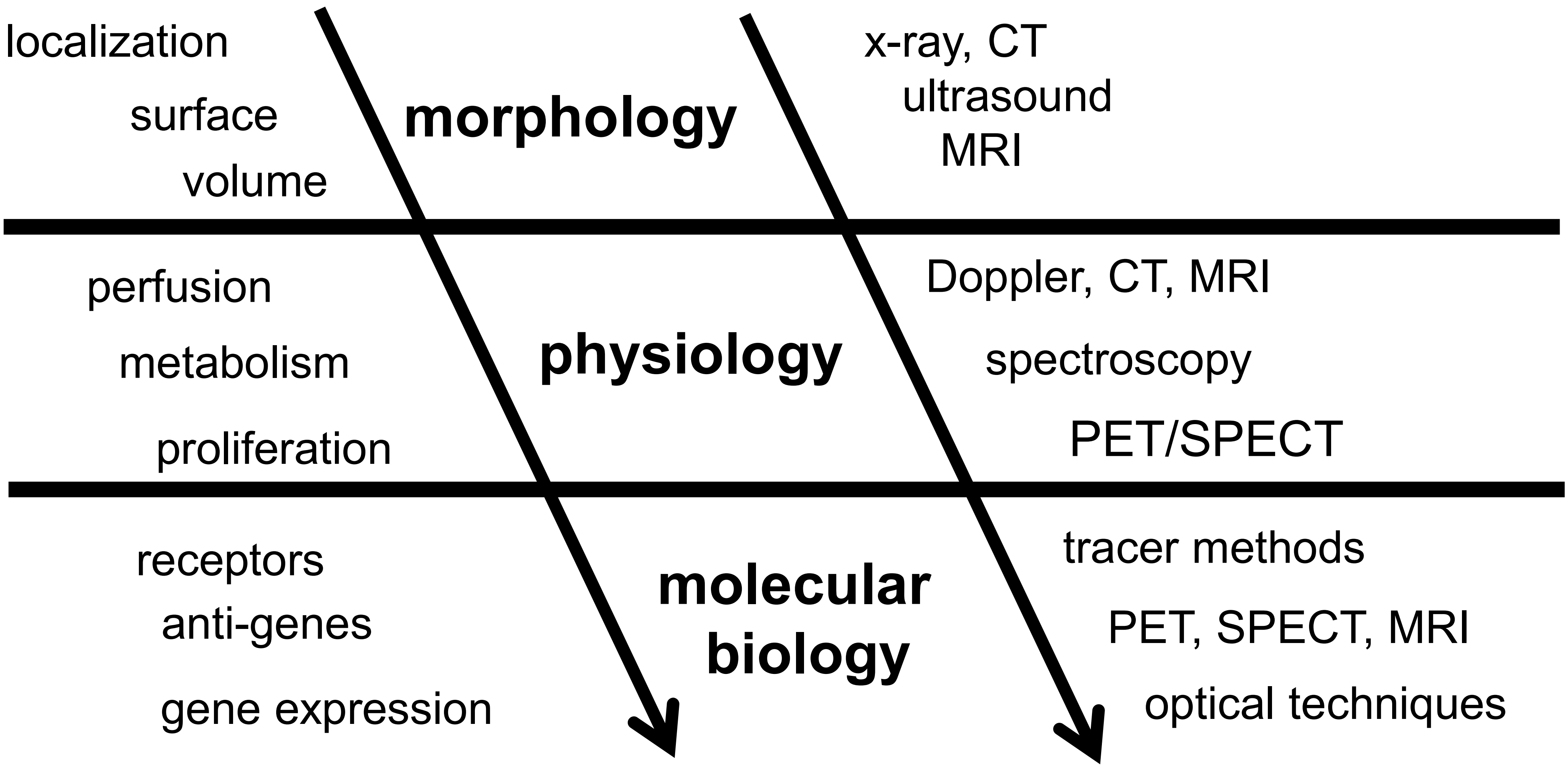
fusion of imaging techniques

Andreas Vesalius
anatomist
1514-1564

Visible Human Project



Development of medical imaging techniques



physical basics

imaging technique	branches of physics	
x-ray CT	QM and atomic physics nuclei, molecules, solid state body radiation physics	solid state physics semiconductor physics + appl. medical physics
PET/SPECT	nuclear structure semiconductor physics + appl. medical physics	particle physics radiation physics
MRI	QM and atomic physics electromagnetism, electrodynamics statistical physics, low temperature physics thermodynamics	
ESI/MSI	medical physics electromagnetism, electrodynamics statistical physics, low temperature physics, thermodynamics	