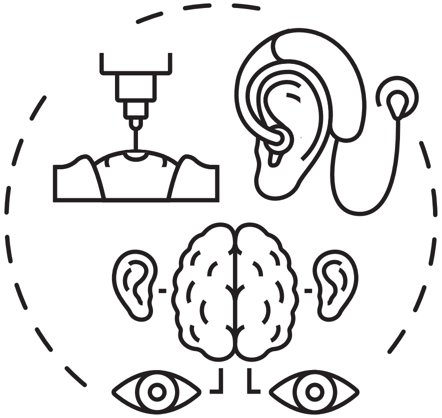
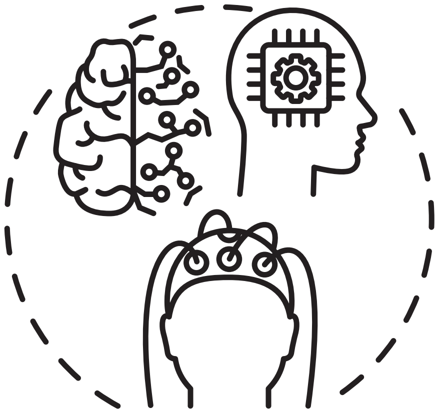
EPFL





Neural Interfaces

NX-422

Clinical interfaces

Stéphanie P. Lacour, Neuro-X Institute

Clinical applications

- Trauma

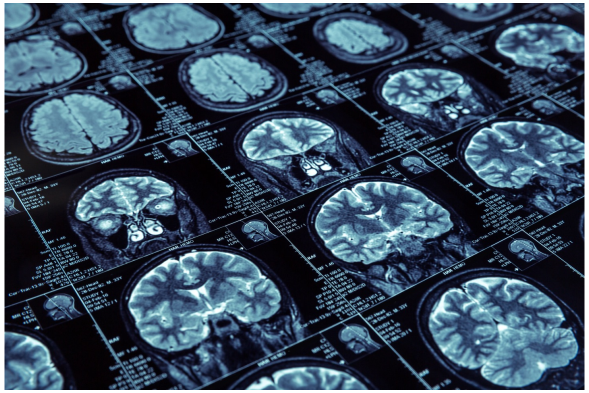
- Neurodegenerative conditions

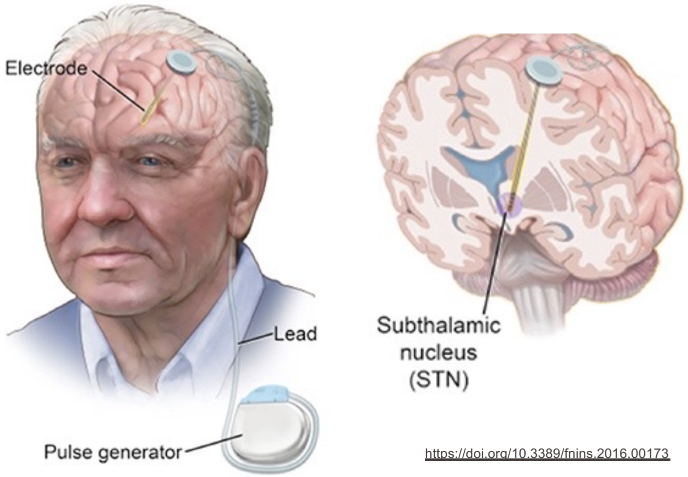
Clinical applications

diagnostic

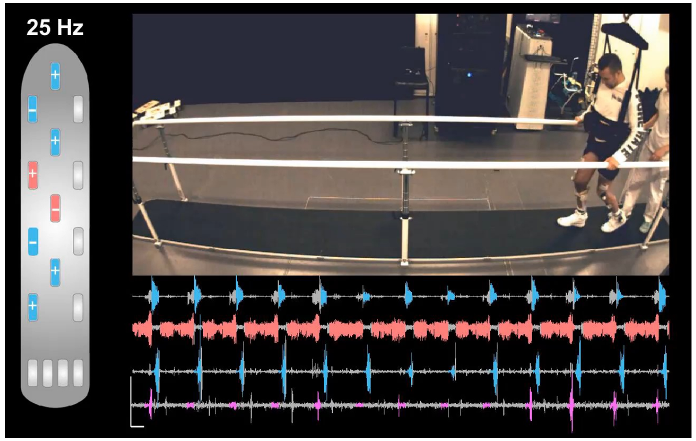
intervention

rehabilitation





https://doi.org/10.3389/fnins.2016.00173



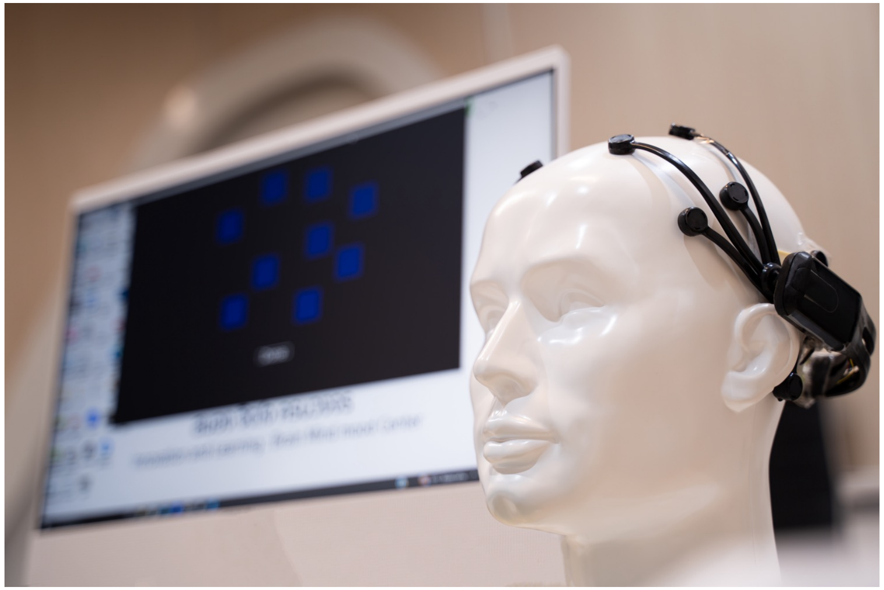
MRI

deep brain stimulation

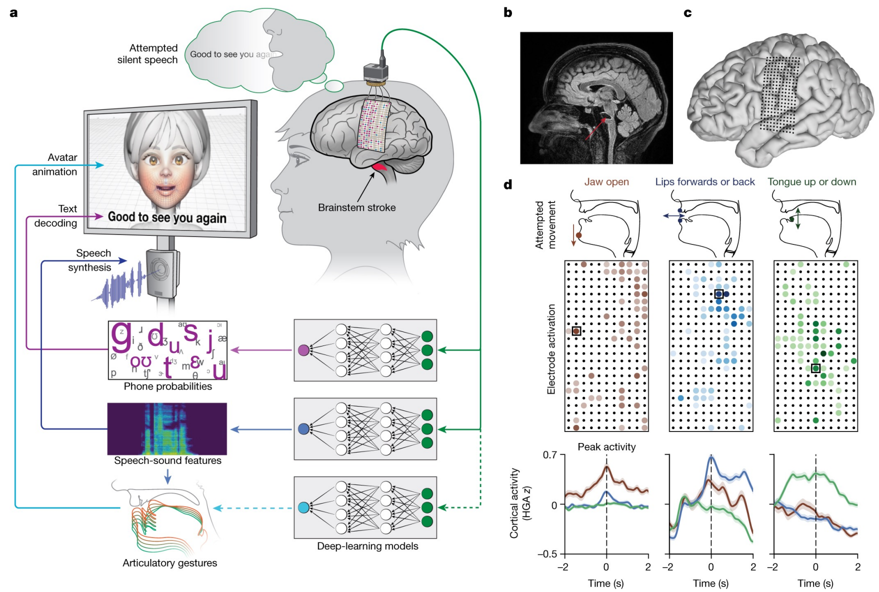
robotic assistance

Two classes of neurotechnology

- Non invasive / wearable



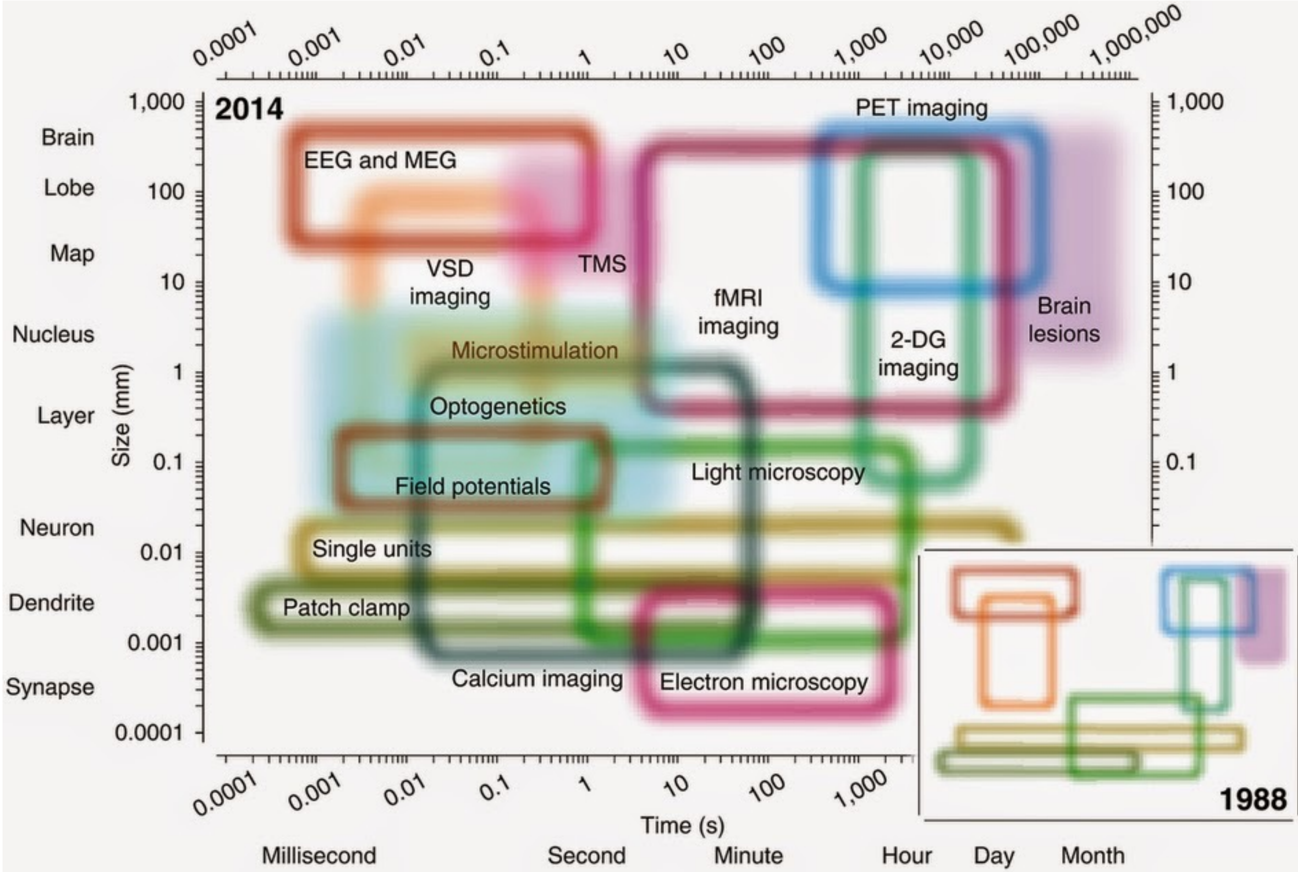
- Invasive



Nature 2023, UCSF

Functional representation of neural signals

- Spatial resolution
- Temporal resolution
- Invasiveness



Nature Neuroscience. 2014 Nov; 17(11): 1440–1441.

Magnetic resonance imaging - MRI

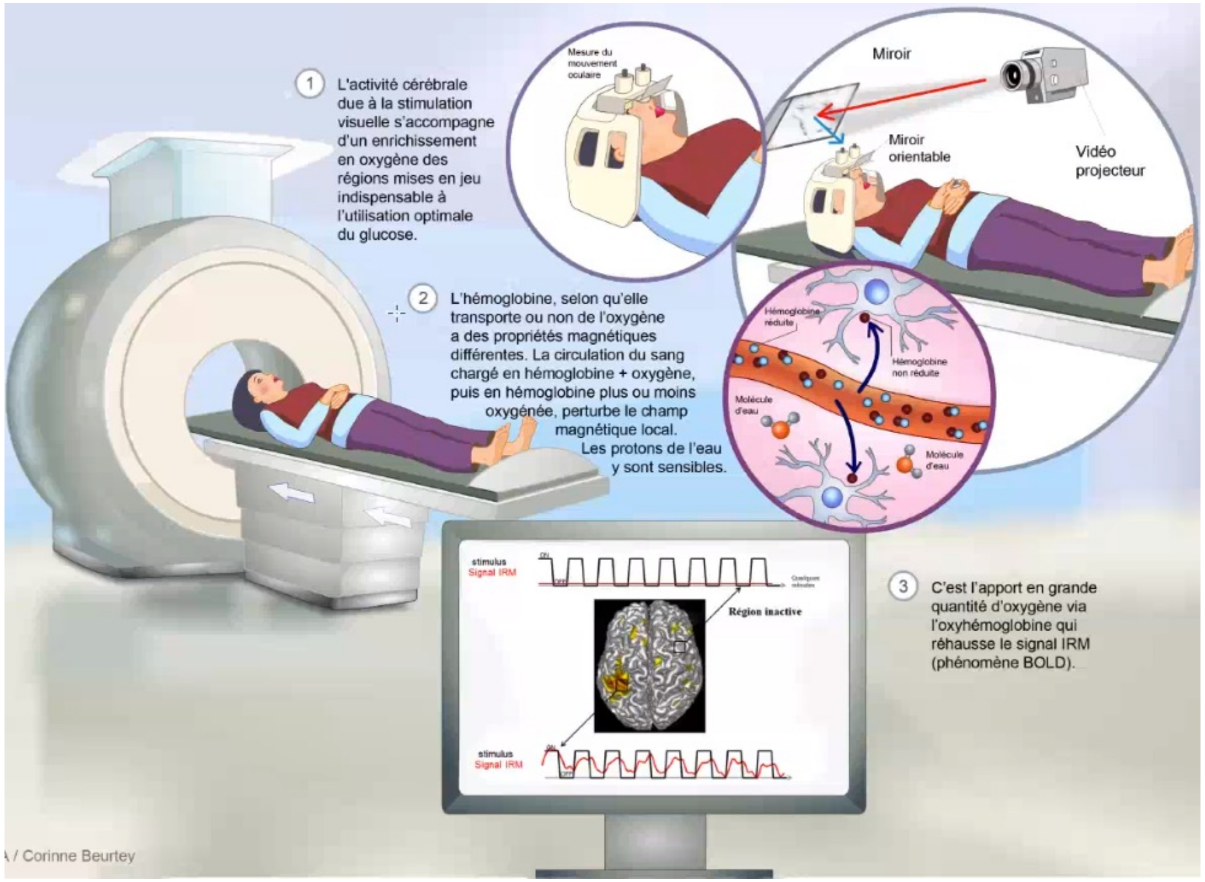
- Reference imaging

- **Magnet**
  - 1.5T
  - 3T
  - 7T
  - 11.5T / research

Siemens Healthineers

MRI and fMRI

- Anatomy
- Functional imaging
  - observation upon stimulation
  - **BOLD** (blood oxygen level dependence)

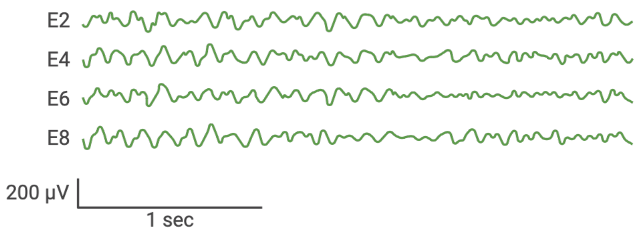


EEG imaging

Brain Products

Electroencephalography **EEG**

5 – 300 μV, < 100 Hz



Brain waves

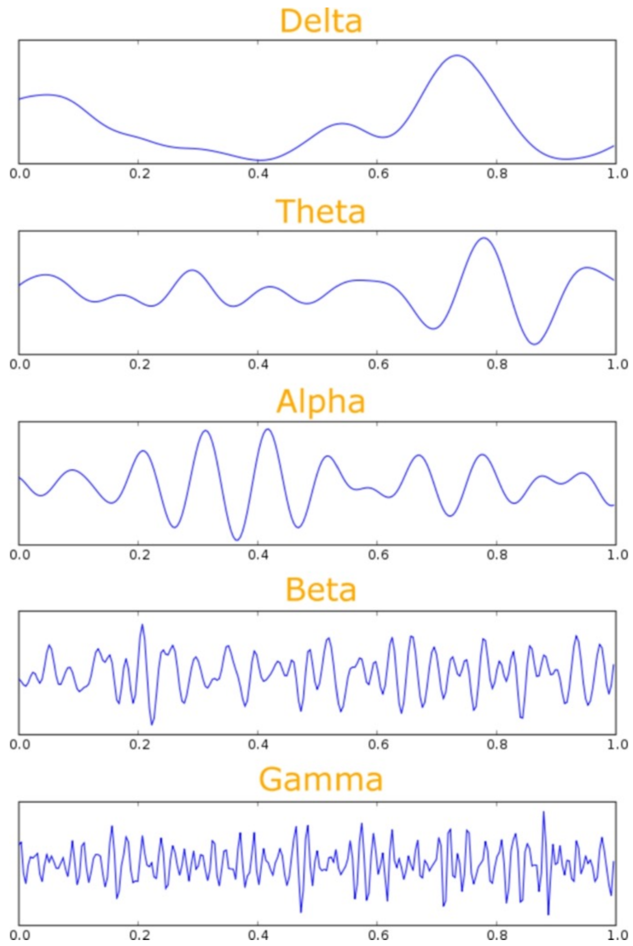
sleep stage — 0.1 – 4 Hz

deep relaxation — 4 – 8 Hz

“white matter” — 8 – 13 Hz

behavior and actions — 13 – 30 Hz

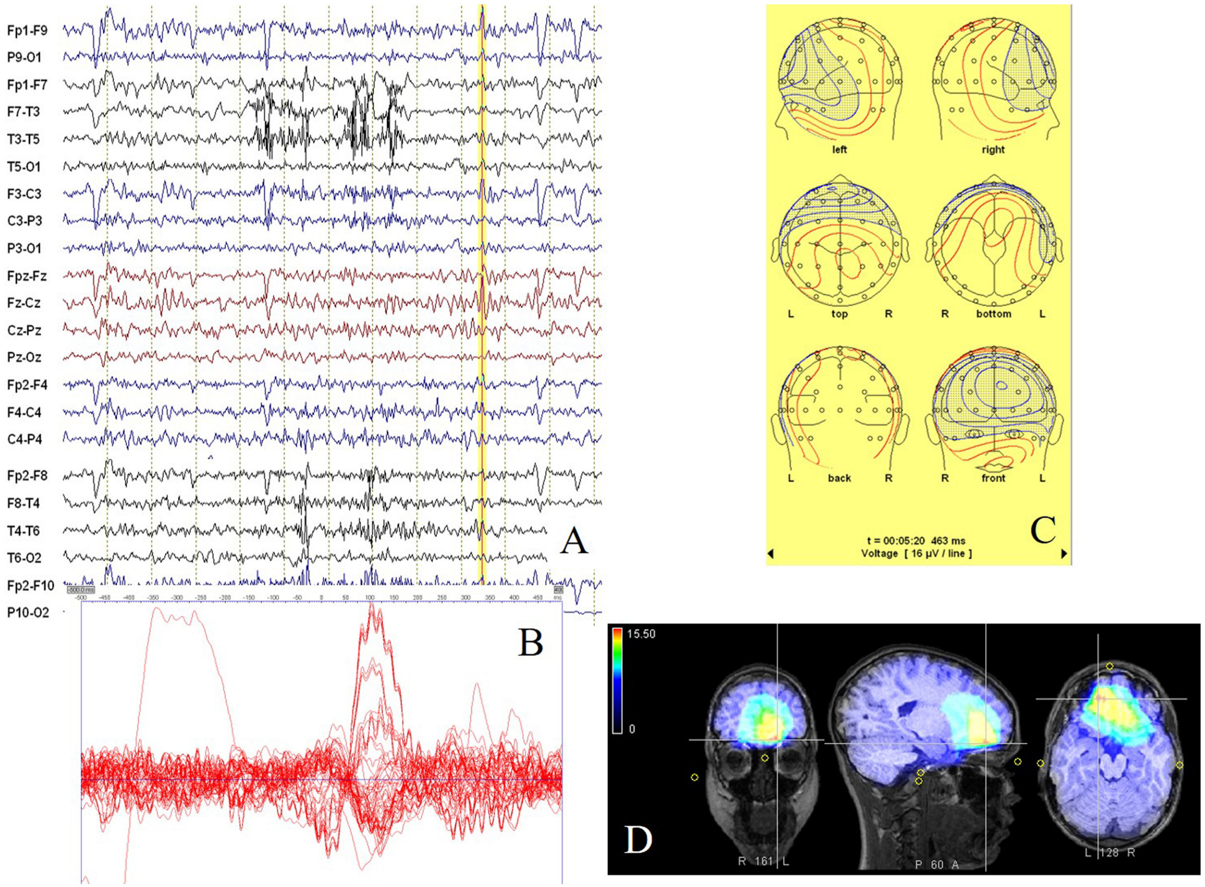
perception consciousness — > 30 Hz



https://doi.org/10.13140/RG.2.2.28622.82240

Frontal epilespy

A. High resolution EEG data
B. Interictal event with the 64 channels superimposed
C. Surface amplitude cartography
D. Epileptic source localisation

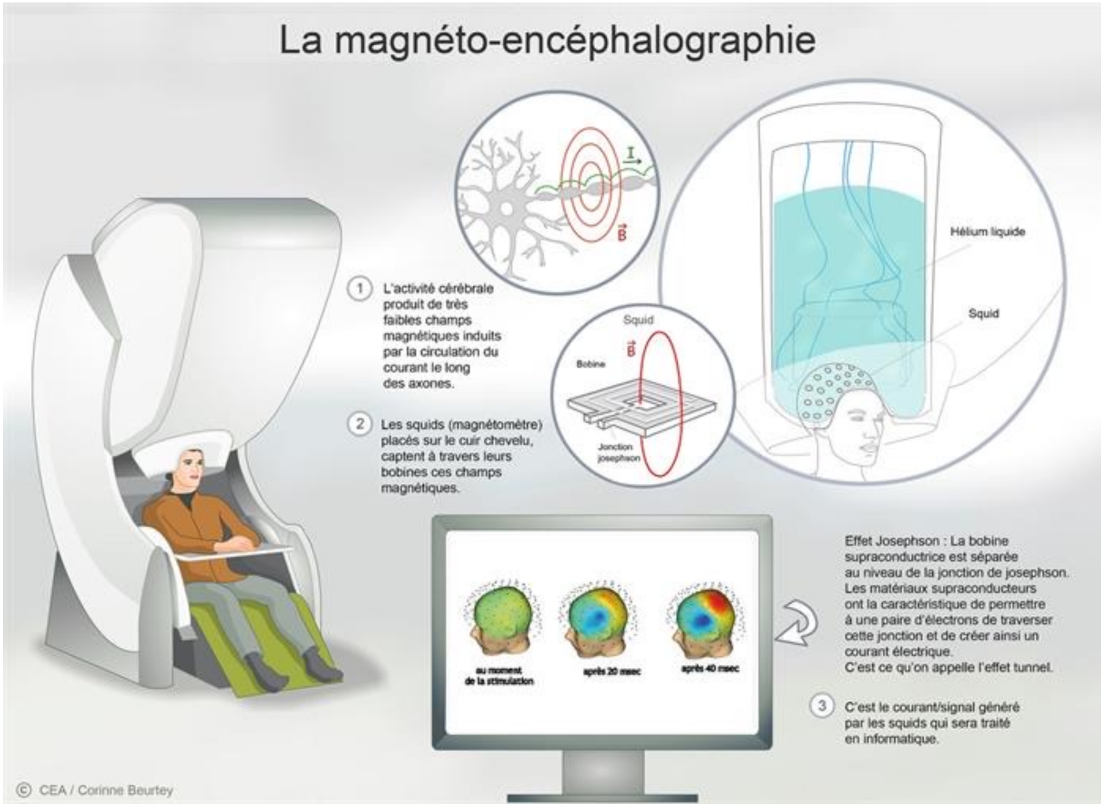


https://doi.org/10.1016/j.neurol.2022.12.008

EPFL

Magnetoencephalography MEG

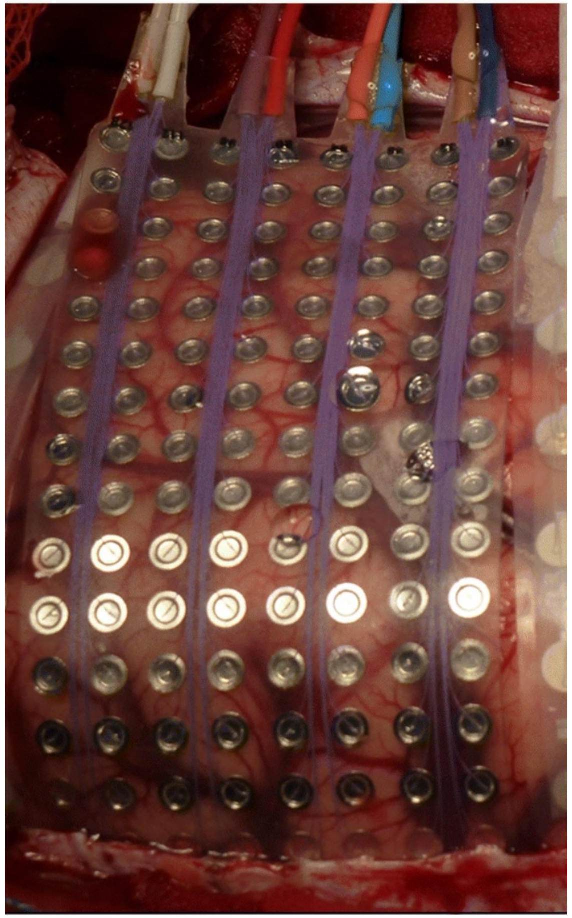
- monitoring magnetic field generated through brain activity



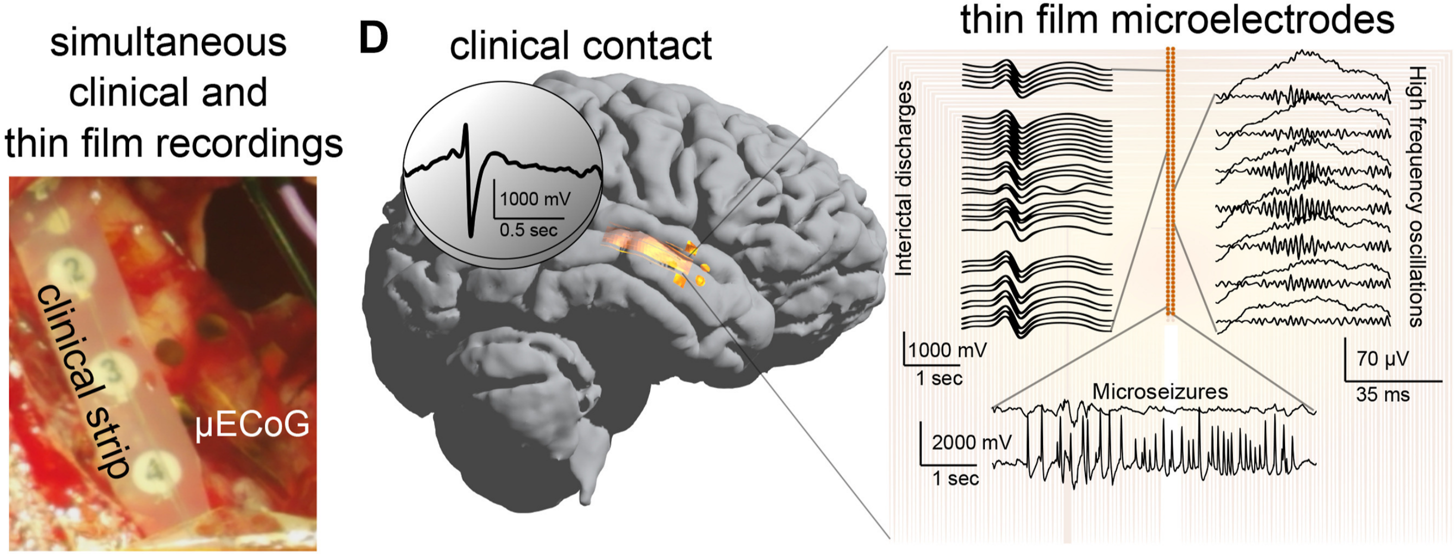
Electrocorticography ECoG

- Diagnostic:
  - Localisation of epileptic sources
  - Guide for tumor resection
  - Diagnostic for brain trauma

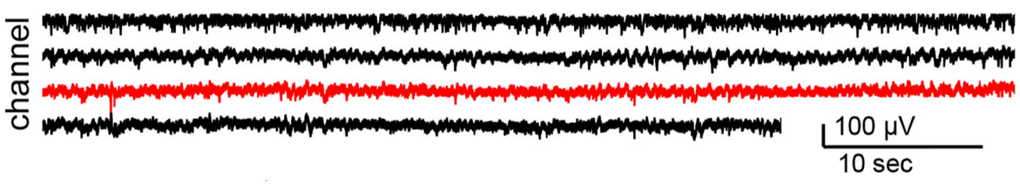
- Intraoperative or short-term (<30 days) monitoring



Signals vs electrode size



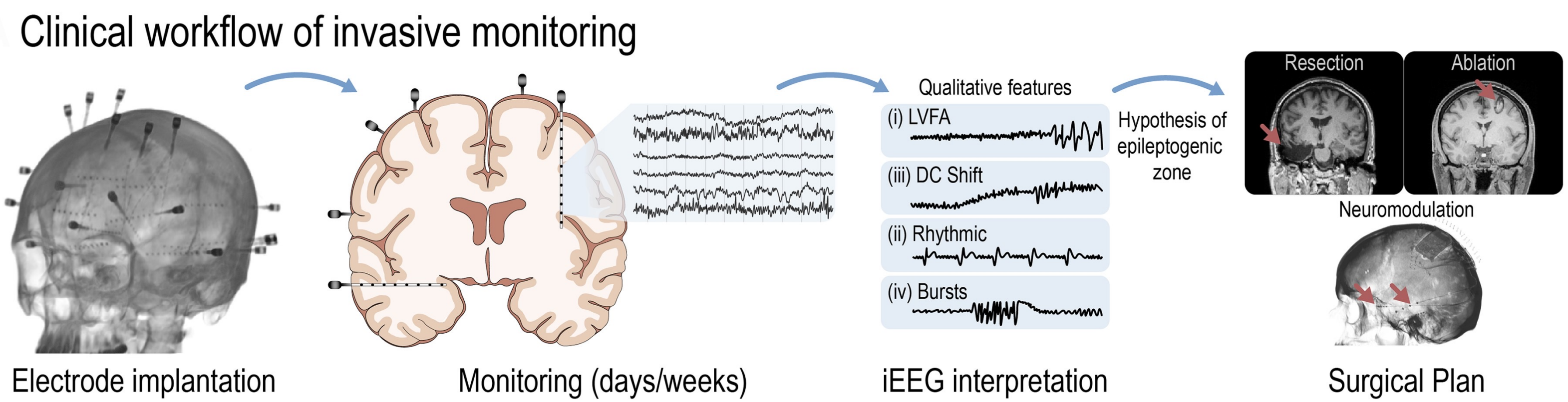
Clinical electrodes
Θ=1mm, 1cm inter-electrode



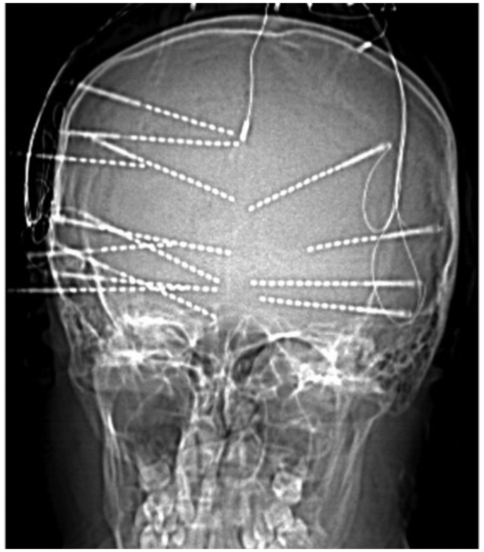
Micro-electrodes
Θ = 50µm, 1mm inter-electrode

https://doi.org/10.1016/j.nec.2023.09.003

sEEG – stereo EEG

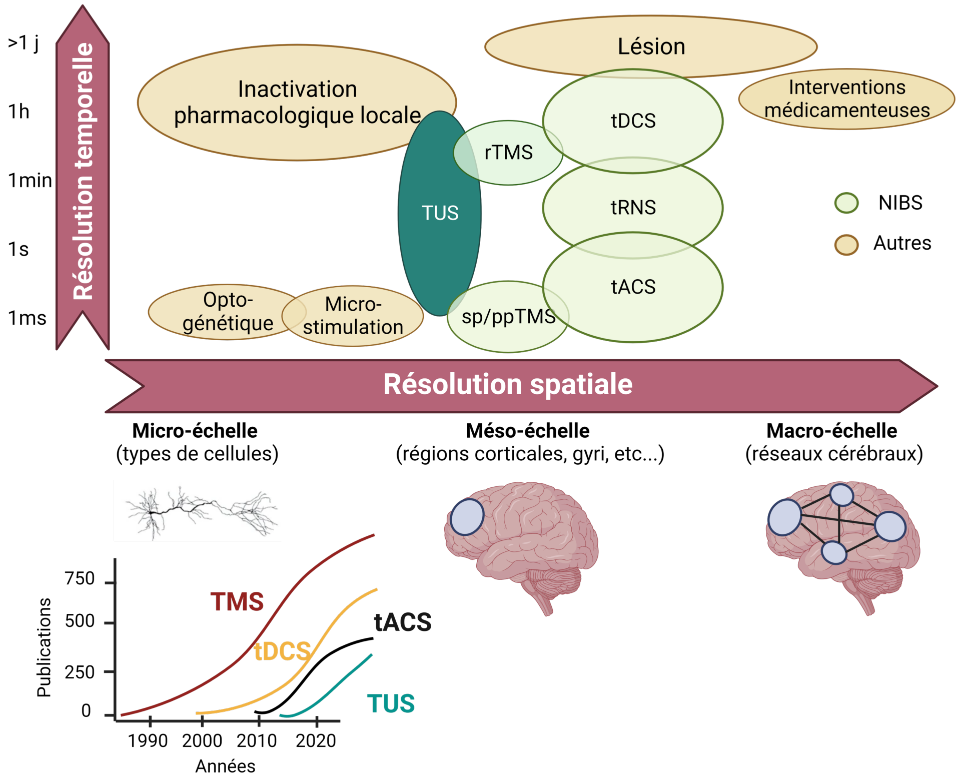


https://doi.org/10.1093/brain/awad007



J Neurosurg Pediatr vol 28 • 2021 404-15

Non invasive neuromodulation



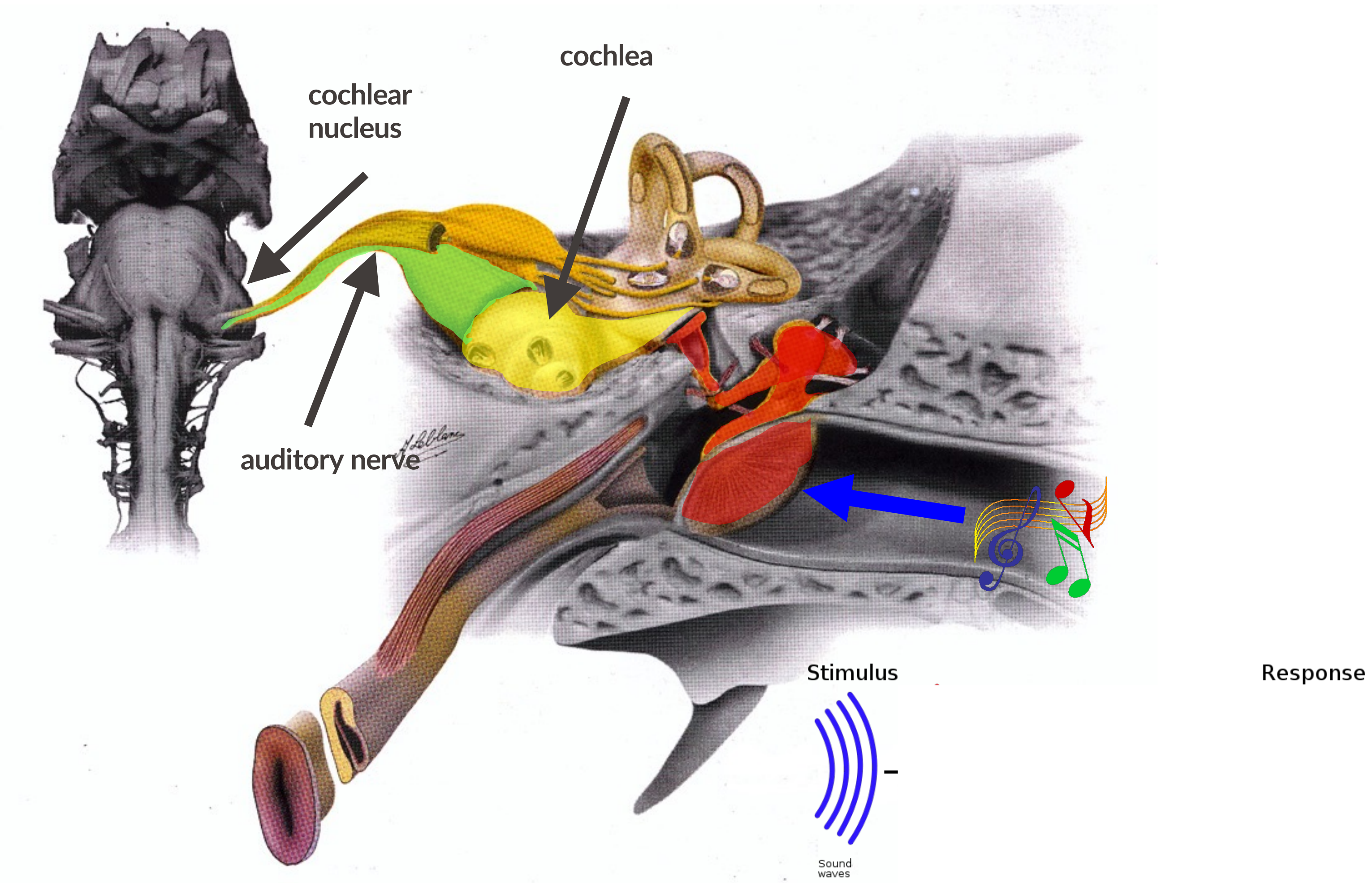
t-. transcranial

DCS: Direct Current Stimulation
ACS: Alternative Current Stimulation
RNS: random Noise Stimulation
TMS: Transcranial Magnetic Stimulation

TUS: Transcranial Ultra-sound Stimulation

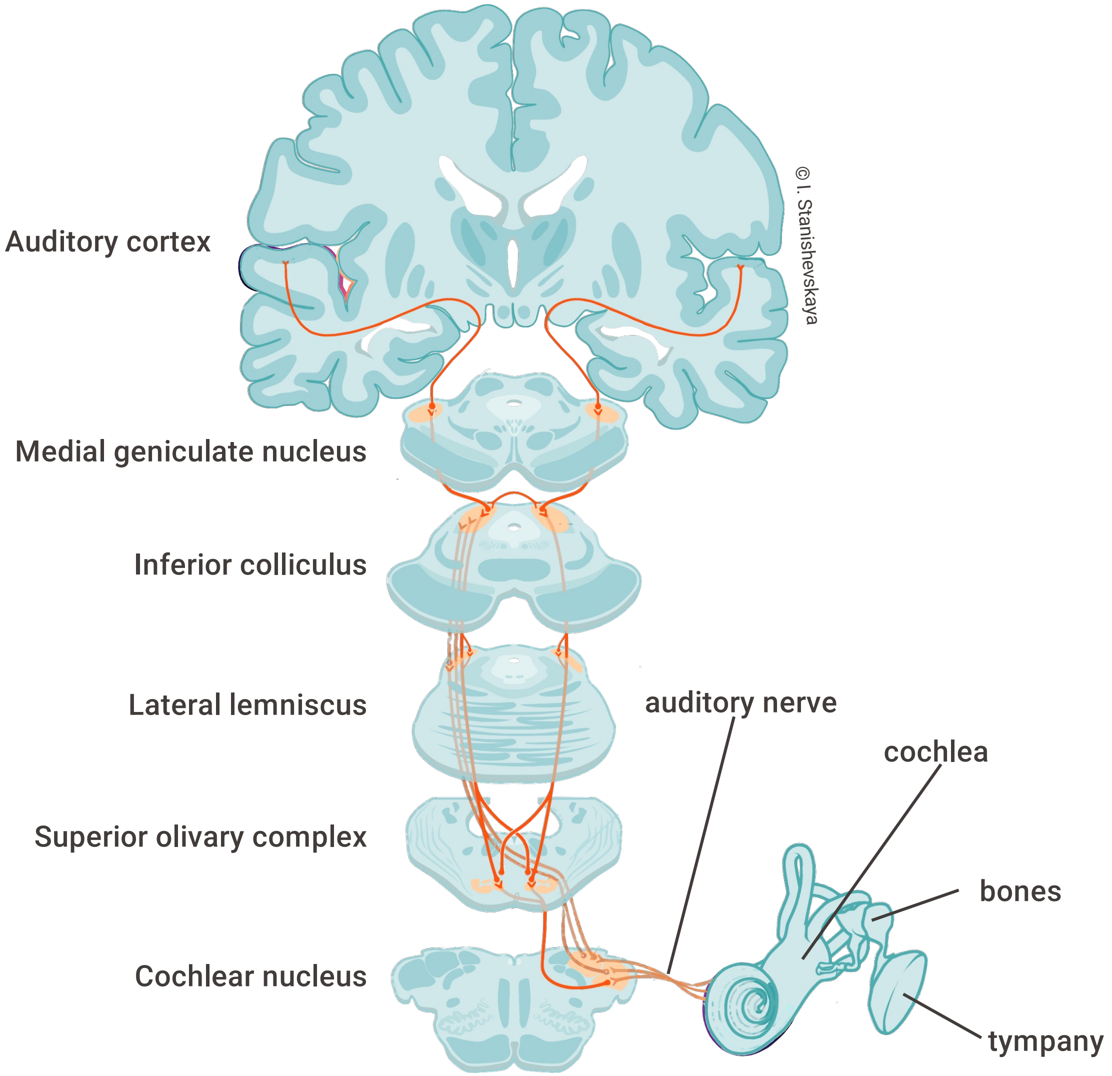
Invasive neurotechnologies

- Cochlear implants
- Deep brain stimulation
- Stimulation of the spinal cord

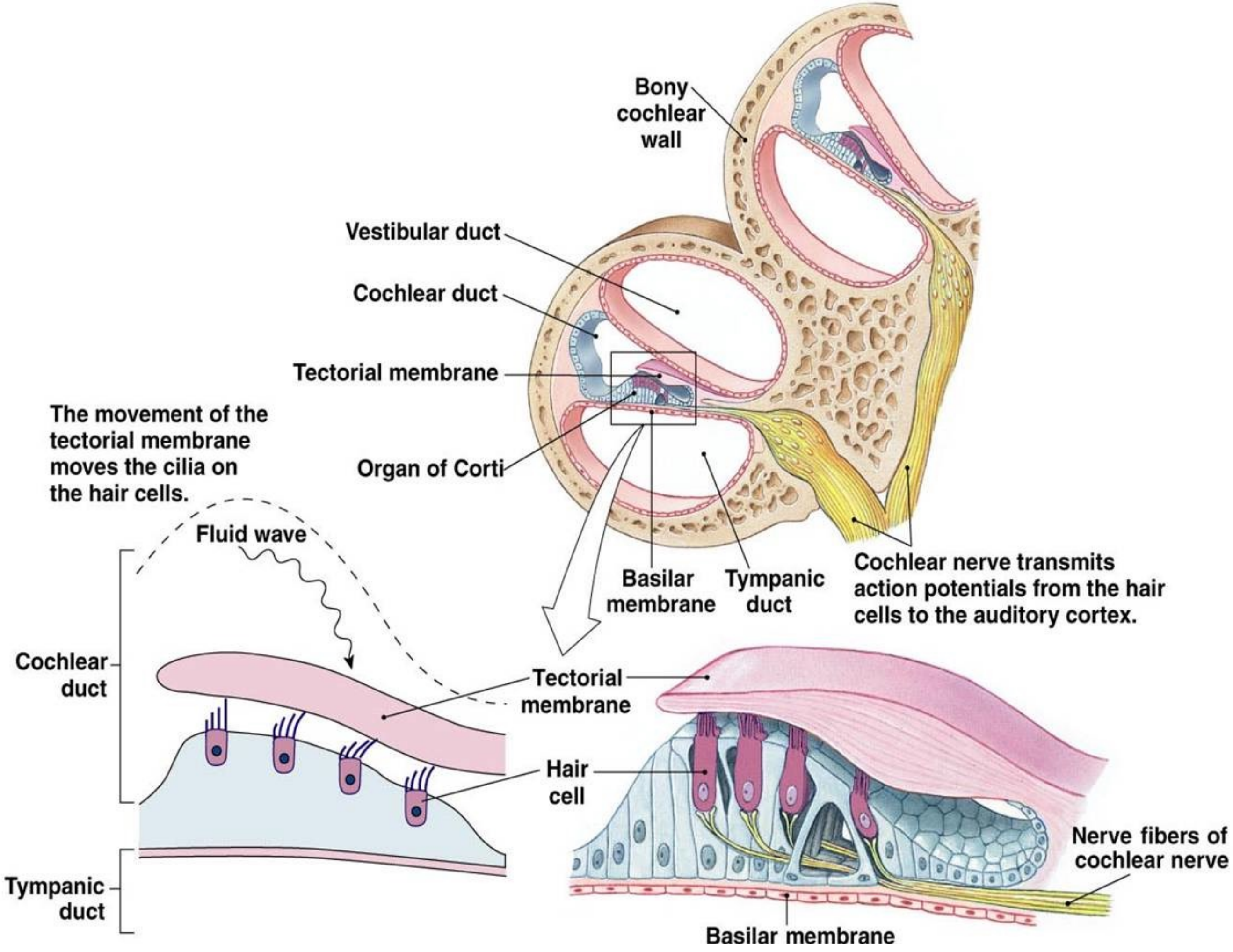


Original diagram by Tim Gollisch, Andreas M. V. Herz, and Public Library of Science. Converted to SVG by Iain 03:57, 12 June 2006 (UTC) Permission

Auditory circuits



The cochlea


Bony cochlear wall
Vestibular duct
Cochlear duct
Tectorial membrane
The movement of the tectorial membrane moves the cilia on the hair cells.
Organ of Corti
Fluid wave
Basilar membrane
Tympanic duct
Cochlear nerve transmits action potentials from the hair cells to the auditory cortex.
Cochlear duct
Tectorial membrane
Hair cell
Tympanic duct
Nerve fibers of cochlear nerve
Basilar membrane

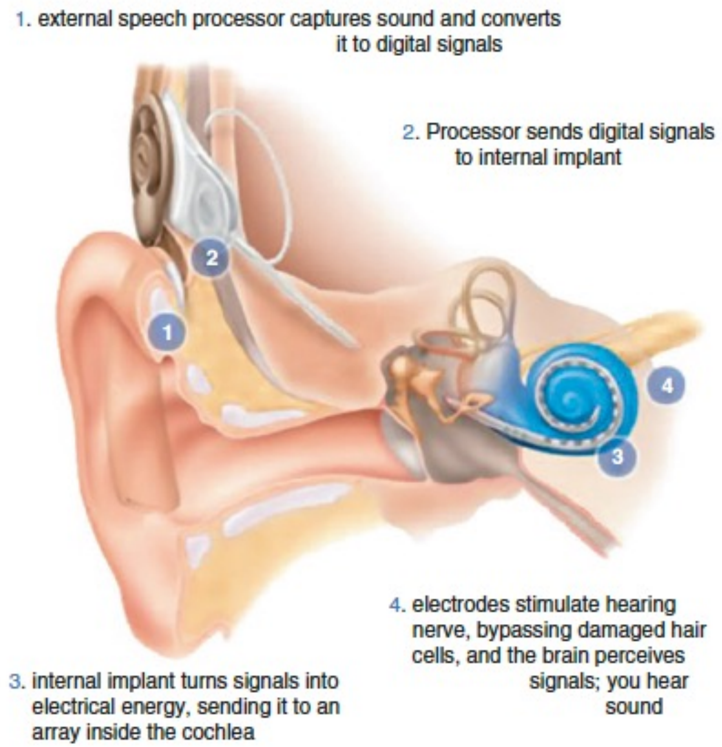
Cochlear implants
History

- First “experience”: Alessandro Volta (1800)
  - Electrical stimulation evoke auditory sensation in humans
- 1957 electrical stimulation of hearing in 2 deafened patients
- 1960s-1970s – multiplied efforts in the USA
- 1984: FDA approves the first cochlear implant (many others ensue)

- **Main players today**:
  - Med-El Corp., AU; Cochlear Corp., AUS; (Advanced Bionics) Sonova Holding, CH
  - audiological criteria for cochlear implantation:
    - from bilateral total deafness (<110 dB HL) in the early 1980s
    - to severe hearing loss (>70db HL) in the 1990s,
    - then to current suprathreshold speech based criteria (< 50% open-set sentence recognition with properly fitted hearing aids).

Cochlear implants

Cochlear Inc.



EPFL

A long-term interface

- **Exceptional constraints on life-time**, reliability of the interface
  - Implantation in new-borns
- **Implantable electronics**: as simple as possible
  - Transmitter of signals received from external device to the electrodes
  - 12-22 channel electrode
  - “no upgrade” over time of the implanted hardware
- **External speech processor**
  - Complex signal processing
  - Positioned behind the ear
  - Energy source (battery)

Surgical positioning

- Difficulty due to configuration of bones around the cochlea
- Proximity of facial nerves
- Alignment of the external and internal coils
  - Implanted magnet (issue with MRI)

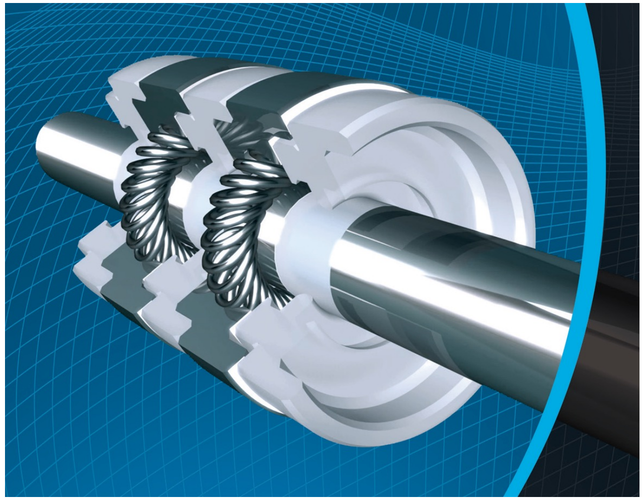
EPFL

Implantable electronics

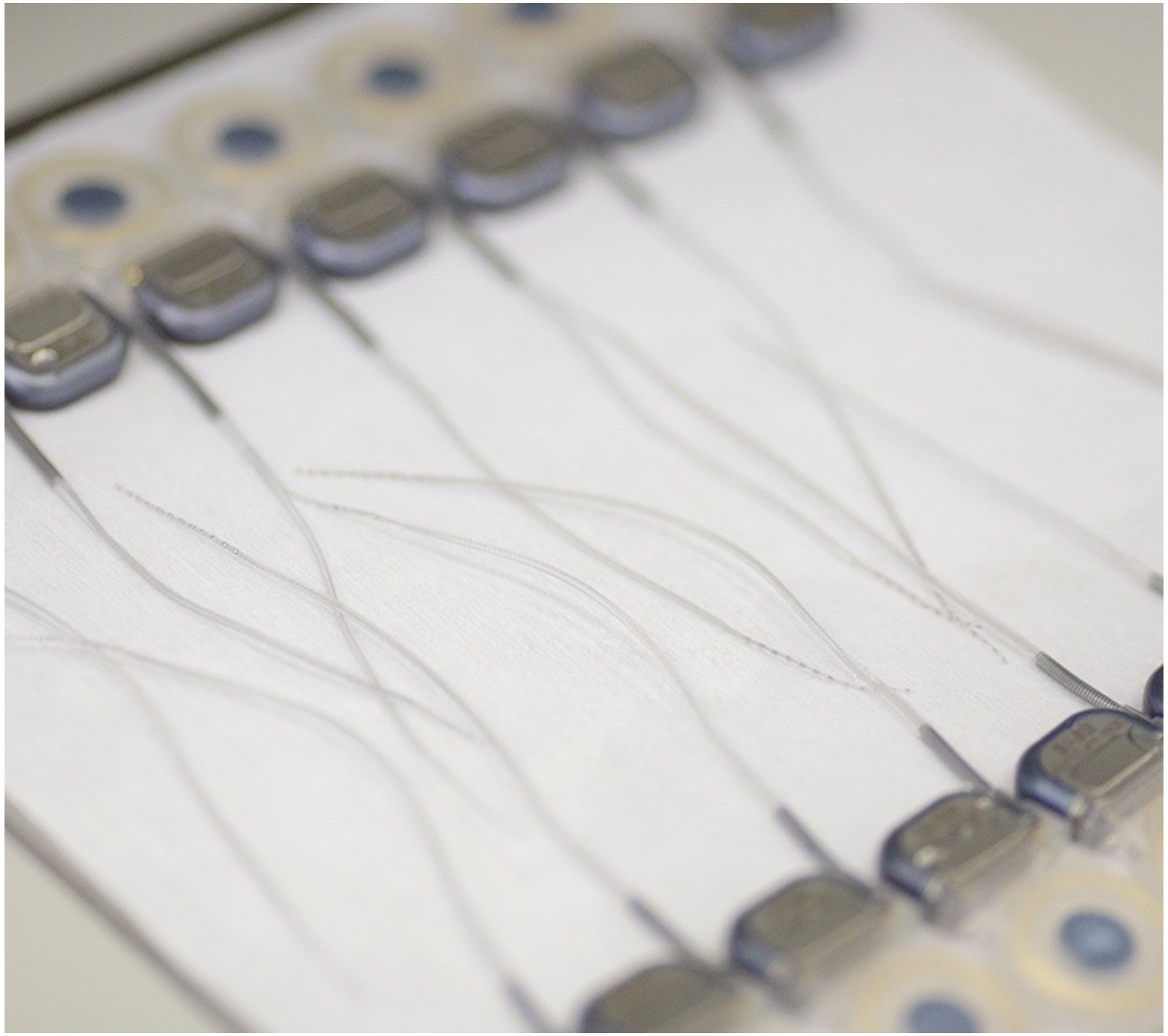
- **Titanium housing** providing hermetic seal to implantable electronics
  - Must be as thin as possible
    - Limited protrusion under the skin
    - Minimal skin erosion
  - Inductive coupling for power transfer
    - Induction coil outside of the casing
    - mm distance between coils
    - Alignment of coils
    - External batteries

- **Connectors**
  - Non detachable lead cable from housing
  - Challenges of number of contacts and hermeticity
  - One company : Bal Seal Engineering Inc.

Bal Spring® technology



Implantable interface



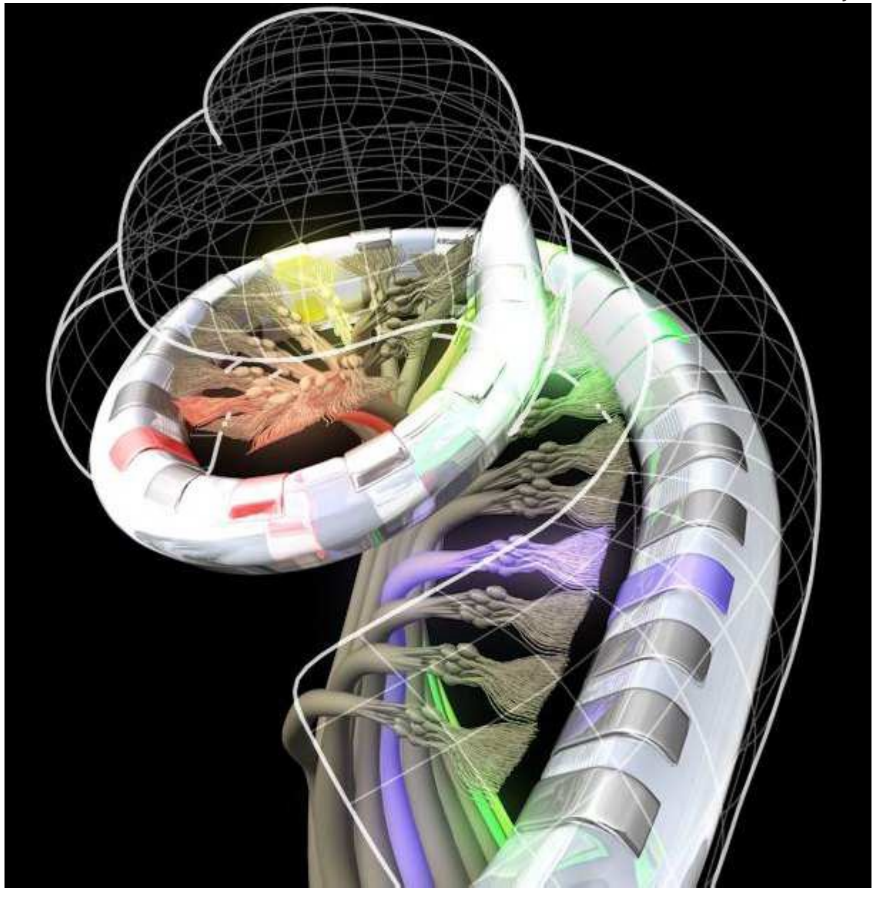
www.medel.com

Cochlear Electrodes

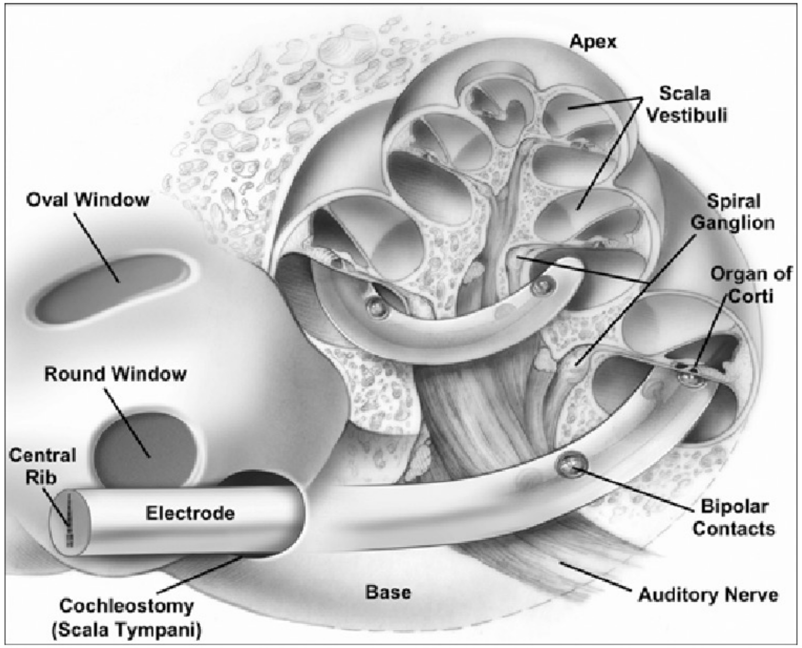
JNE 2006 6 055002

- Invasive electrodes (surgical positioning)
- **Electrode contacts**
  - non-insulated surface
  - Metal: **Platinum**
- **Insulated wires**
  - gathered in a coiled cable or a flat ribbon
  - Materials: **Platinum-Iridium 90/10**
    with Teflon insulating coating

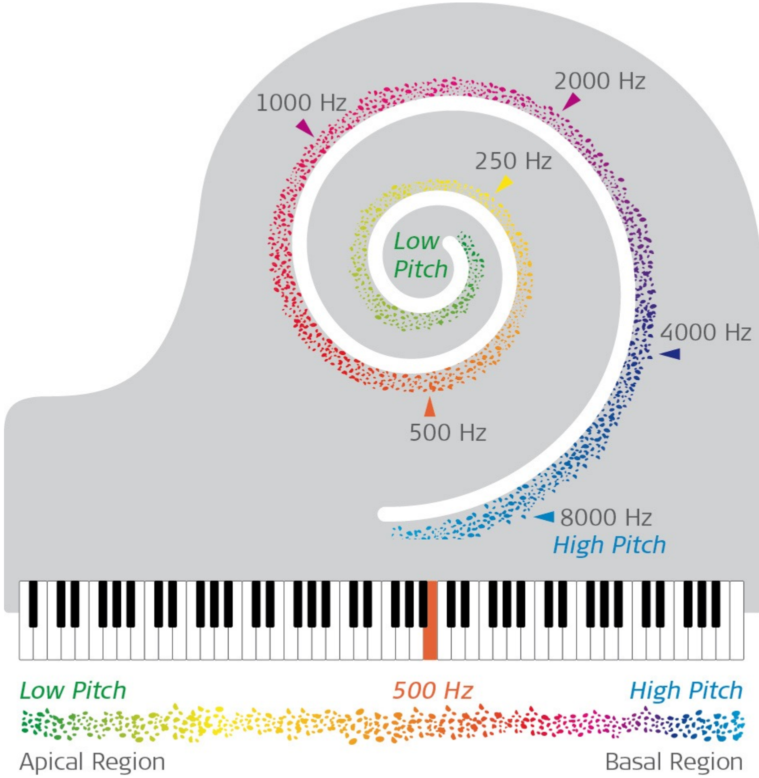
➢ Embedded in **silicone** to form the lead



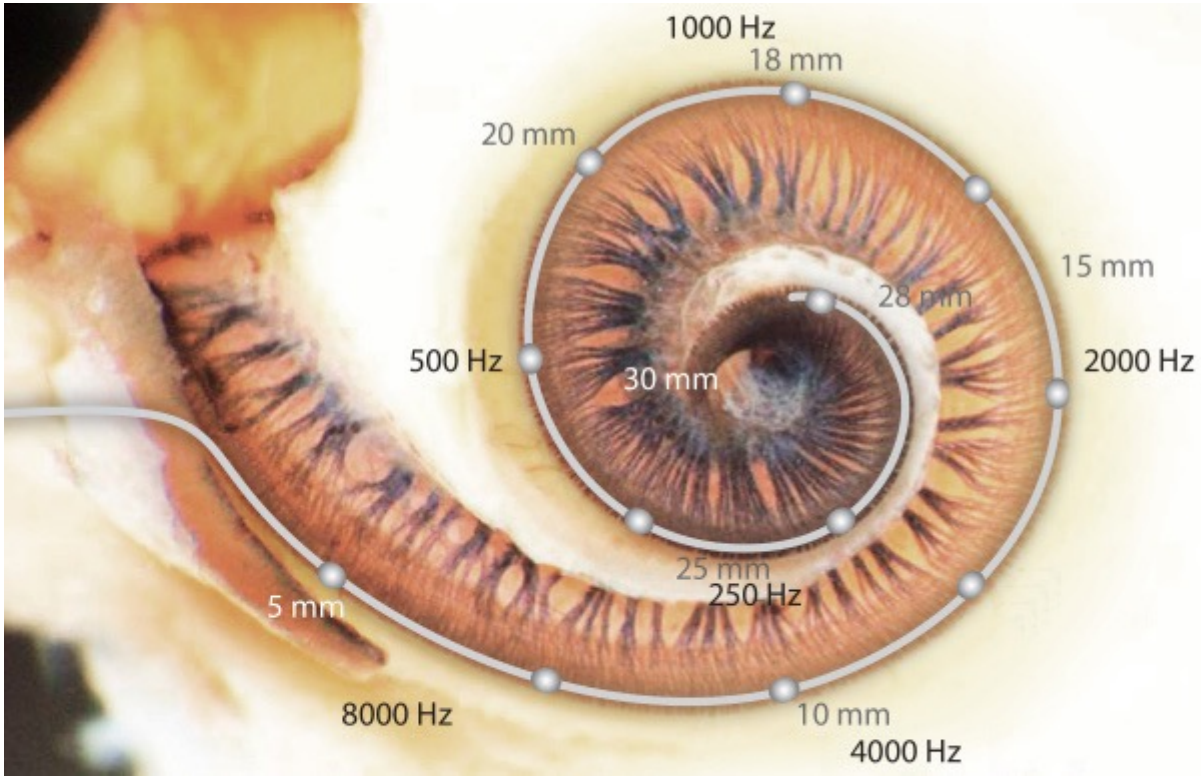
The cochlear implant



https://www.youtube.com/watch?v=bDx12M5u4uY#t=45



Accessing the cochlear tonotopy



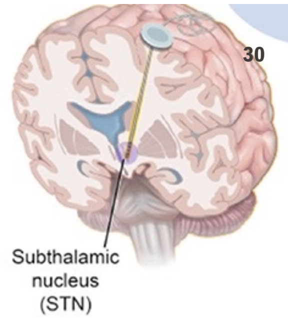
The diameter of the cochlea canal is about **1mm** at the widest
Radius of curvature: **~ 4mm**

Cochlear implant

Enables speech understanding
in quiet and some noisy environment

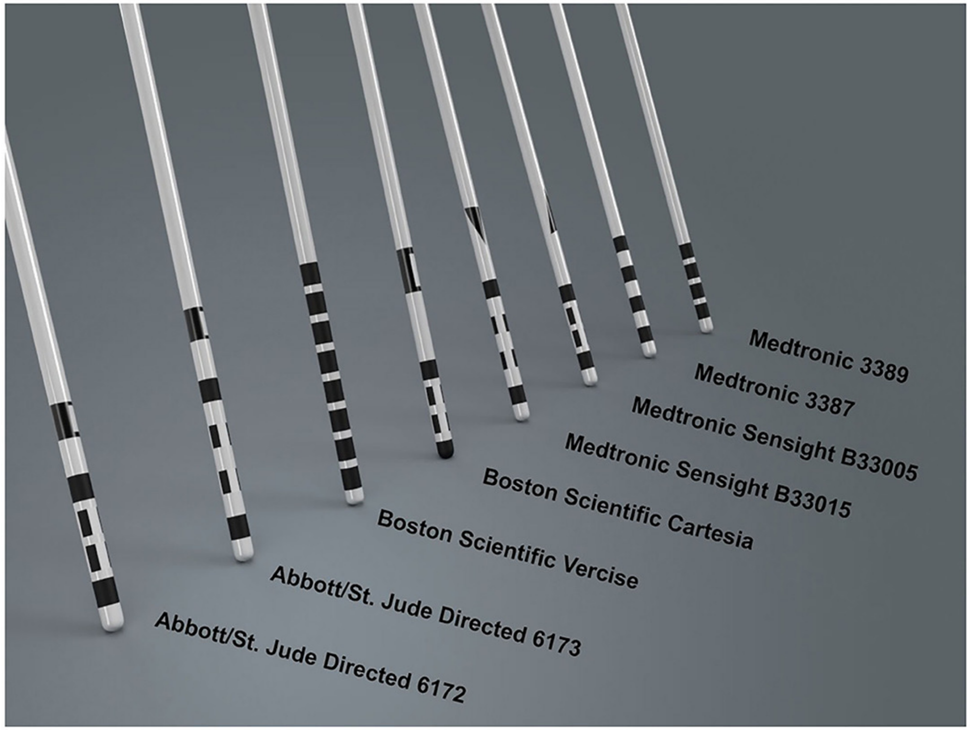
Deep brain stimulation DBS

- Electrodes
- Cable (lead)
- Implanted electronics
- Control
- Recharge



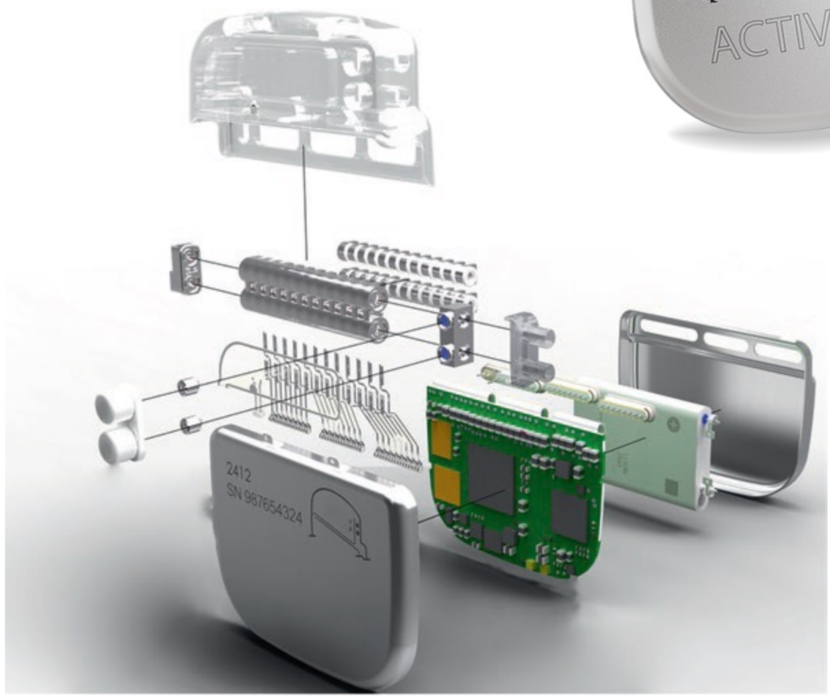
DBS electrodes

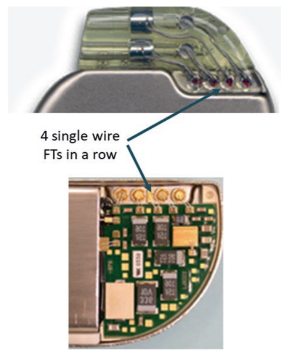
- **DBS lead (Electrodes)**
- Extension
- Neurostimulator
- Adjustment



DBS Implantable Pulse Generator (IPG)

- DBS lead (Electrodes)
- Extension
- **Neurostimulator**
- Adjustment



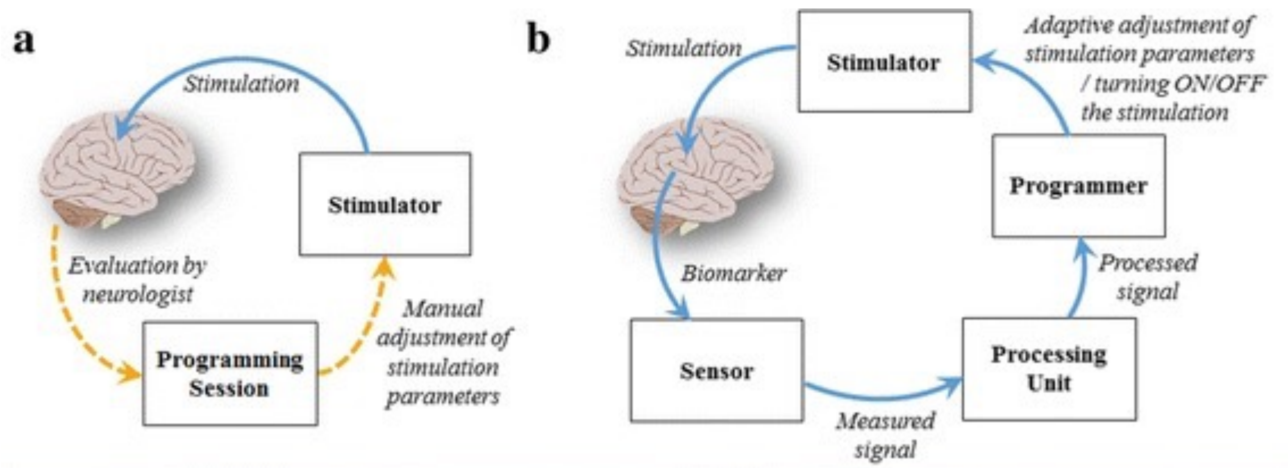


Select and adjust

Medtronic

- DBS lead (Electrodes)
- Extension
- Neurostimulator
- **Adjustment**

DBS & closed loop systems

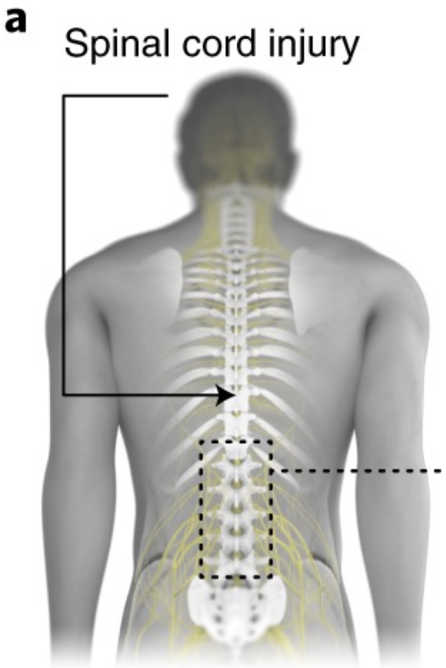


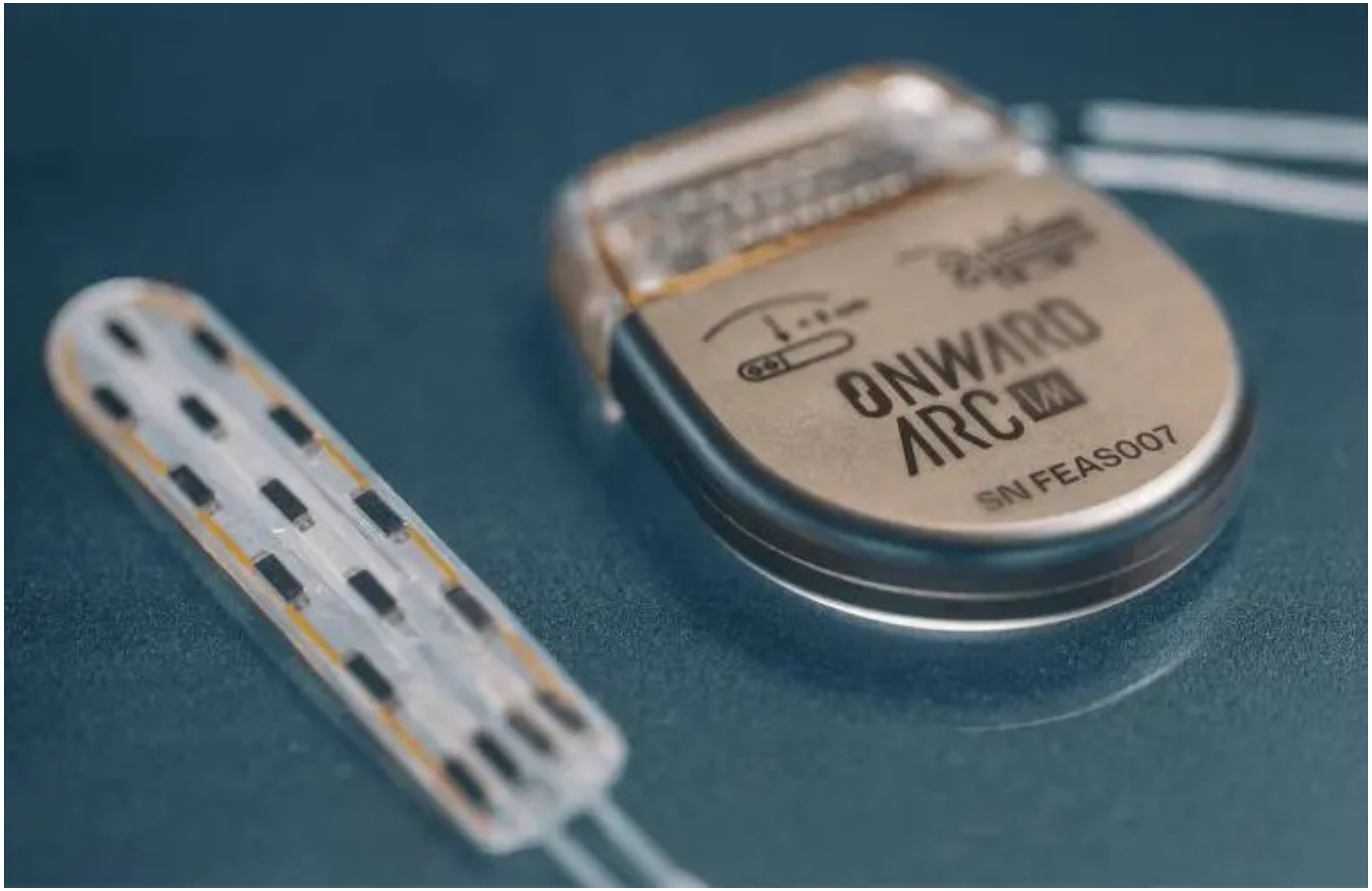
introduced in 2000s

Realtime adjustment of stimulation parameters as a function of biological metrics

J Neuroeng Rehabil. 2017; 14: 79.

Stimulation of the spinal cord





G. Courtine, J. Bloch EPFL/CHUV/UNIL

Rowald et al. **Nature Medicine** 2022

G. Courtine, J. Bloch EPFL/CHUV/UNIL

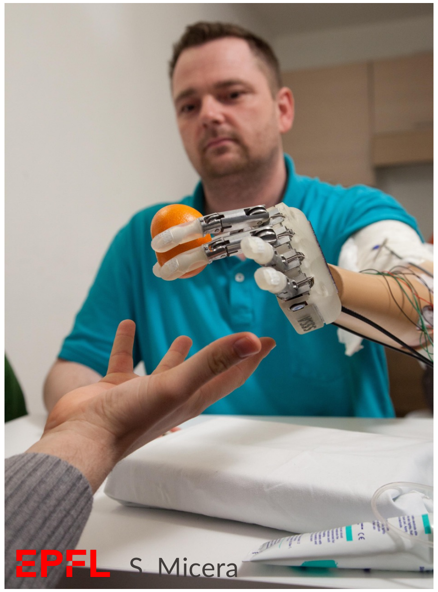
Wagner et al. **Nature** 2018

Human-machine interfaces

upper limb movement following paralysis

Nature 2012

Tactile sensation with a robotic hand



Science Trans. Med. 2014

Speech restoration through a BCI and an avatar

Nature 2023

Biological metrics (1/2)

- **The aqueous internal environment**
  - Water: 55 – 75% in weight
  - Intercellular fluid (1/3) and extracellular fluid (2/3)
  - Body temperature: 37℃

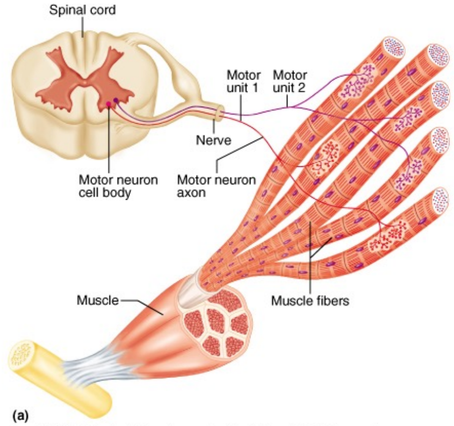
- **Biological fluidics**
  - **Bulk flow**: transport with the carrying medium (blood, air)
  - **Passive diffusion**: concentration gradient

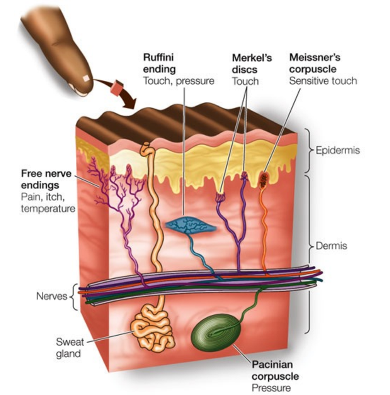
Biological metrics (2/2)

- **Biological electricity**
  - Movement of ions across the membrane of the cells → **ionic currents**
    - Membrane potential E_m, between -60mV and -90mV
  - Excitable tissues can generate **action potentials**
    - Transient depolarization of the cell as a result of ion channel activity
    - Action potentials transmit information to nerve cells
    - Action potentials trigger contractions in muscle cells

Biological devices

- **Actuators: Muscles**
  - Soft tissues, which change size and shape
  - Produce force and motion
  - Skeletal / cardiac / smooth (involuntary)
- **Sensors**
  - Mechanoreceptors (touch)
  - Chemoreceptors (taste)
  - …
- **Processor**
  - Neural circuits
  - Peripheral nerves / spinal cord / brain





LIFE 8e, Figure 45.6

Brain vs CPU

	Whole brain	CPU
weight	1.4 kg	< 100g
power	~22W	> 25W
units	10^{11} neurons	10^{8} transistors
Glial cells	~3 x neurons	
connections	10^{15}	> 10^{10}
wiring	8 million of km of axons	~ 100 km

Based on
Intel Core i7-1260U

EPFL

Supercomputers vs the brain

- the human brain: ~85 billion neurons with 1/10'000 connectivity
- the brain computing: very hard to estimate
  - 1 – 10 petaFLOP/sec, maybe 1 exaFLOP/sec and under **50W power**

- Supercomputers
  - 1960:
    - IBM7030 Stretch: > 1 million instruction per second
  - 2012:
    - IBM Blue Gene Q ® 16 petaFLOP/sec using 7.9MW (!)
  - 2024:
  - Train ChatGPT4 108 ExaFLOP/s, **50GWh**

ref. wikipedia

Important considerations when designing a neural interface

- Assess the **topology** of the medium to interface
- Assess the **dynamics** of the host medium
- Assess the **function(s)** of the biological tissue
- Define **the form-factor** and **eventual range of compliance** of the neural interface (application-driven)

- Select the appropriate device **technology** (including biocompatibility)

- Manufacture the required **function** and assess its **reliability**