Neurorobotics, and brain-machine interfaces

Oct. 10th, 2006.

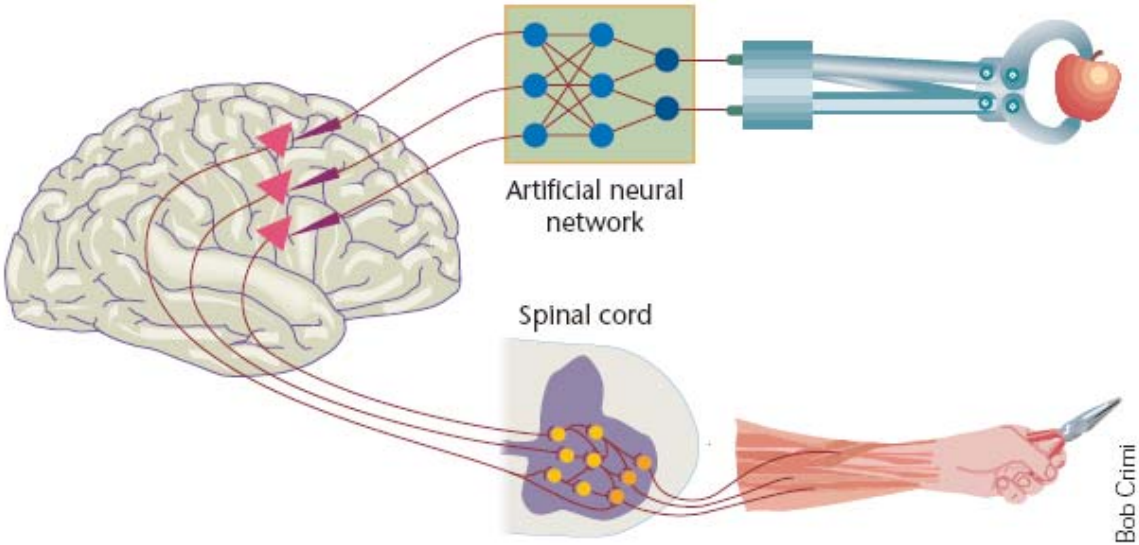


Fig. 1. Cortical neurons controlling voluntary arm movement could provide signals used to control a prosthetic arm. Large pyramidal neurons in motor cortex (red triangles) send axons to spinal cord, ending on interneurons and motoneurons. Motoneurons project to and contract arm muscles. Microelectrodes could record neural activity, which is transformed by an artificial neural network into signals required to operate a prosthetic arm.

Real-time control of a robotic arm by neuronal ensembles

Eberhard E. Fetz

Catching up from last class

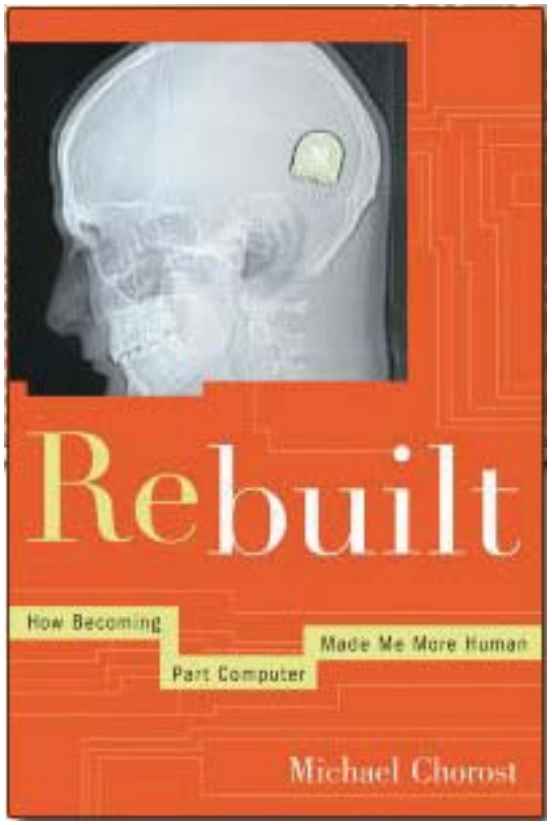
- Pg 121 – Wessberg (…) Nicolelis, *Real-time* ***prediction*** *of hand trajectory by ensembles of cortical neurons in primates* Nature, 2000.

- Please decipher what the three regions and two lines of a usual Porbaix diagram are.

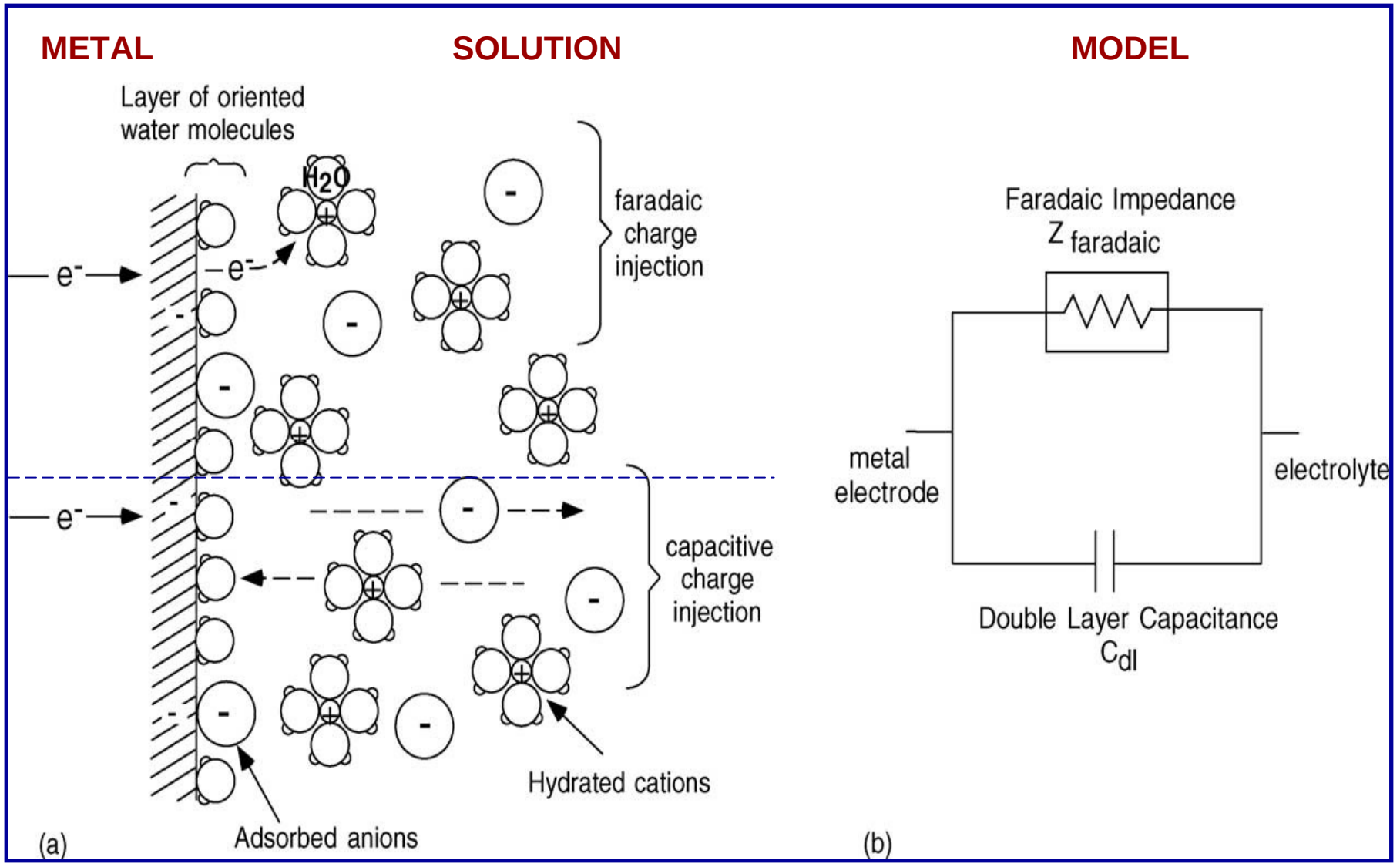
- Next class will be short: a couple of solutions to previous homework will be discussed, and you will receive the exam

Cochlear implant: in the media

Rebuilt: How Becoming Part Computer Made Me More Human (Houghton Mifflin, 2005) is a scientific memoir of going deaf and getting my hearing back with a cochlear implant, that is, a computer embedded in my skull. Science fiction writers and filmmakers have speculated about cyborgs (human-computer fusions) for decades, but in this book I reveal what it's really like to have part of one's body controlled by a computer.

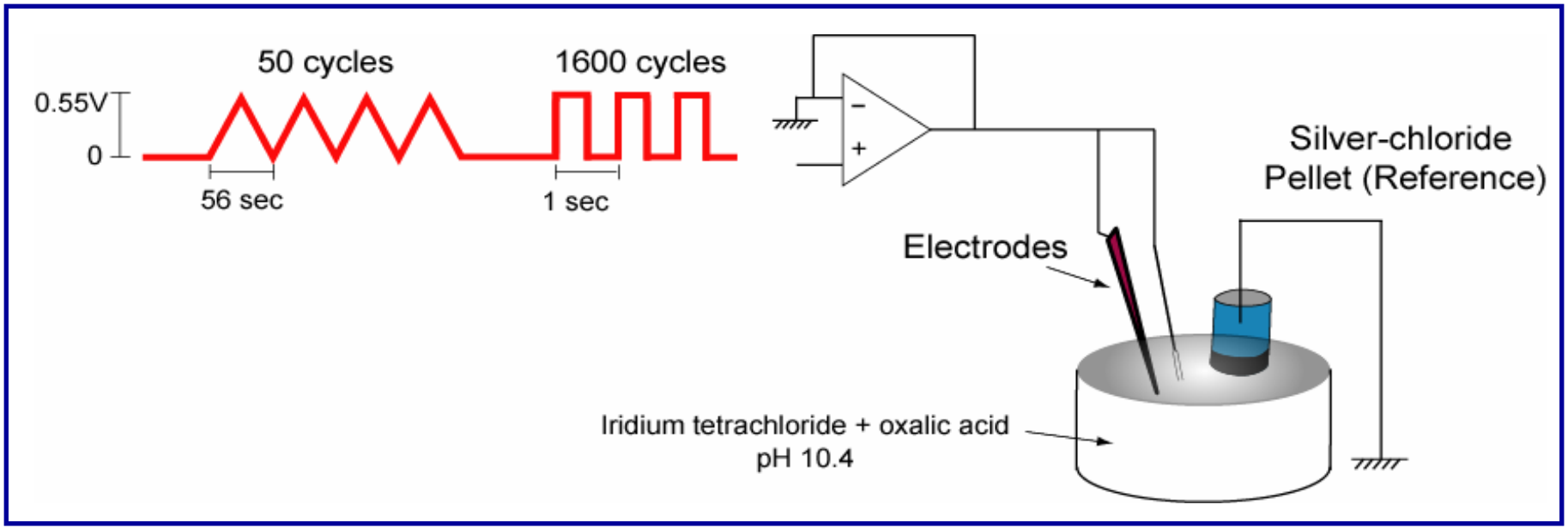


Interface Electrochemistry



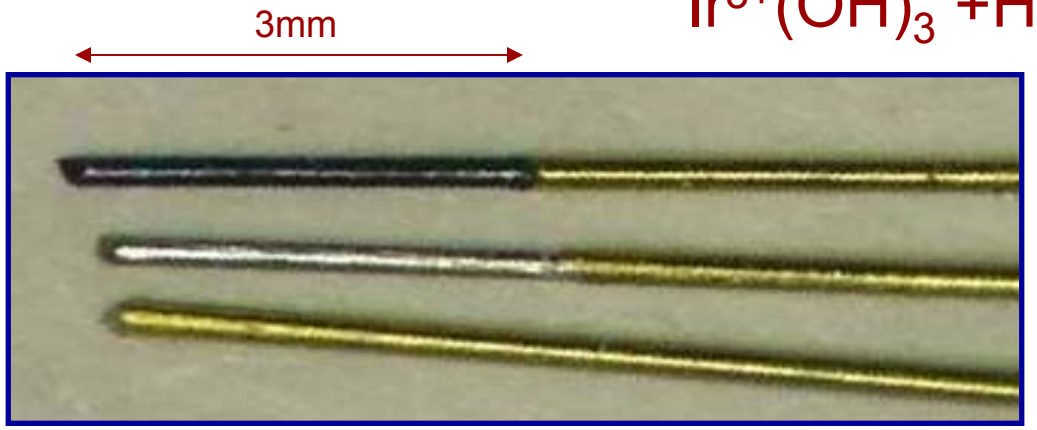
Modified from Merrill, J Neurosci Meth 2005

Iridium oxide film deposition



$$Ir^{4+}(OH)_4 + H^+ + e^- \leftrightarrow Ir^{3+}(OH)_3 + H_2O$$

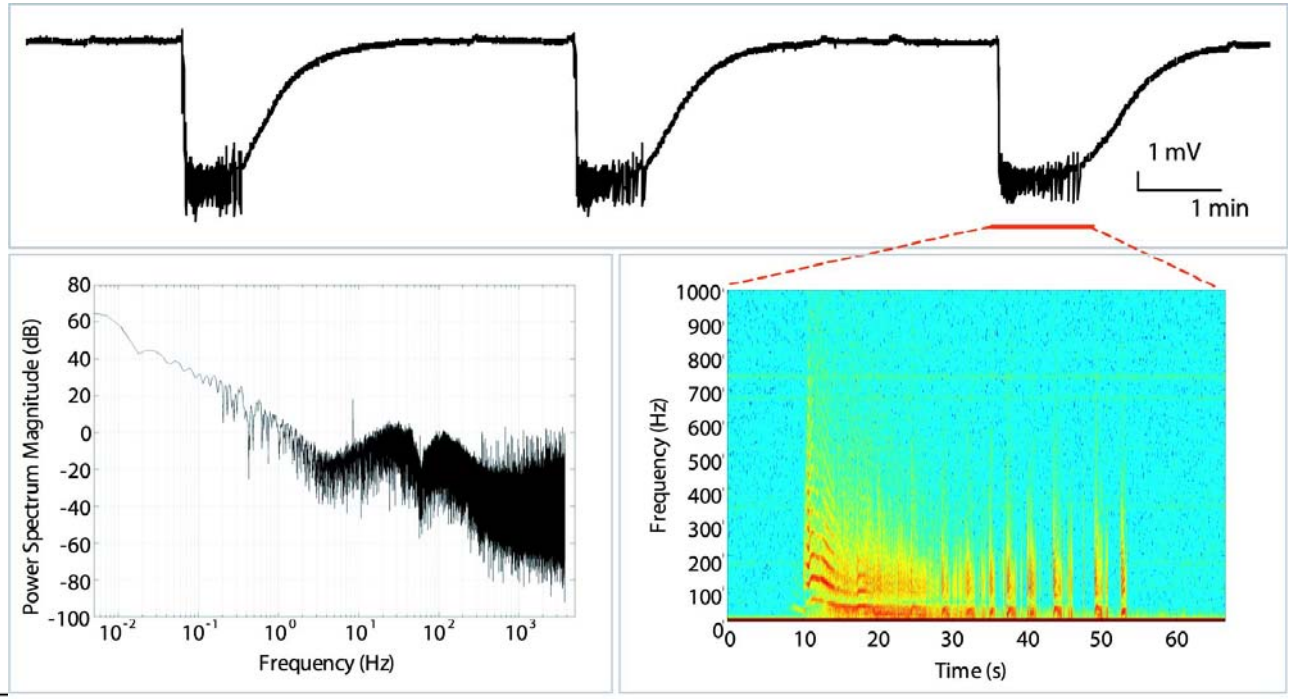
$$Ir^{3+}(OH)_3 + H^+ + e^- \leftrightarrow Ir^{2+}(OH)_2 + H_2O$$



iridium coated

stainless steel

insulated stainless steel



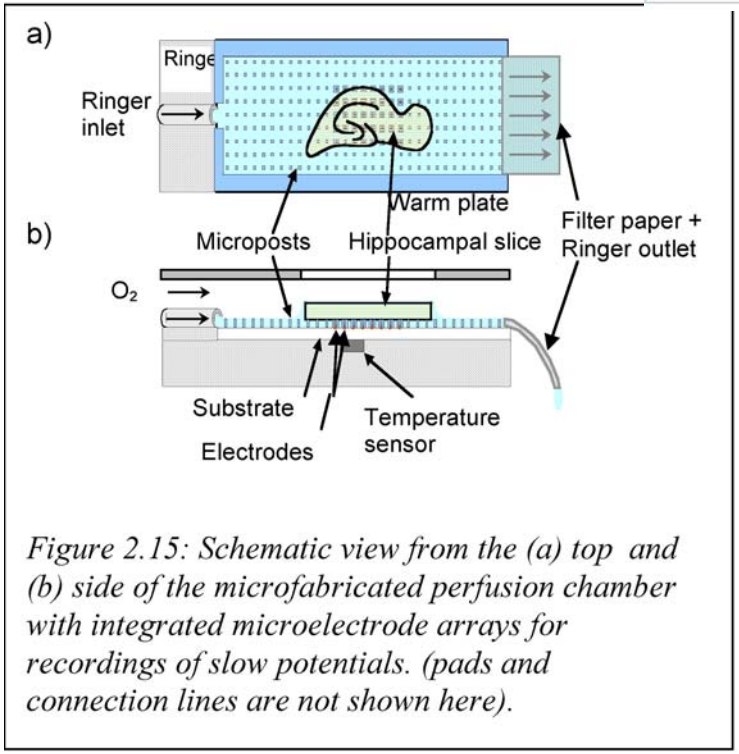
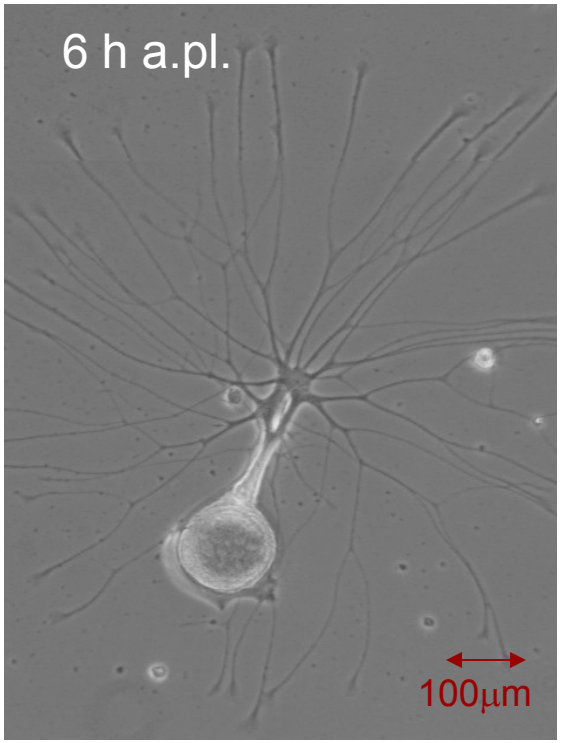
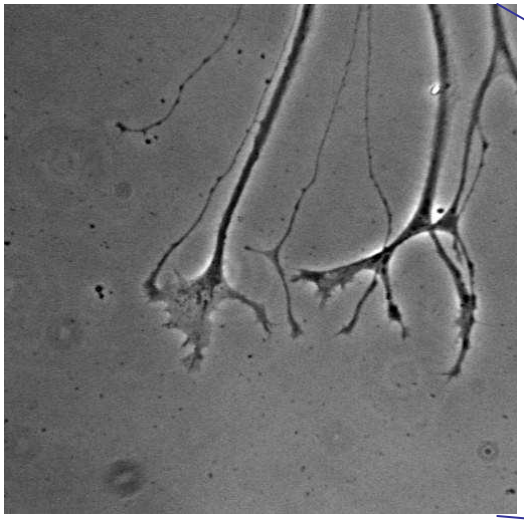


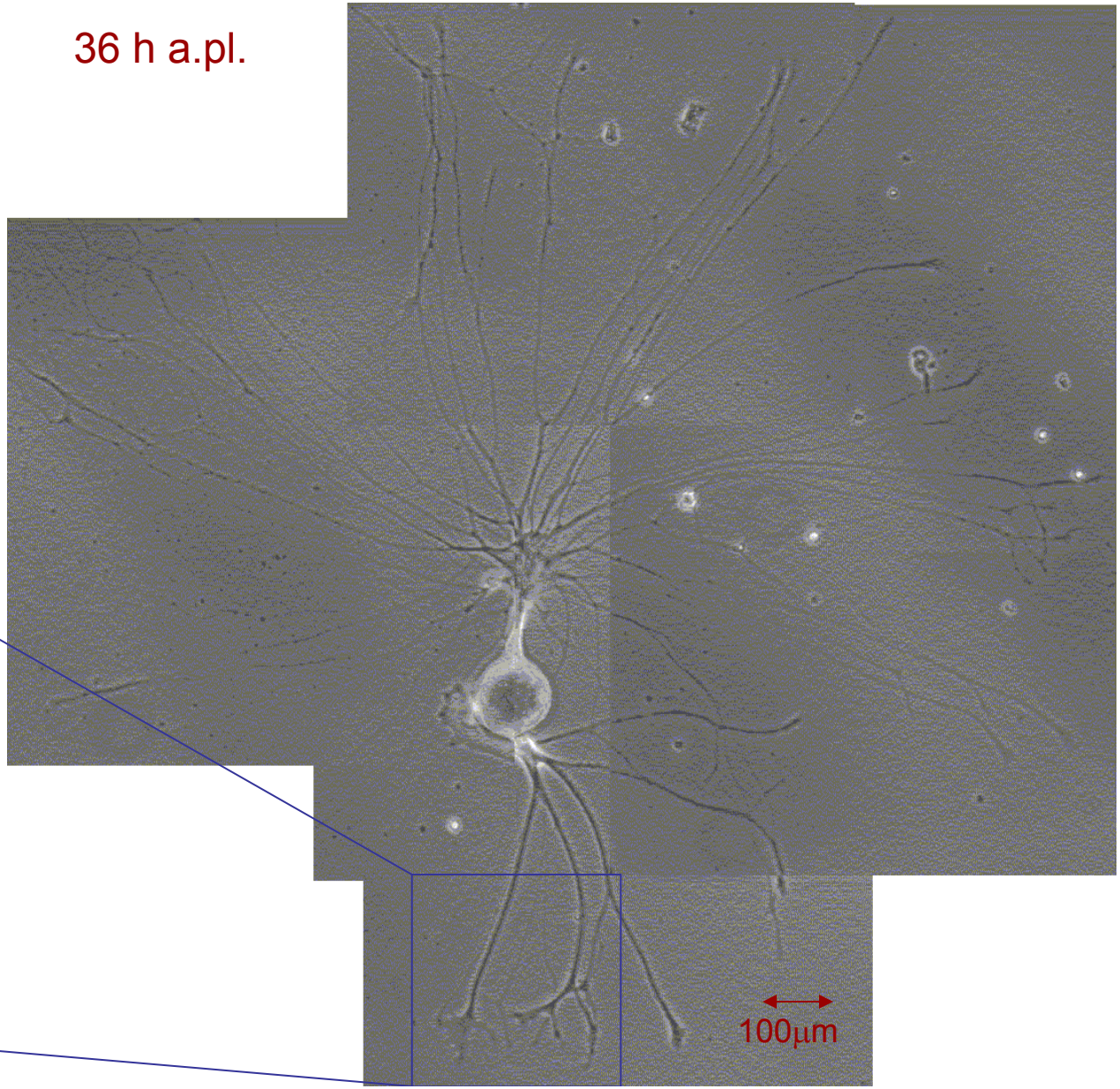
Figure 2.15: Schematic view from the (a) top and (b) side of the microfabricated perfusion chamber with integrated microelectrode arrays for recordings of slow potentials. (pads and connection lines are not shown here).

Snail neurons on silicon, process extension rate: 10μm/h

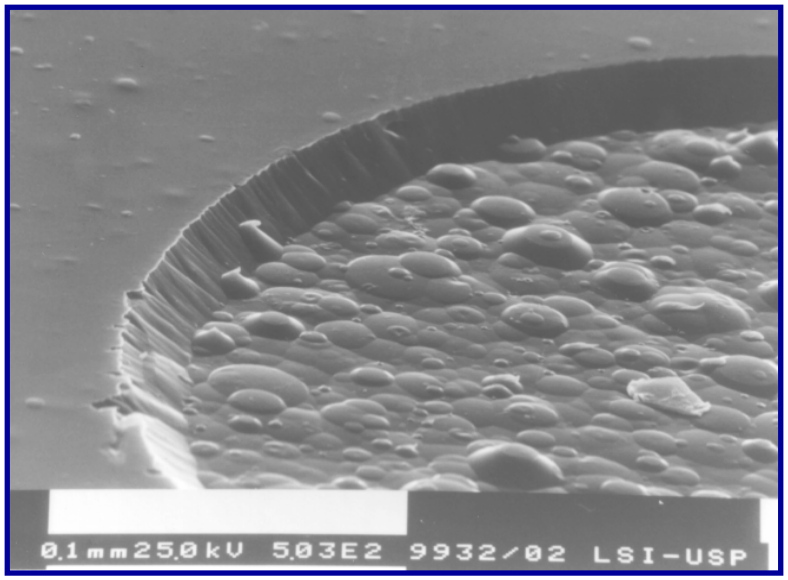




36 h a.pl.

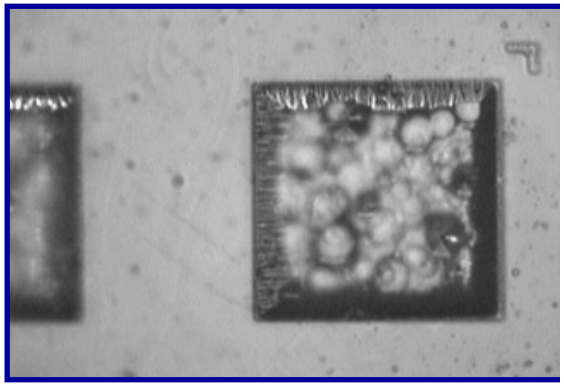


Transparency & flexibility



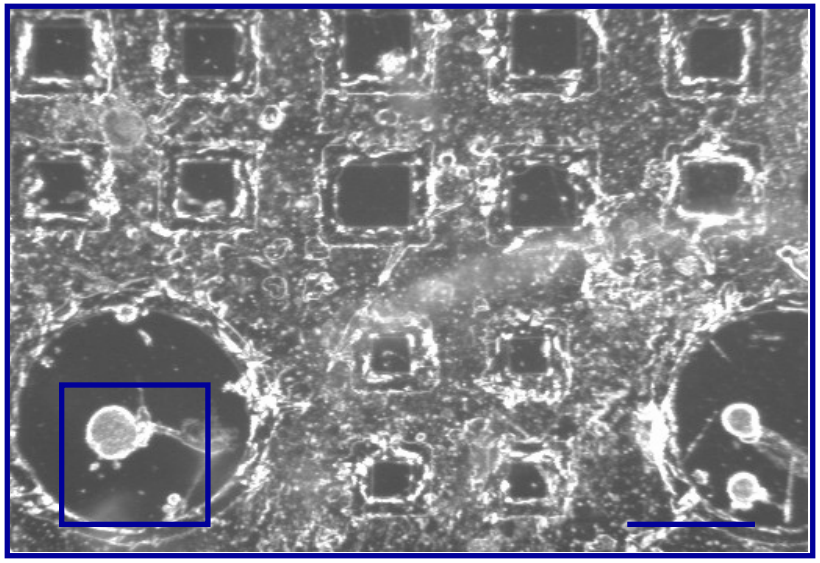
Desirable characteristics of MEAs:

- passivation
- post-processing
- biocompatibility
- packaging

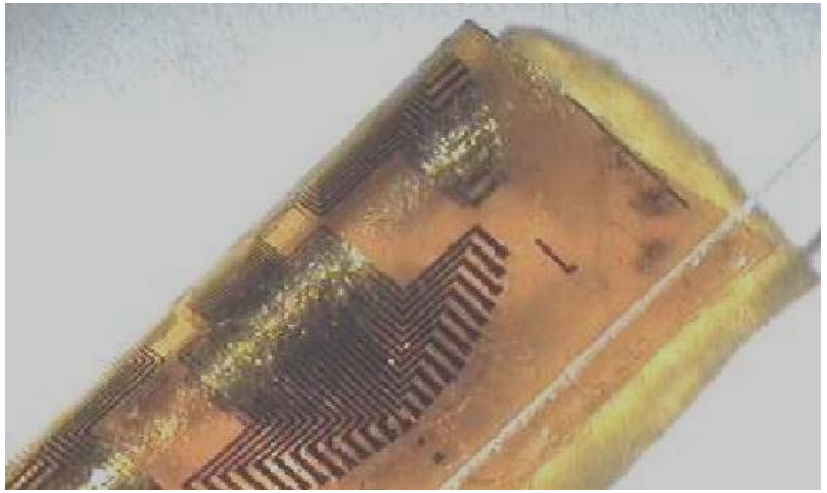


100μm

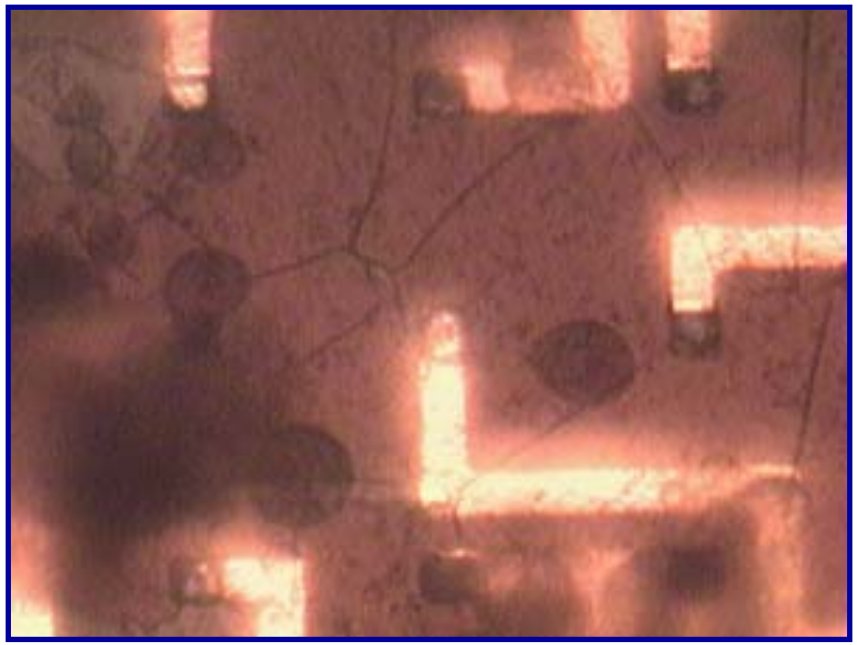
Wet etching of polyimide:
Flexible substrate for cultures.



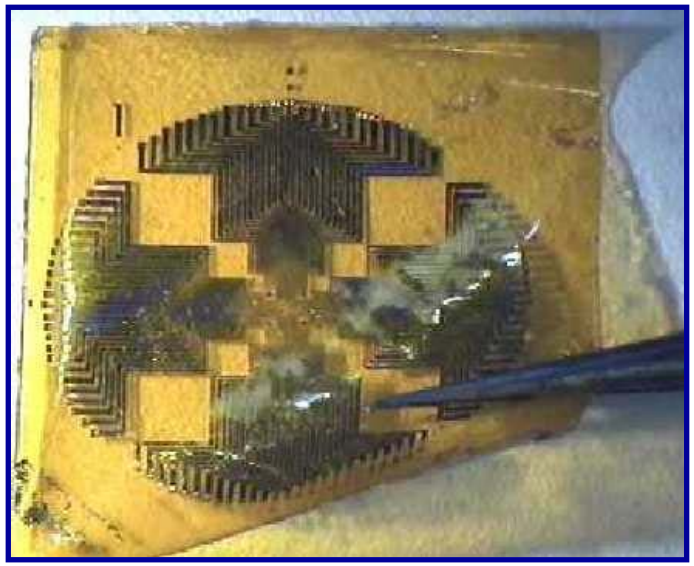
100μm



Electrodes for cell cultures



100μm

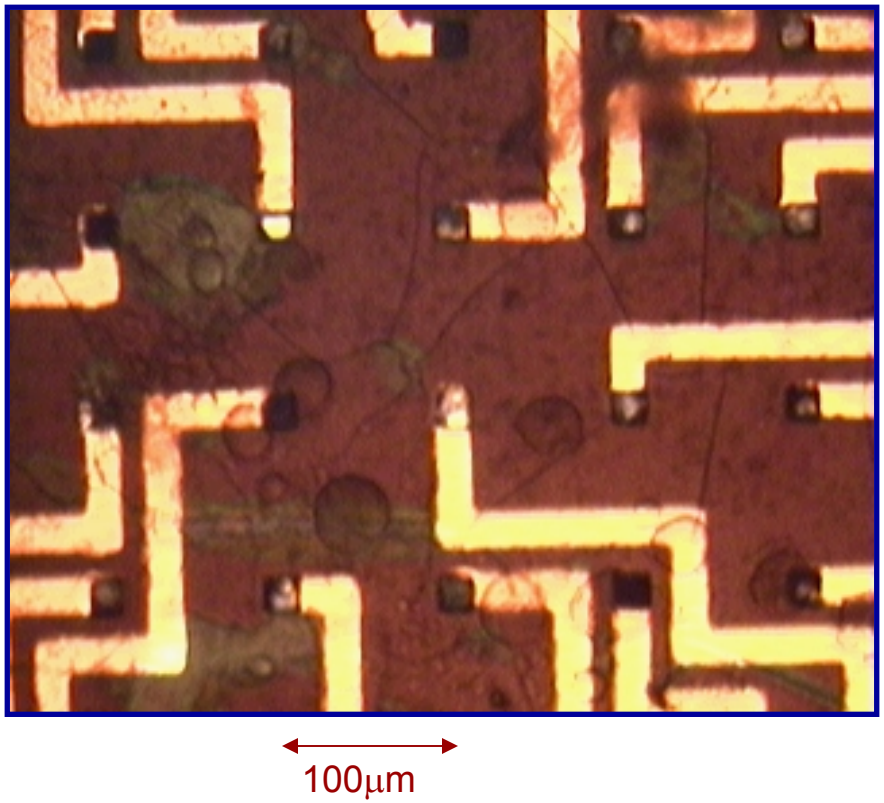


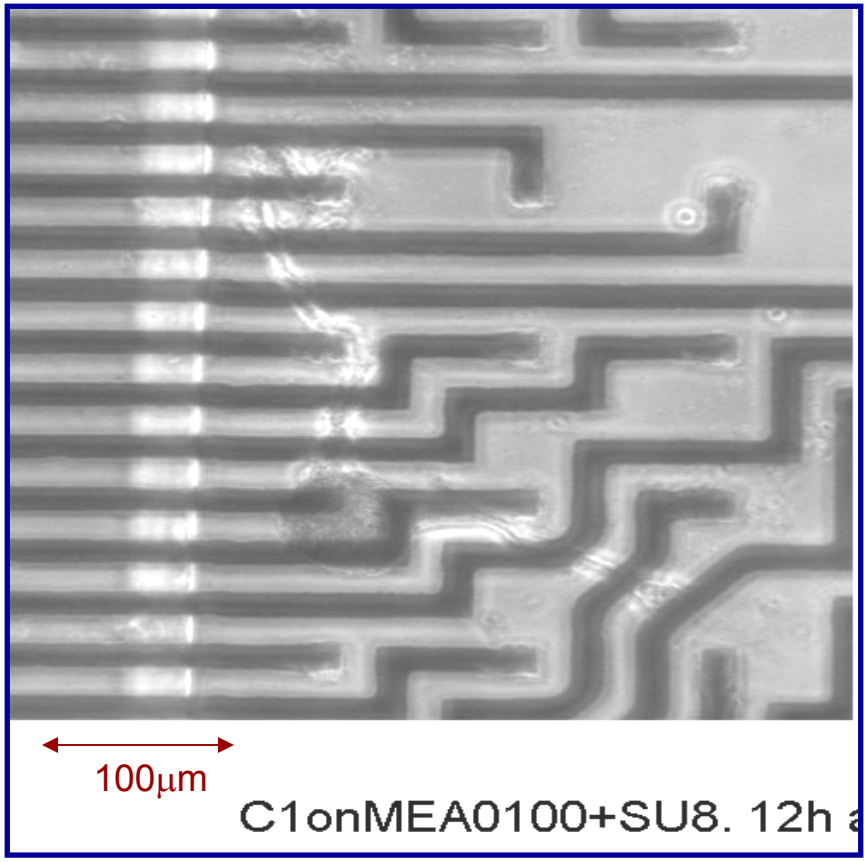
1cm

- Array design
- Biocompatible electrodes
- Cultured healthy cells
- Automatic stimulation with acquisition

Peixoto, Biosignal 2000.

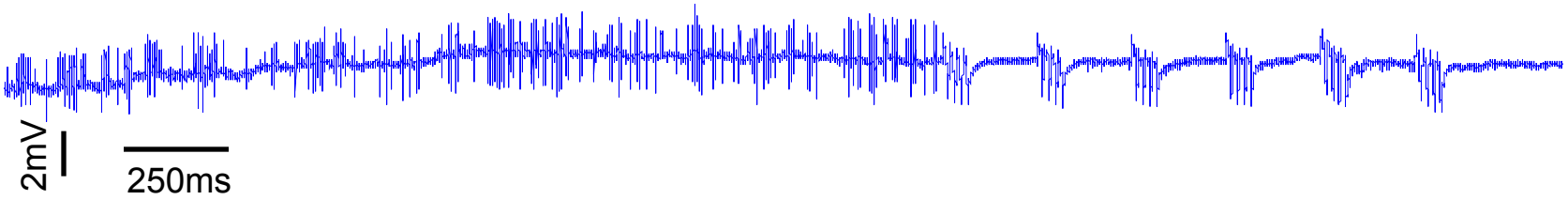
Live neurons on arrays





spontaneous activity

stimulated activity



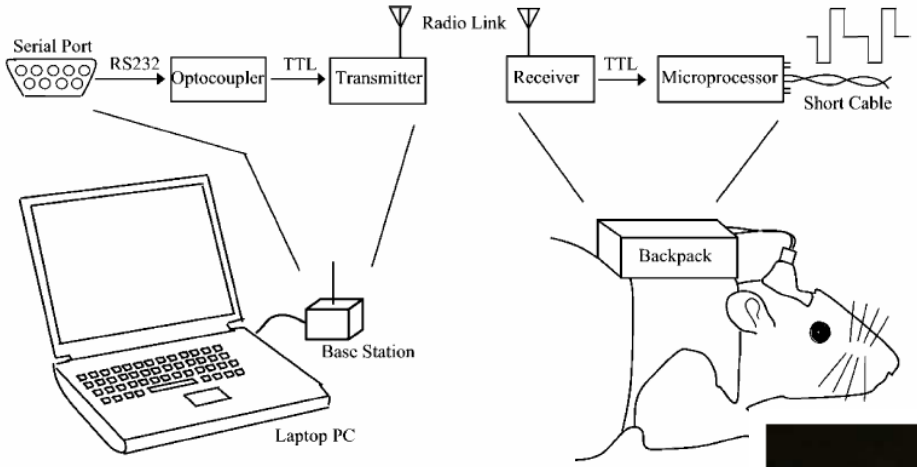


Fig. 1. Overview of the multi-channel telestimulation system. The main components of the system as well as the s

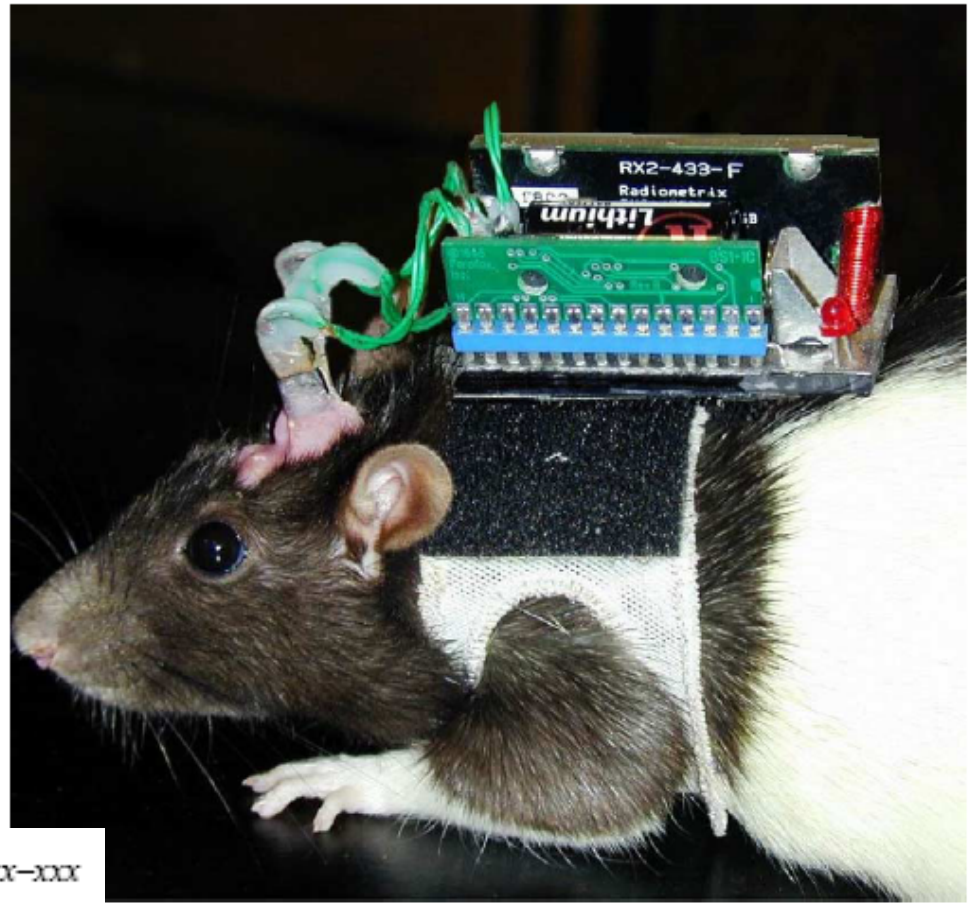
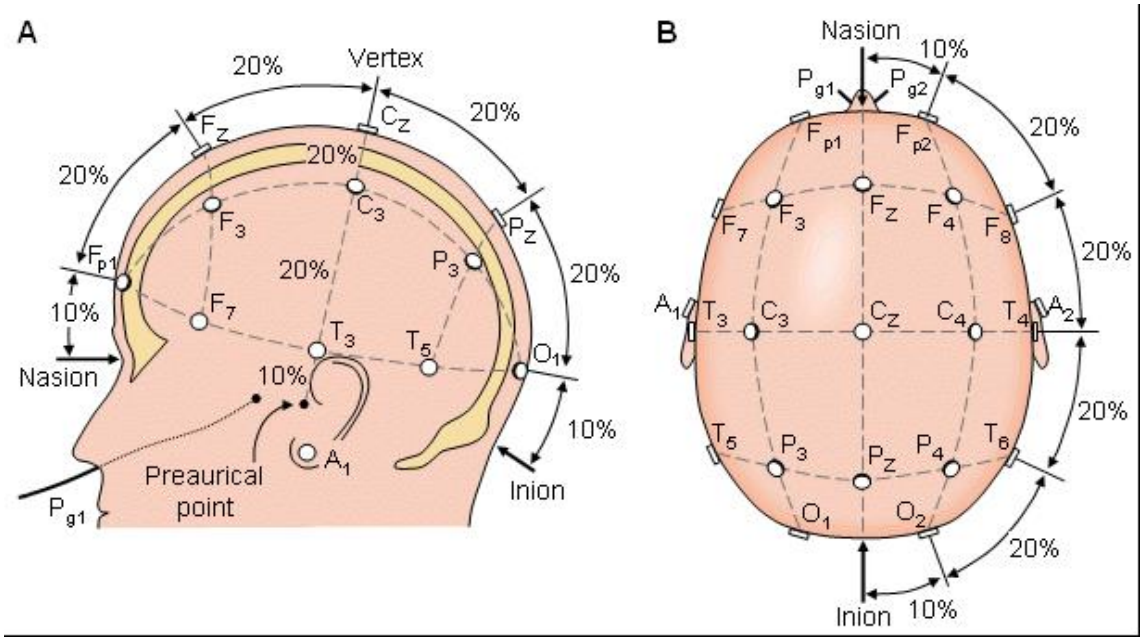
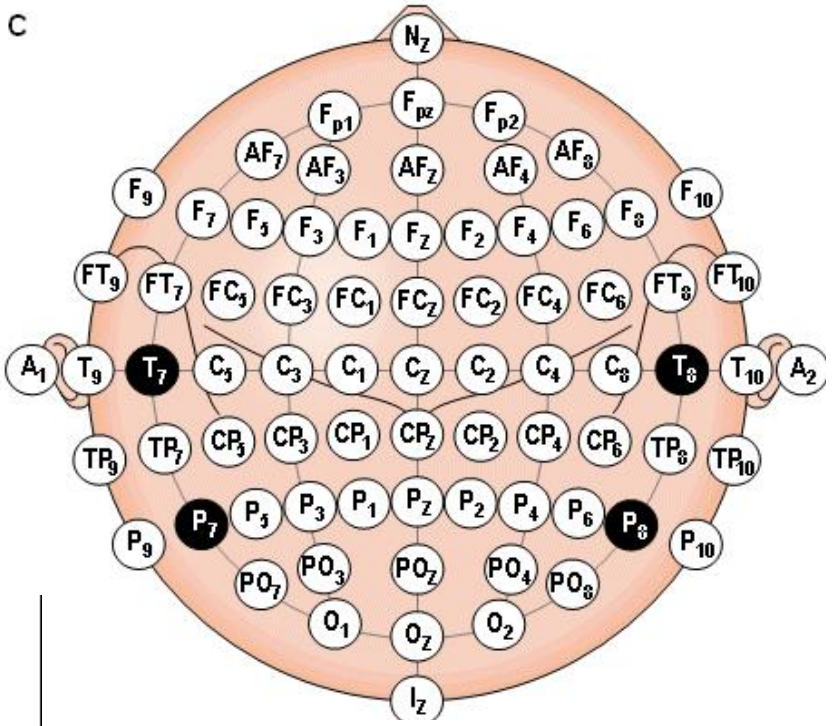


Fig. 3. Rat wearing a backpack under telemetric control.

EEG, international 10/20 system

From Malvimuo, Bioelectromagnetics.





Measuring EEG: bipolar or referential?

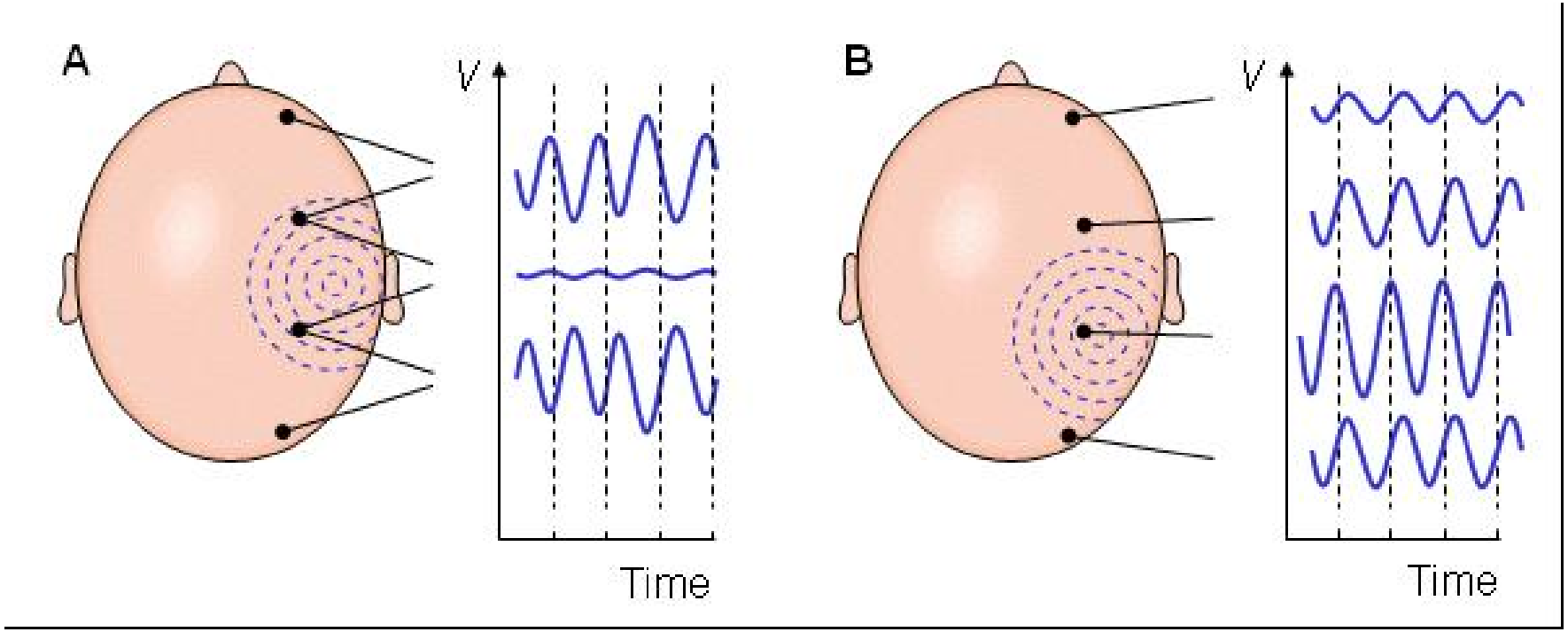


Fig. 13.3. (A) Bipolar and (B) unipolar measurements. Note that the waveform of the EEG depends on the measurement location.

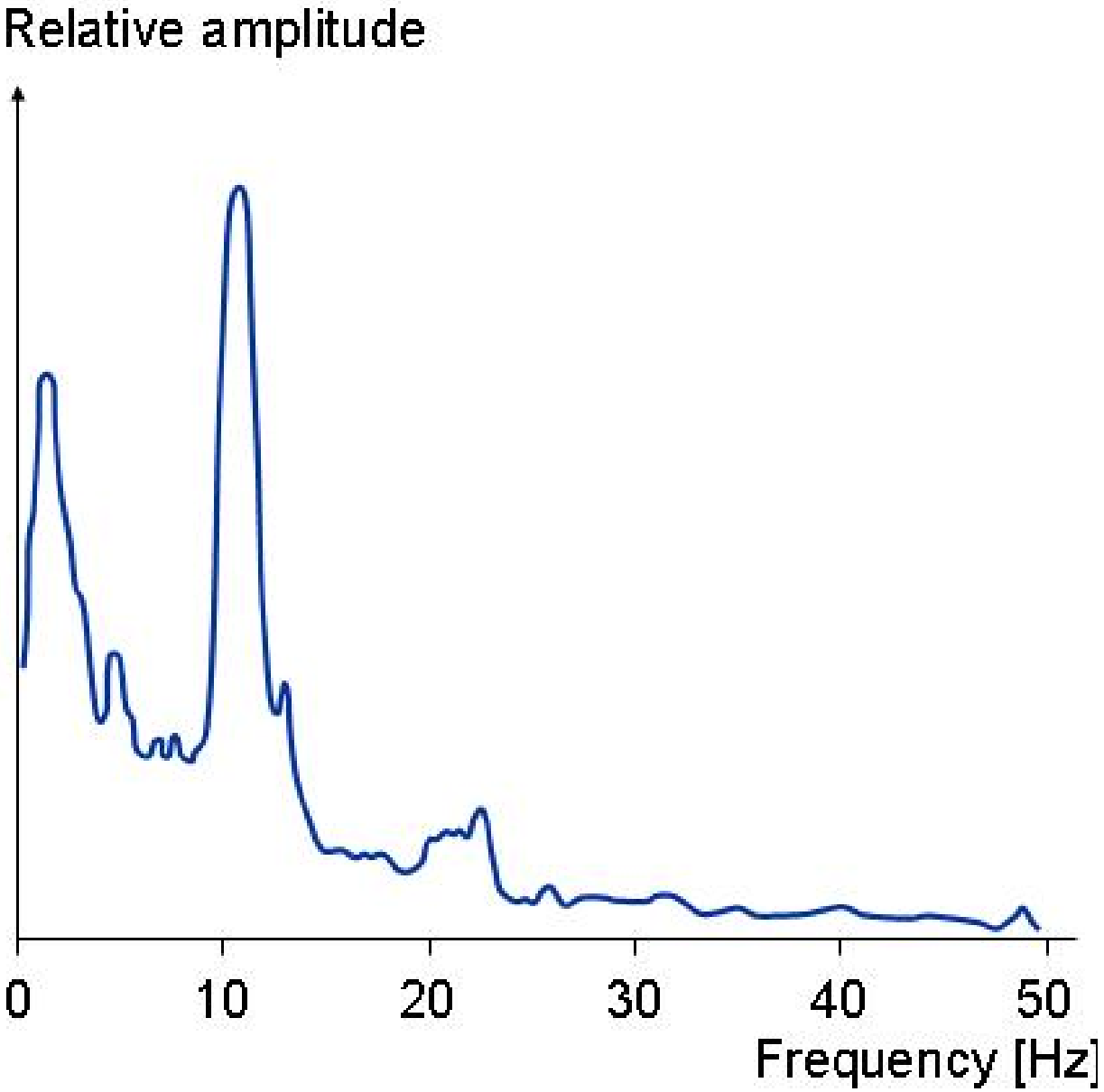
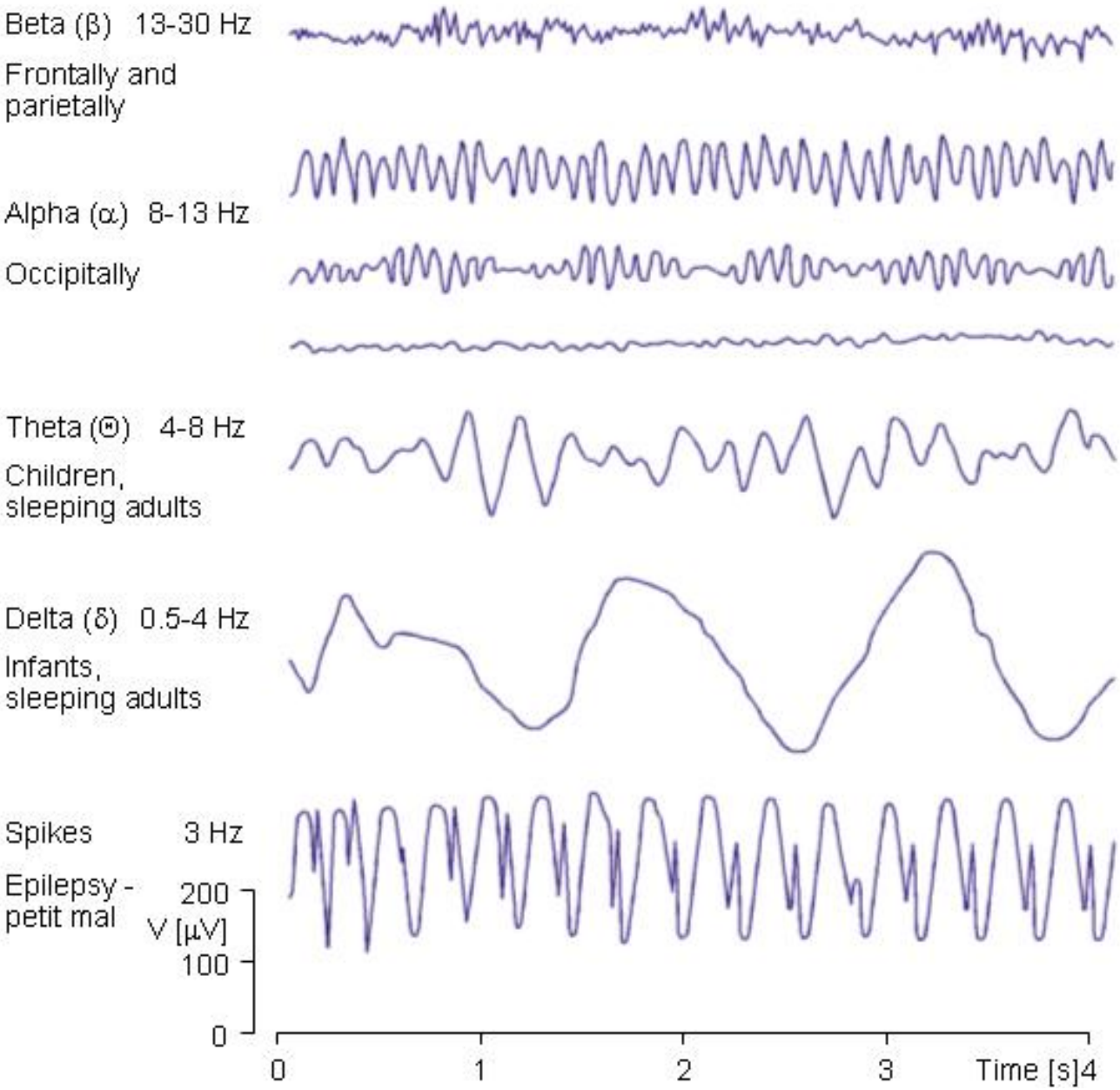


Fig. 13.1. Frequency spectrum of “normal” EEG.

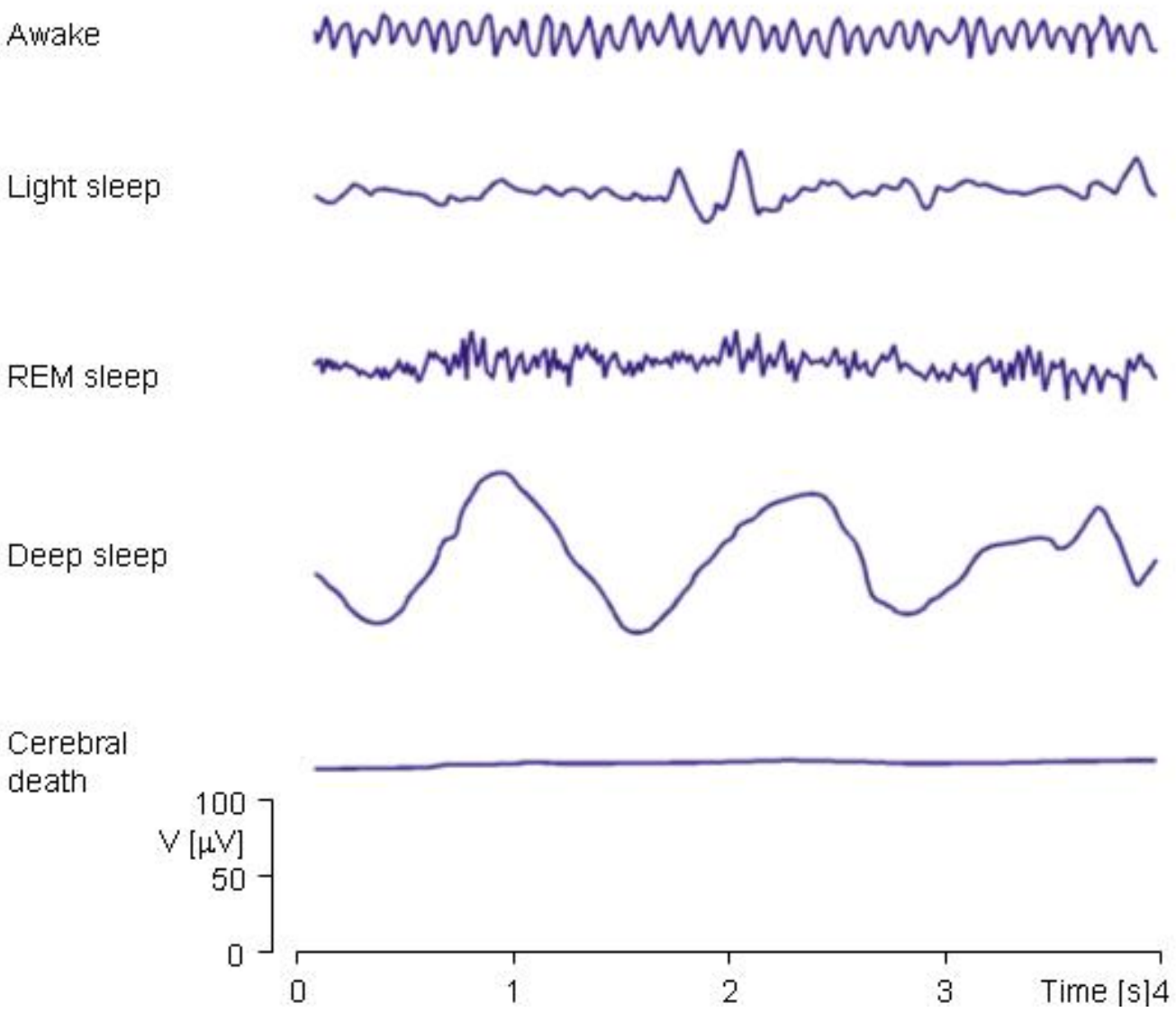
When you measure and read EEG, what can you detect?

- Seizures
- Normal EEG
- Sleep/rest
- Abnormal activity
- Activity

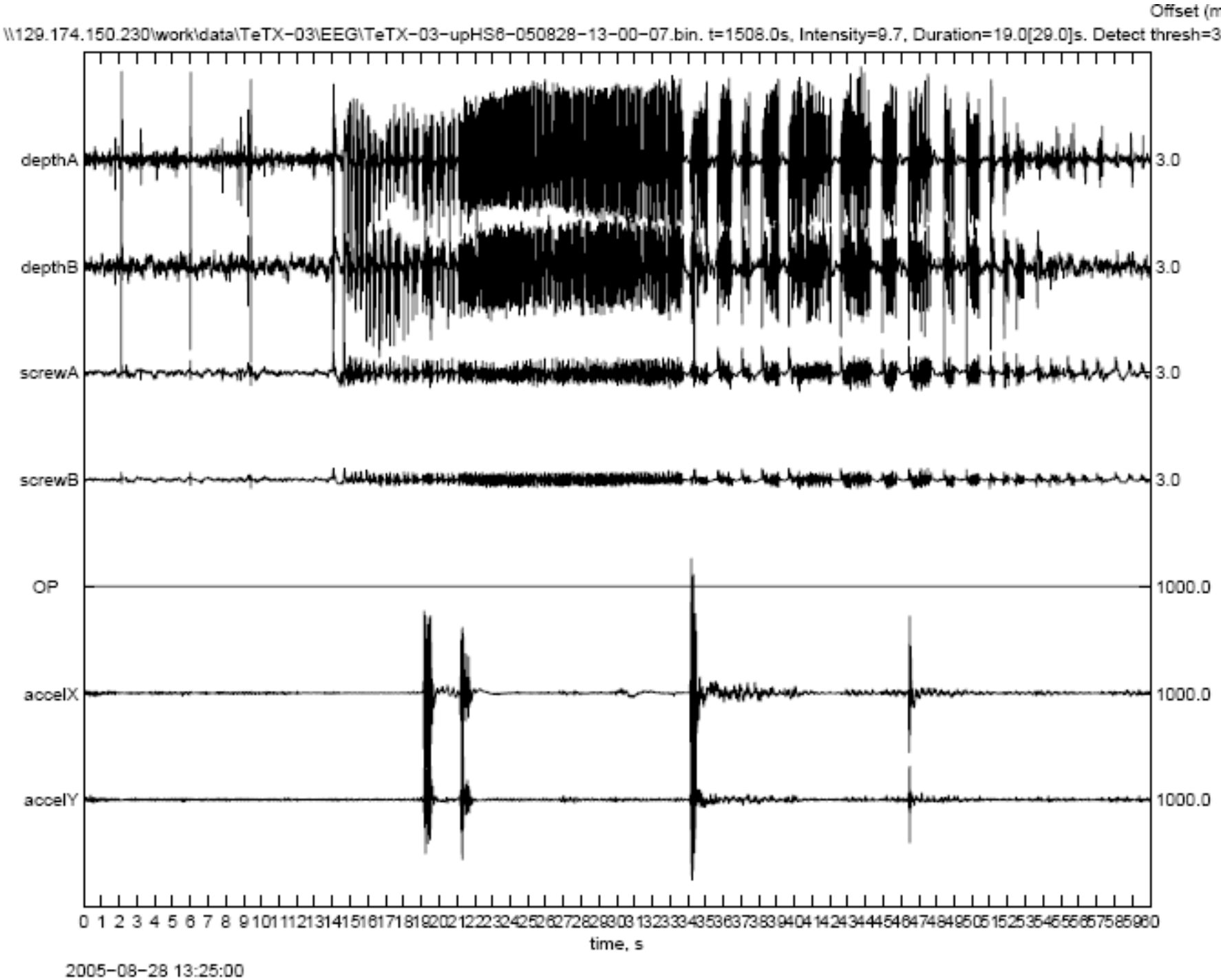
- Typical signal size: _____
- Frequency: _____
- Acquisition rate: _____



From the EEG signal it is possible to differentiate alpha (a), beta (b), delta (d), and theta (Q) waves as well as spikes associated with epilepsy. An example of each waveform is given in Figure 13.5.
The alpha waves have the frequency spectrum of 8-13 Hz and can be measured from the occipital region in an awake person when the eyes are closed. The frequency band of the beta waves is 13-30 Hz; these are detectable over the parietal and frontal lobes. The delta waves have the frequency range of 0.5-4 Hz and are detectable in infants and sleeping adults. The theta waves have the frequency range of 4-8 Hz and are obtained from children and sleeping adults



The EEG signal is closely related to the level of consciousness of the person. As the activity increases, the EEG shifts to higher dominating frequency and lower amplitude. When the eyes are closed, the alpha waves begin to dominate the EEG. When the person falls asleep, the dominant EEG frequency decreases. In a certain phase of sleep, rapid eye movement called (REM) sleep, the person dreams and has active movements of the eyes, which can be seen as a characteristic EEG signal. In deep sleep, the EEG has large and slow deflections called delta waves. No cerebral activity can be detected from a patient with complete cerebral death. Examples of the above-mentioned waveforms are given in Figure 13.6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depthA
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accelX
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3.0
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0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43 44 45 46 47 48 49 50 51 52 53 54 55 56 57 58 59 60
time, s
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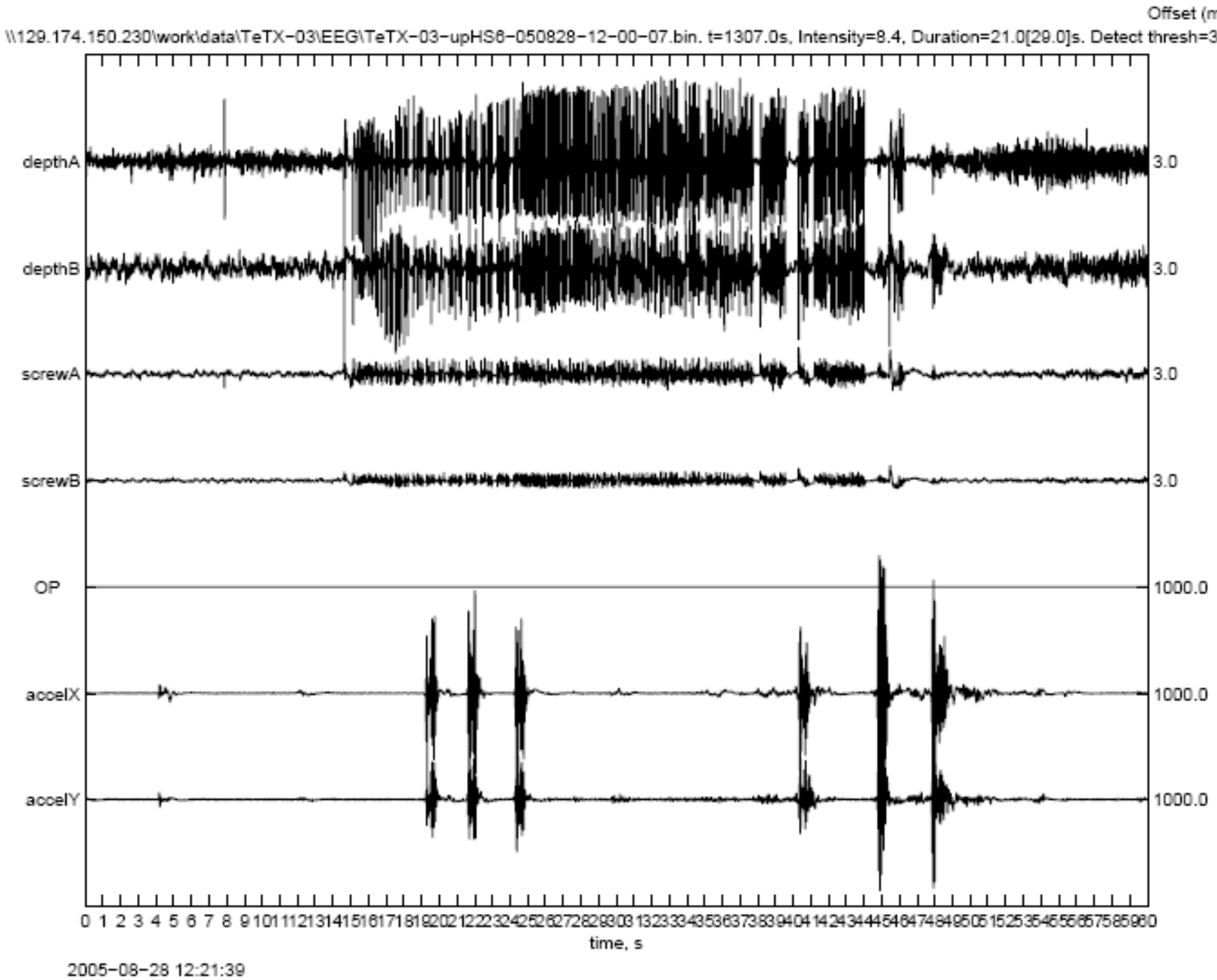
Offset (mV)
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depthA
depthB
screwA
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0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43 44 45 46 47 48 49 50 51 52 53 54 55 56 57 58 59 60
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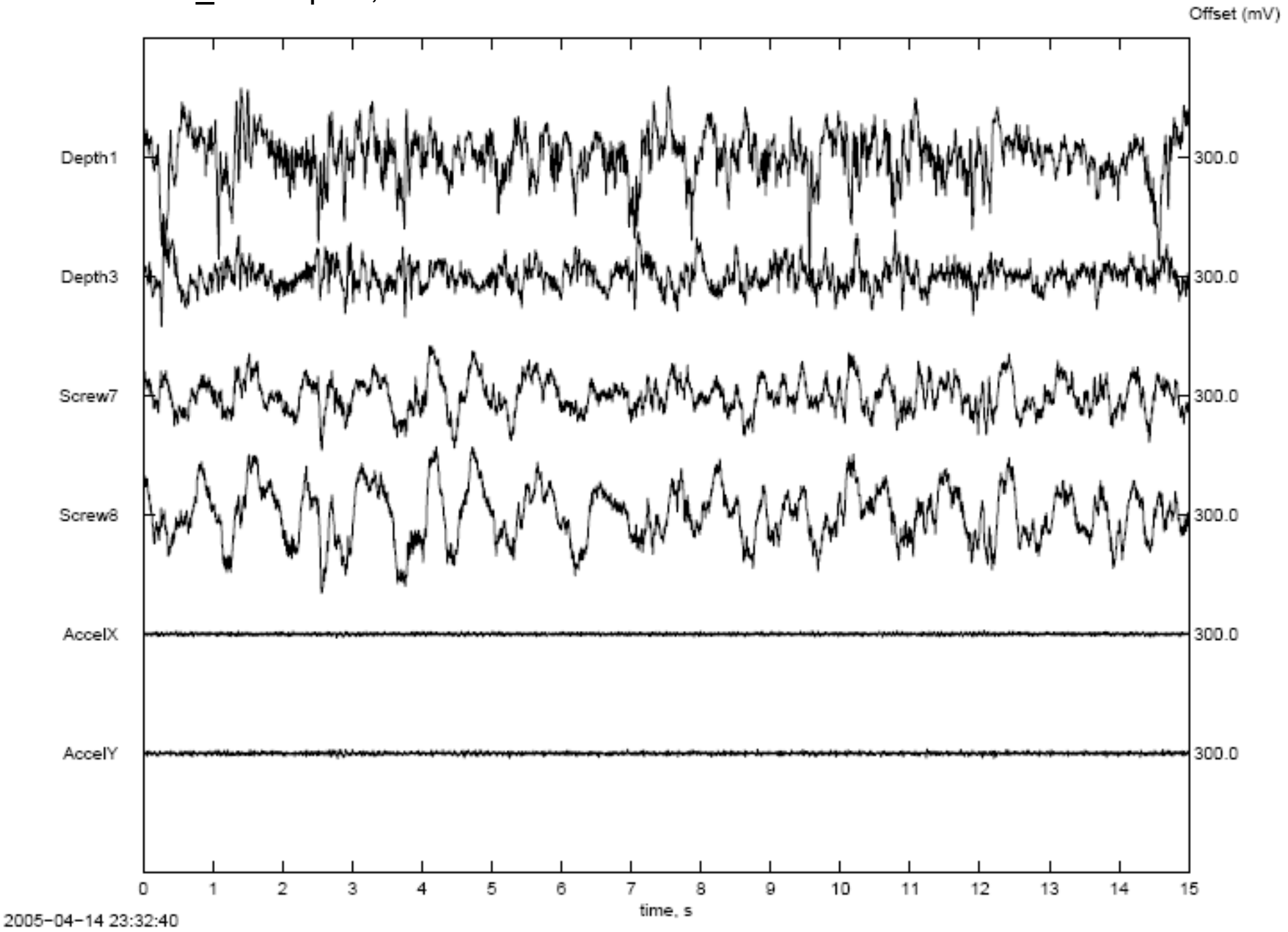
22R050414_two depths, four screws.



Spinal cord: why is a “simple” compression so damaging?

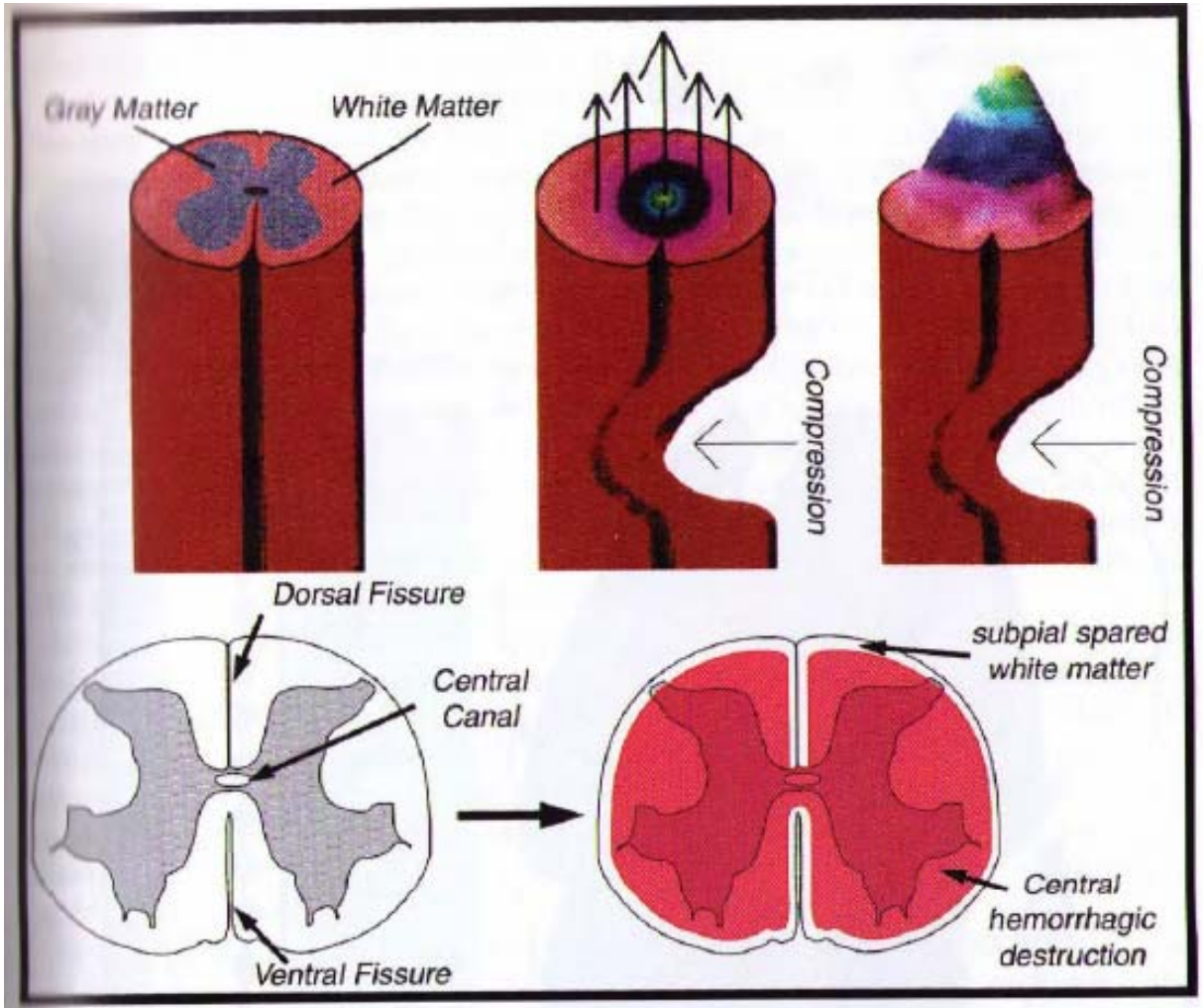


Fig. 4. Spinal cord and spinal cord compression. Mechanical damage to the spinal cord in humans usually arises from compression, not transection. The tissue of the spinal cord may be lacerated by bony fragments arising from the shattered vertebral column (as in burst fractures of the spine), or

Because the white matter matters.

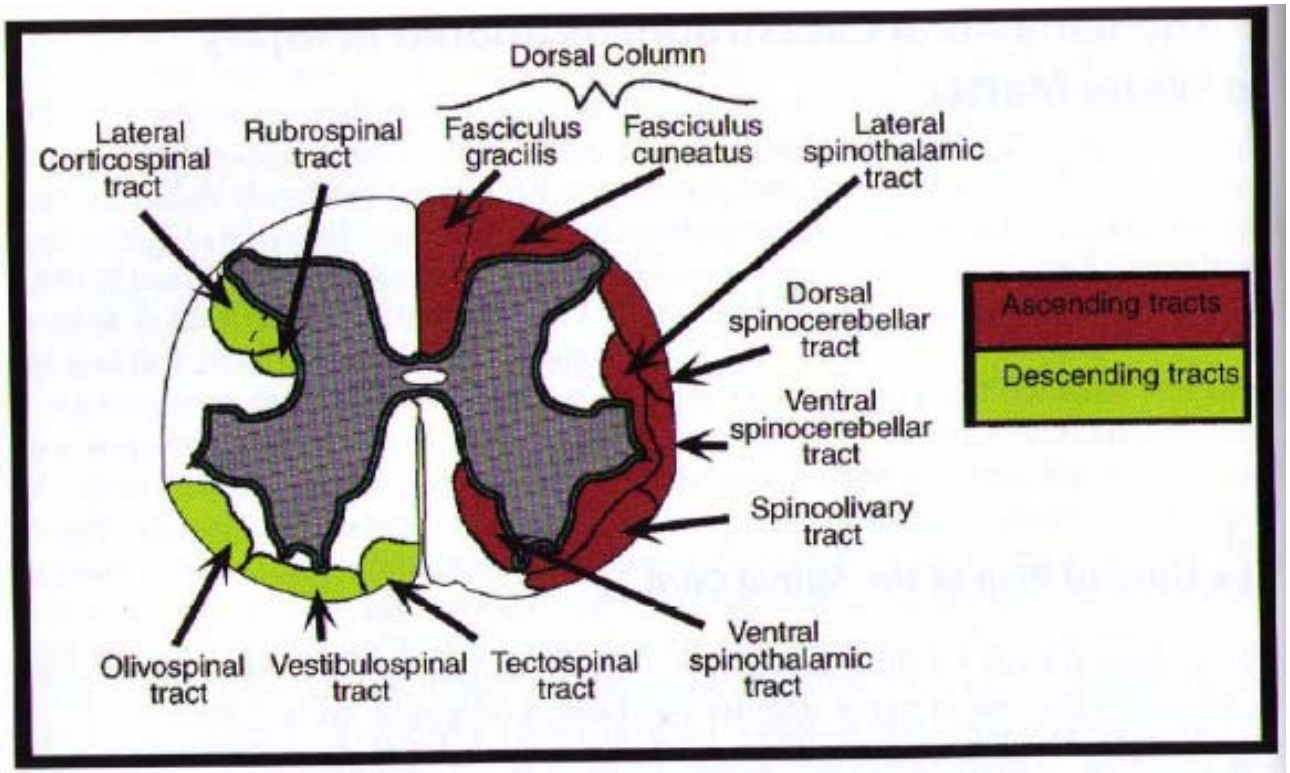


Fig. 1. Anatomy of the human spinal cord; ascending and descending tracts. Note the familiar appearance of the gray matter in cross section. The location of a few of the major ascending and descending tracts in the surrounding white matter are shown. These bilateral long tract columns of nerve fibers traverse much of the length of the cord. The two components of the dorsal column are shown, the fasciculus cuneatus and gracilis. The former builds its substance upon the entry of sensory nerves from the extremities at each dorsal root as axons are added laterally with each ascending vertebral level. Both of these tracts terminate in the hindbrain at the nucleus cuneatus and gracilis. They convey the sense of light touch and vibration, among other sensations. Another ascending sensory tract discussed in the text, the spinothalamic, is also found in two components bilaterally ascending the spinal cord. It conveys the senses of superficial pain and temperature, among others sensations. Descending tracts originate from first order neurons in the brain. Descending tracts discussed in the text include the vestibulospinal tract, involving balance and posture, and the corticospinal tract, projecting to motor neurons in the cord. It is the interruption in nerve impulse traffic traveling in these ascending and descending pathways that results in the catastrophic behavioral loss associated with spinal cord injury

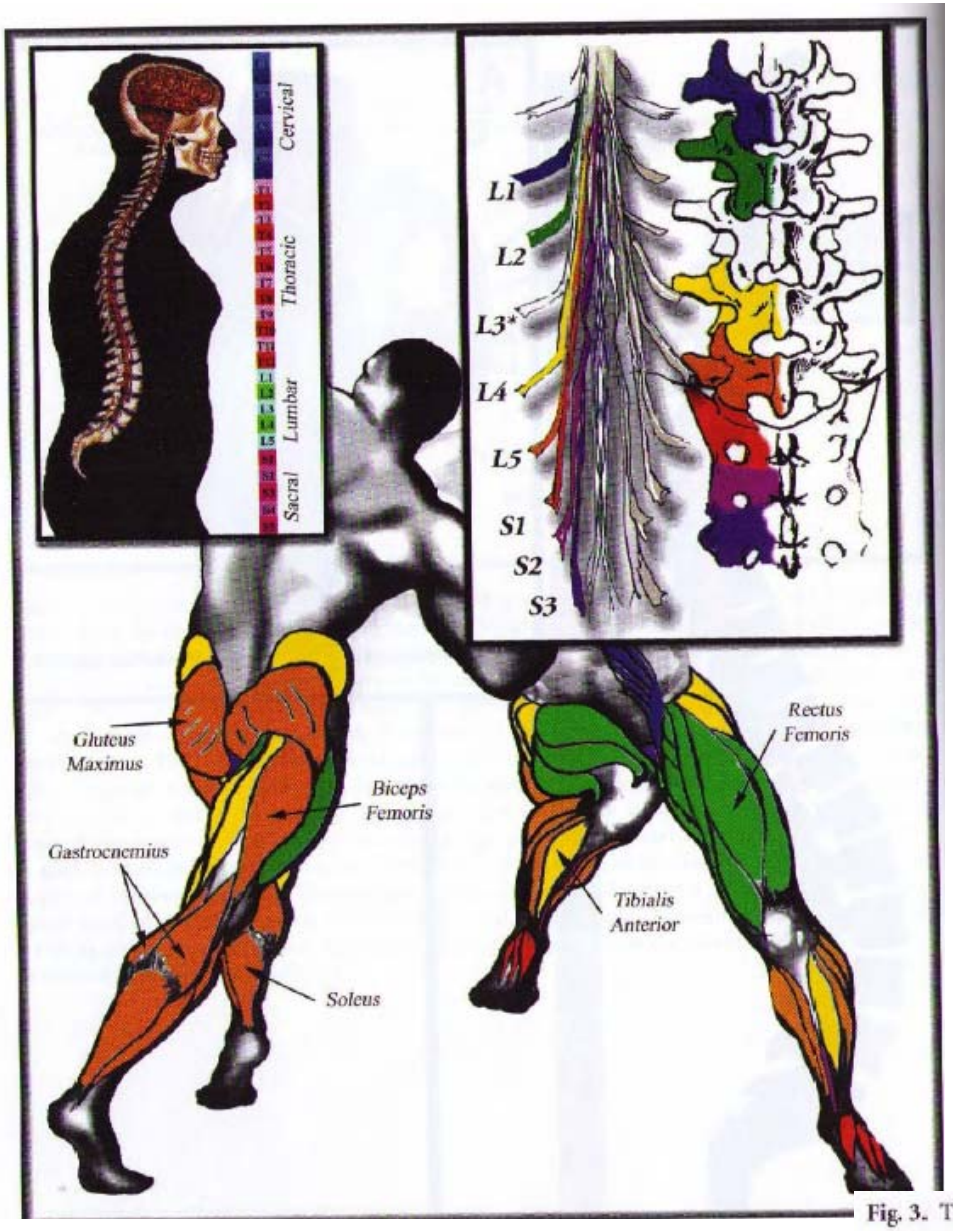


Fig. 3. The spinal cord, levels of injury, and paraplegia. The *inset* to the *left* repeats some of the anatomy shown in Fig. 2; however, the two components of the CNS, the brain and spinal cord, are *highlighted*. Note again, in the *inset* to the *right*, that the human spinal cord ends at L1. The spinal nerves at this level and below continue to project downwards towards the tip of the sacrum, exiting at the vertebral segments shown. These are *color-coded* for the sacral levels where the ventral spinal roots exit the vertebral column (for simplicity, only the left side is rendered). The major muscles of the lower extremities that receive these bilateral motor nerve fibers from L1 to S3 are *color-coded* to the vertebral levels servicing them. These muscles, especially the larger ones, receive motor neuron

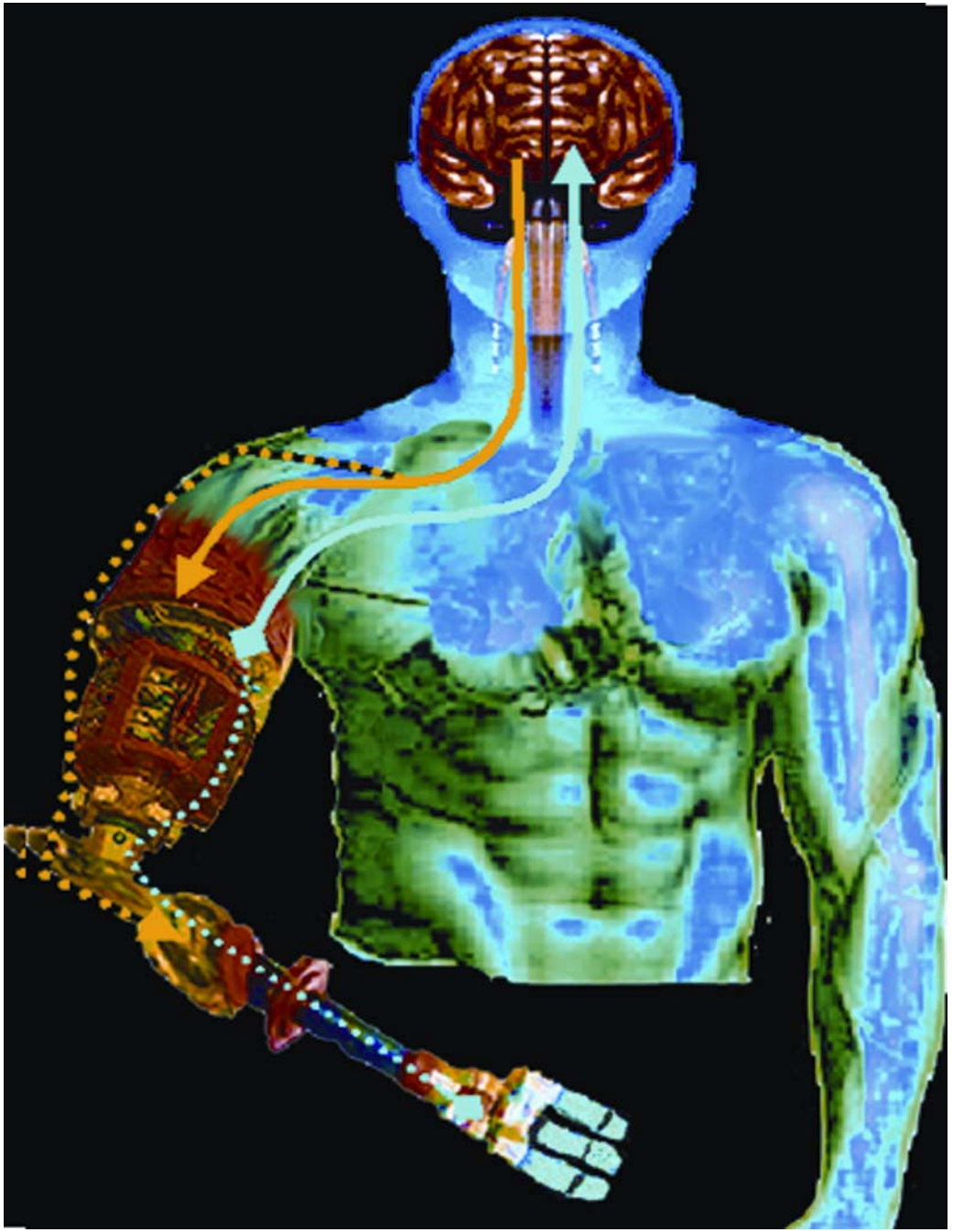
Neurorobotics - motivation

Why would you want to learn this?
Who would you help?

What can you do to help?

Neurorobotics

- Introduction
- Brain interface
- Control
- Hardware req.
- Future



Introduction

Neurorobotics: the establishment of any interface between ensembles of single neurons in the brain and an external device.

In this presentation: recent advances in Neurorobotics; tools for neuroscientists to probe brain functions; uses in clinical settings.

Where do advances come from?

- Hollywood ideas
- Need to improve quality of life
- Interest in “Biology” (how does the brain process info? How does it work? Can we control it? Can we controllably make it change?
- _____ (suggestions from the audience?)
- _____

Directly interfacing with the human brain

Characteristics of the brain: complex system; convergence; divergence; redundancy; summation; parallel and serial signal processor.

Principles of brain function emerged 50-100 years ago through recordings from the nervous system:

(1) Coordinated patterns of activity
(2) Theory of mass action
(3) Synaptic plasticity
(4) Theory of cell assemblies (information representation is stochastic, redundant, related to function, not to anatomy)

(1) coordinated patterns of activity

(1) Information is transferred in the nervous system by ***coordinated patterns of activity*** involving interconnected neurons.
Idea suggested by Sherrington in 1906 (J.Physiol.): “circularities”,
Now called “recurrent loops”. Cramps, spinal seizures, spasticity, scratching, swimming. Spinal cord, deprived of descending modulation, can organize such behaviors.

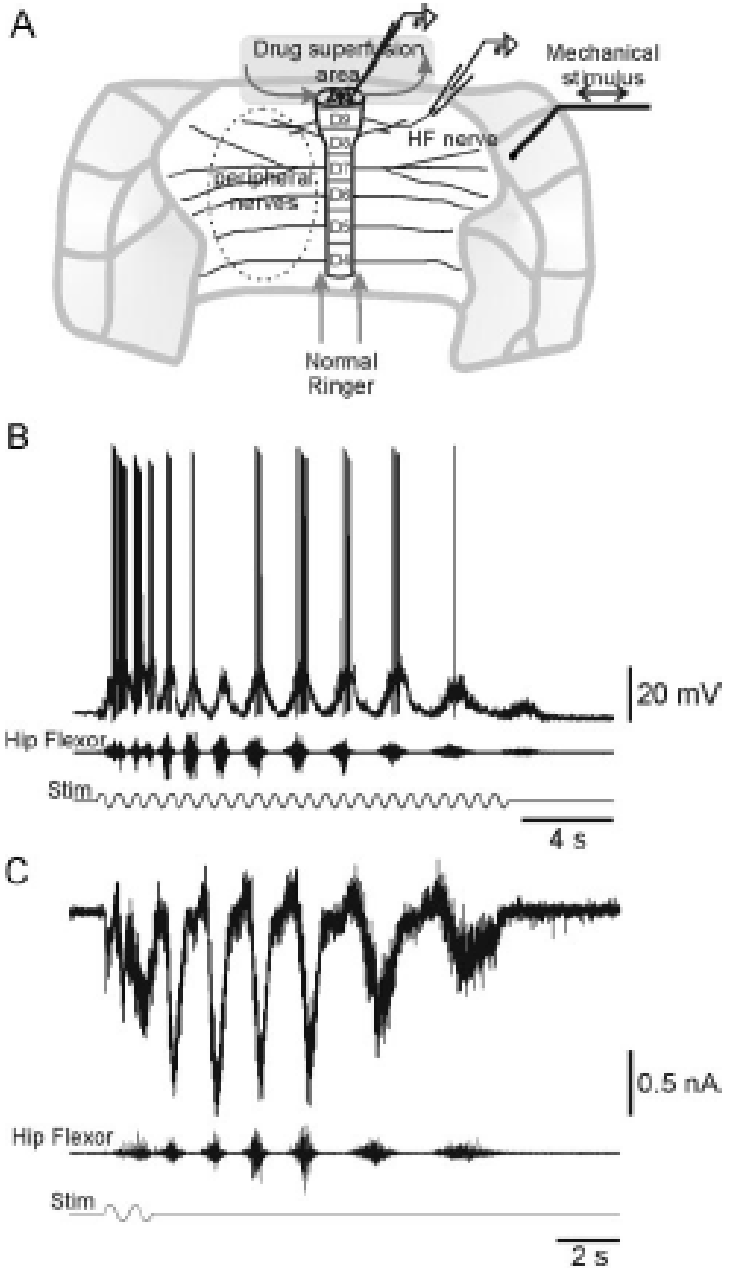


Figure 1. Integrated lumbar carapace–spinal cord preparation. *A*, Sketch of the integrated preparation and experimental setup. Shown is the response of a motoneuron and the hip flexor nerve to mechanical stimulus (stim) recorded simultaneously in current-clamp (*B*) and voltage-clamp mode (*C*).

(2) Theory of equipotentiality; theory of mass action.

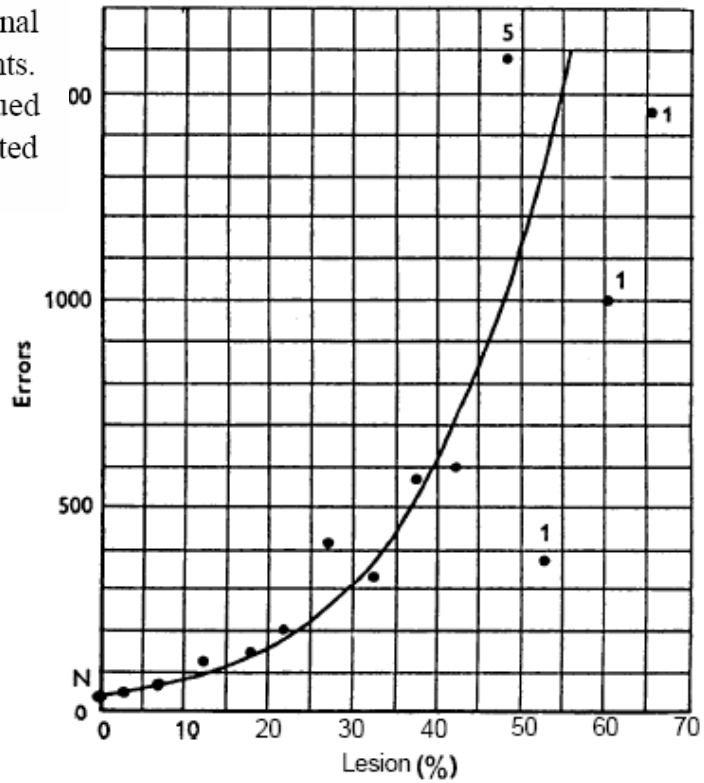
Results such as these have led me to formulate a theory of mass action or mass facilitation. It is, essentially, that performance of any function depends upon two variables in nervous activity. The reaction mechanism, whether of instinctive or of learned activity, is a definite pattern of integrated neurons with a variable threshold of excitability. The availability of such patterns, the ease with which they can be activated, is dependent upon less specific facilitative effects. This facilitation can come from a variety of sources. Some instinctive behaviour seems to require hormonal activation, probably a direct chemical effect upon specific nervous elements. Emotional facilitation may produce a temporary activation. Continued activity of related mechanisms may facilitate the whole group of associated reactions; a sort of warming-up effect.

IN SEARCH OF THE ENGRAM

BY K. S. LASHLEY

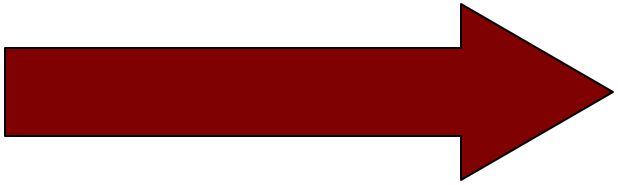
Harvard University and the Yerkes Laboratories of Primate Biology

Lashley, K.S., 1950.



Text-fig. 8. The relation of errors in maze learning to extent of cerebral damage in the rat. The extent of brain injury is expressed as the percentage of the surface area of the isocortex destroyed. Data from 60 normal and 127 brain-operated animals are averaged by class intervals of 5 % destruction. The curve is the best fitting one of logarithmic form. For lesions above 45 % the number of cases (indicated by numerals on the graph) is too small for reliability. (After Lashley & Wiley, 1933.)

(3) Synaptic plasticity
Hebb 1949.



8.1 Concept of a Hebbian Synapse

In his 1949 book, *The Organization of Behavior*, Donald Hebb proposed that an important condition for triggering enhanced synaptic efficacy would be the repeated conjunction of presynaptic activity and the firing of the cell on to which this activity was afferent [43, p. 62]:

> "When an axon of cell *A* is near enough to excite a cell *B* and repeatedly or persistently takes part in firing it, some growth process or metabolic change takes place in one or both cells such that *A*'s efficiency, as one of the cells firing *B*, is increased."

This idea has come to be known as "Hebb's postulate" for learning [18,97]. Hebb proposed this change as the basis of a memory formation and storage process that would cause enduring modifications in the elicited activity patterns of spatially distributed "nerve cell assemblies." Thus, it specifies the *location* of the modification and provides a qualitative statement of the *conditions* for change. In brief, a *Hebbian synapse* strengthens when the presynaptic and postsynaptic elements tend to be coactive.

Hebb's postulate can be seen as the synthesis of two earlier ideas about memory [18]. First, the American psychologist William James (1890) proposed that the most basic law of association was the *law of neural habit*, which maintained that if two "elementary brain processes" are active at the same time, then each will tend to "propagate its excitement into the other." James did not suggest a cellular correlate or substrate for these elementary brain processes. The second idea concerns the physical nature of the changes underlying memory. The Italian neuroanatomist Eugenio Tanzi (1893) proposed that the synapse might be the locus of the modification, an idea that was later advanced by Cajal (1911). Thus, Hebb's postulate can be seen as the synthesis of the law of neural habit and the synaptic hypothesis for memory.

(4) Theory of cell assemblies (information representation is stochastic, redundant, related to function, not to anatomy)

Switchboard versus Statistical Theories of Learning and Memory

Coherent patterns of neural activity reflect the release of memories and may mediate subjective experience.

E. Roy John

1972

SCIENCE, VOL. 177

These considerations and related data led me to propose (*26*) an alternative to switchboard theories: the statistical configuration theory. The critical event in learning is envisaged as the establishment of representational systems of large numbers of neurons in different parts of the brain, whose activity has been affected in a coordinated way by the spatiotemporal characteristics of the stimuli present during a learning experience. The coherent pattern of discharge of neurons in these regions spreads to numerous other regions of the brain. Sustained transactions of activity between participating cells permit rapid interaction among all regions affected by the incoming sequence of stimuli as well as the subsequent spread.

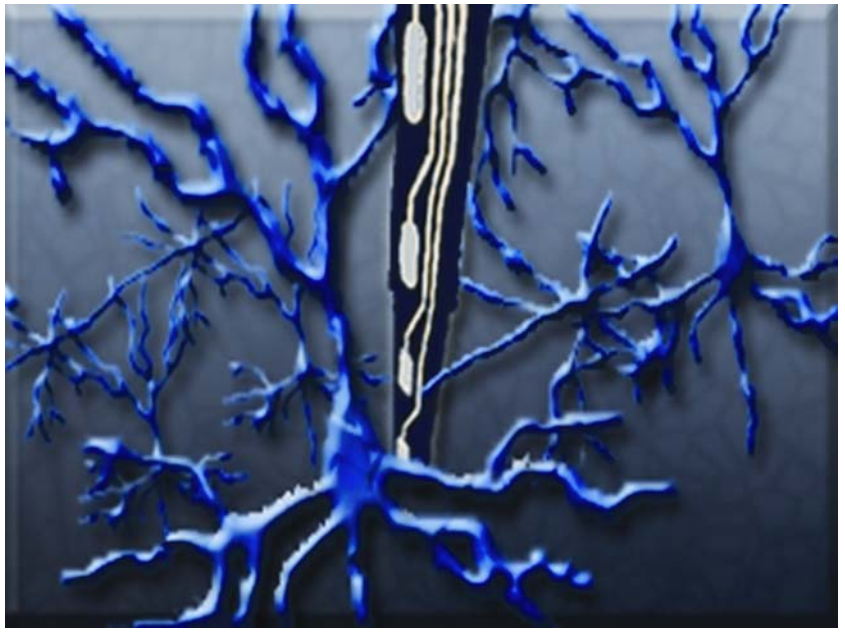
(...) Whether such changes are alterations of "synaptic efficiency" or not, it is assumed that the critical feature of these changes is to increase the probability of recurrence of that coherent pattern in the network. Certain types of preexisting neuronal *transactions* become more probable, but no new connections are assumed to be formed.

Coding strategies of ensembles of single neurons

Main advantage of BCIs based on EEG recordings: noninvasive system.
Main disadvantages: slow and error prone.
Investigators interested in the “neural code” or in high yield prosthesis opt for invasive systems.

Decoding the neural signal:

Ultimate goal: view multiple “functional states” of neurons through the recording of enough of them.



First individually adjustable micro-electrode array implanted and recorded from: Humphrey, 1970.

Since that time: both temporal AND rate coding matter.

Experiment:
5min of data acq
Switch over to arm control
Rats realize and stop mvmt

Real-time control of a robot arm using simultaneously recorded neurons in the motor cortex

John K. Chapin[1], Karen A. Moxon[1], Ronald S. Markowitz[1] and Miguel A. L. Nicolelis[2]

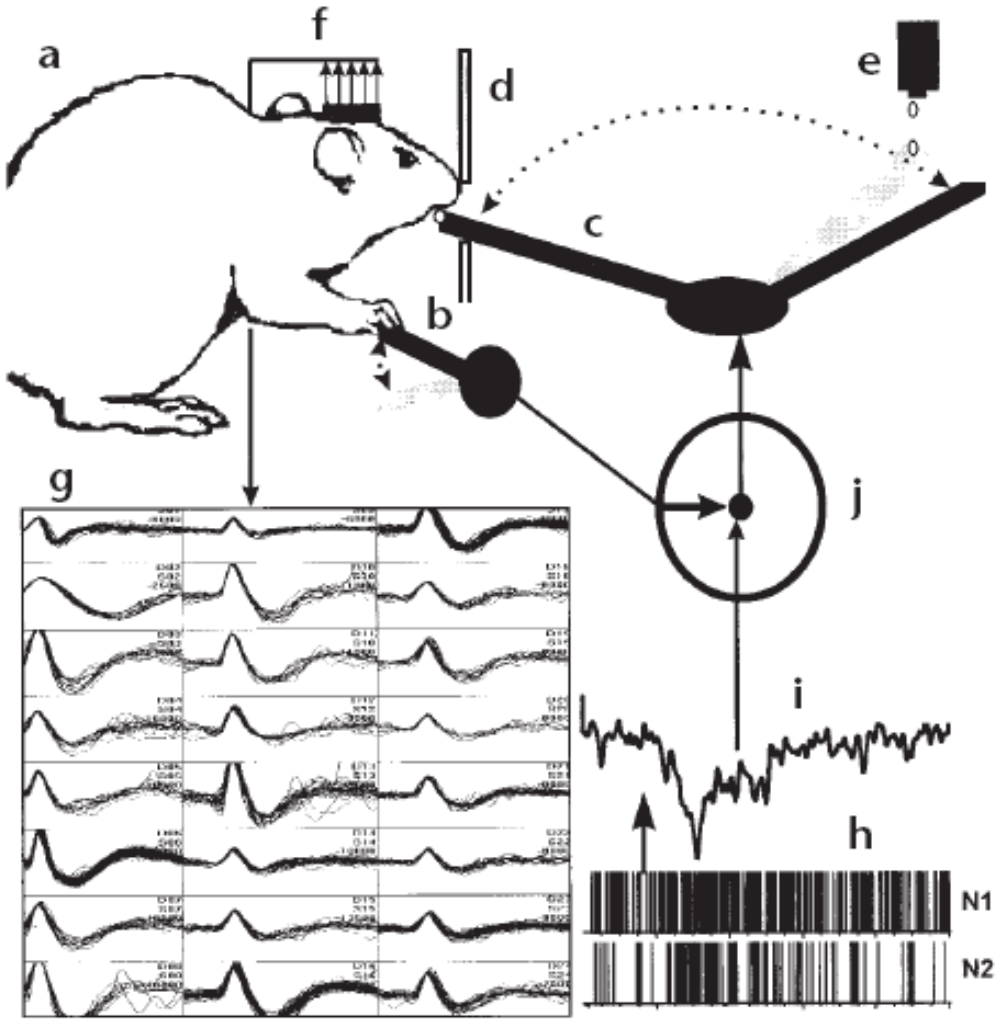


Fig. 1. Experimental protocol. **(a)** 'Lever-movement/robot-arm' mode: rats were trained to press a lever **(b)** for a water reward; displacement was electronically translated to proportionally move a robot arm **(c)** from rest position through a slot in barrier **(d)** to a water dropper **(e)**. The robot arm/water drop moved passively to the rest position (to the rat). **(f)** 'Neuronal-population-function/robot-arm' mode: Rats were chronically implanted with multi-electrode recording arrays in the MI cortex and VL thalamus, yielding simultaneous recordings of up to 46 discriminated single neurons. **(g)** Superimposed waveforms of 24 such neurons. **(h)** Sample spike trains of two neurons (N1, N2) over 2.0 s. **(i)** Neuronal-population (NP) function extracting the first principal component of a 32-neuron population. **(j)** Switch to determine input source (lever movement or NP function) for controlling robot-arm position. In experiments, rats typically began moving the lever. The input was then switched to the NP function, allowing the animal to obtain water through direct neural control of the robot arm.

'Pre-flexion' neurons (13% of task related in MI; 43% in VL) discharged before brachial flexion to initiate lever reach; 'flexion' neurons (16% in MI; 21% in VL) discharged mainly after the onset of antebrachial flexion; 'pre-extension' neurons (28% in MI; 15% in VL) were best correlated with the pre-onset and onset of carpal

What do we know about connecting electrodes to the brain?

We learned from early neurorobotics experiments in animals:

- A single neuron by itself does not predict or correlate well with movement on single trials;

- Neural activity from tens of neurons can reliable code for limb movement, even in individual trials;

- Best correlations between neural population activity and limb movement happen during short interval immediately preceding the limb movement;

- Brain activity is independent of actual movement.

Neurorobotic control after injury

1989, Kennedy: cone electrode.

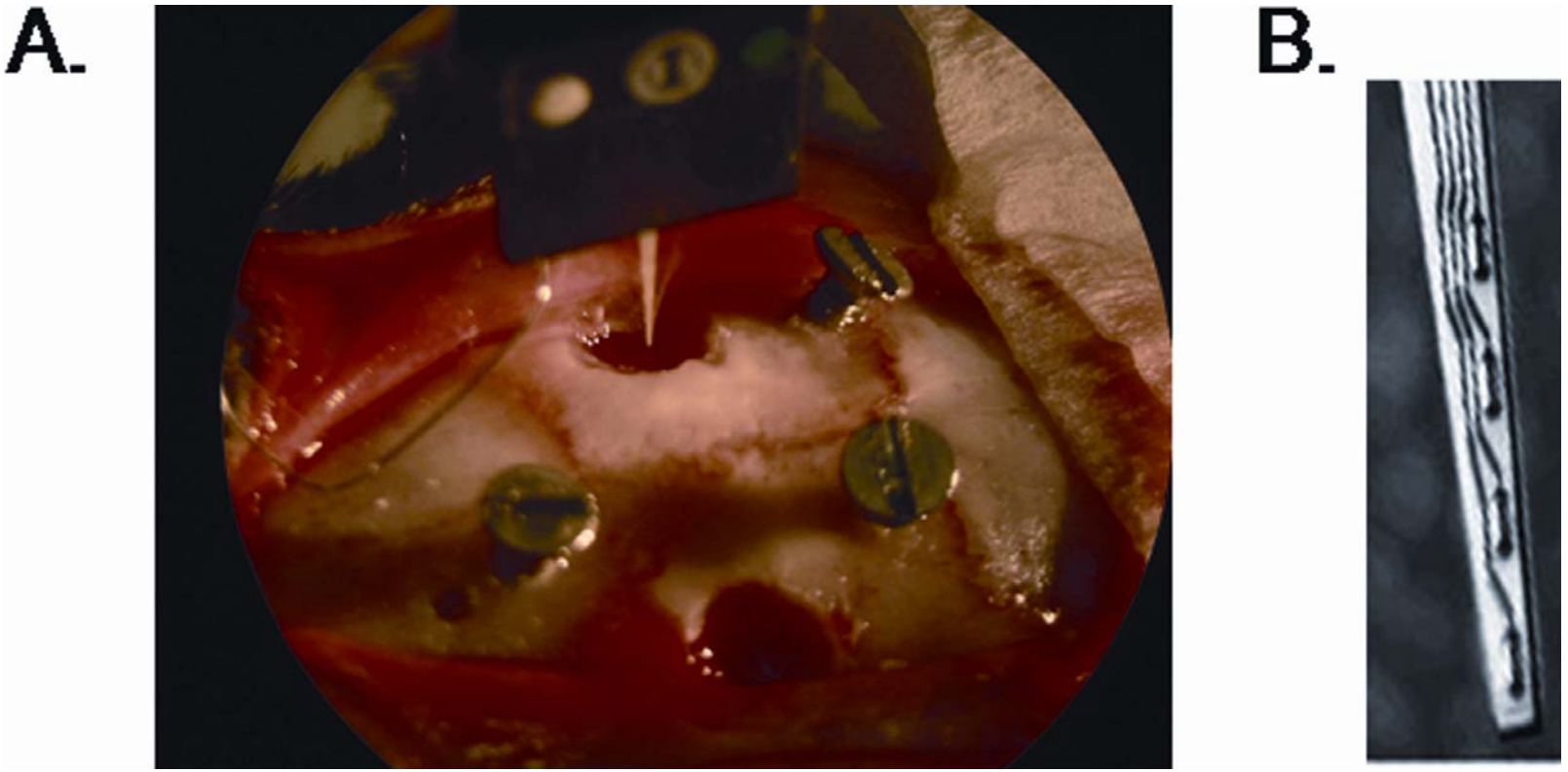
Microwire electrode inside a glass cone, with neurotrophic factors.

Patient: no part of the body could be moved except for small face movements (eyelids, eyebrows).

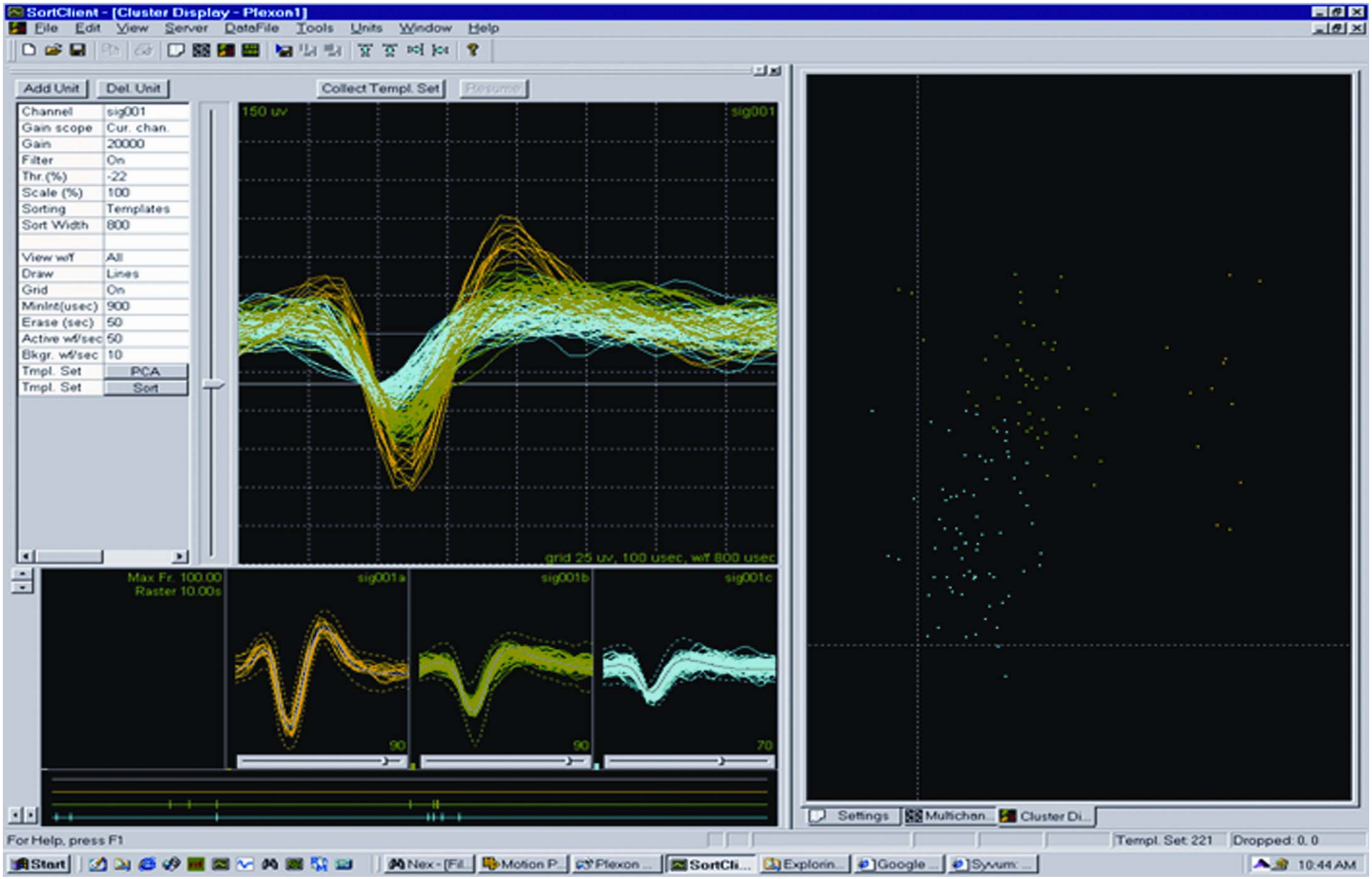
- **3wks** after implant: neural activity appeared
- **3 months**: robust neural activity recorded successfully
- But: somatotopic area for hand had been taken up by eyebrow (*plasticity*!)
- Neural activity could not be correlated to any sensorial input from hand
- **6 months**: patient is able to move cursor to a target.

- **Unexpected** result: patient “says” that he is actually thinking about moving the cursor when he moves it (he’s not thinking about his hand, for example)

Implant details: screws (080) and needle array through hole in the skull



Unit identification through spike matching algorithms



What is Principal Components Analysis (PCA)?

It is a way of identifying patterns in data, and expressing the data in such a way as to highlight their similarities and differences. Since patterns in data can be hard to find in data of high dimension, where the luxury of graphical representation is not available, PCA is a powerful tool for analyzing data.

If you want to learn it through a couple of easy steps:
http://csnet.otago.ac.nz/cosc453/student_tutorials/principal_components.pdf