DSP for Bioelectrical Signals

Some examples of signals and methods

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Objectives

- Reduce the subjectivity of the analysis *(diagnosis more robust)*
- Cross the visual frontier *(hidden information)*
- Cancel the noise and artifacts *(muscular, powerline, thermal)*
- Enhance signals and separate sources *(sources are observed simultaneously)*
- Compress information and extract parameters *(Database, datamining, pathologies correlation)*
- Model and simulate *(ethical issues, artificial organs and devices) accounting for physiological knowledge (not black box)*

Clinical context

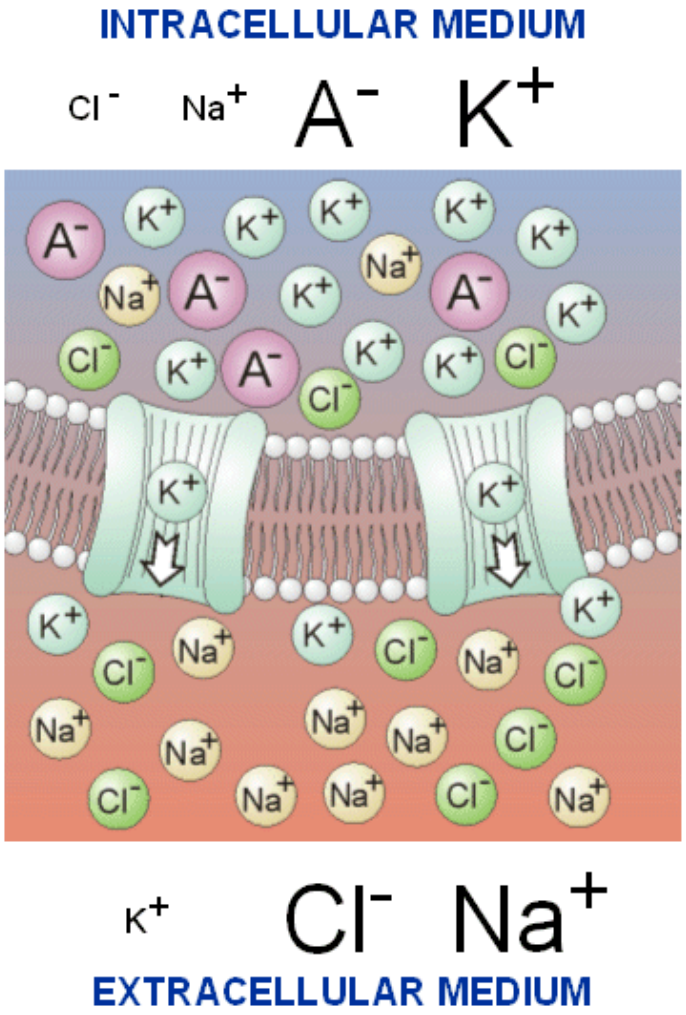
- Diagnosis *(decision tool, data fusion, subjectivity robustness)*
- Therapy *(smart prosthesis-BCI, implantable device, CRT)*
- Monitoring *(e-health, telemedicine, personal health)*

Outline

- The excitable cell
- The Action Potential
- Signal acquisition
- ECG, EEG, EMG
- Signal preprocessing
- Some particular DSP techniques

Books: Bioelectromagnetism (Malmivuo & Plonsey), Bioelectrical signal processing in cardiac and neurological applications (L. Sörnmo & P. Laguna)

The excitable cell

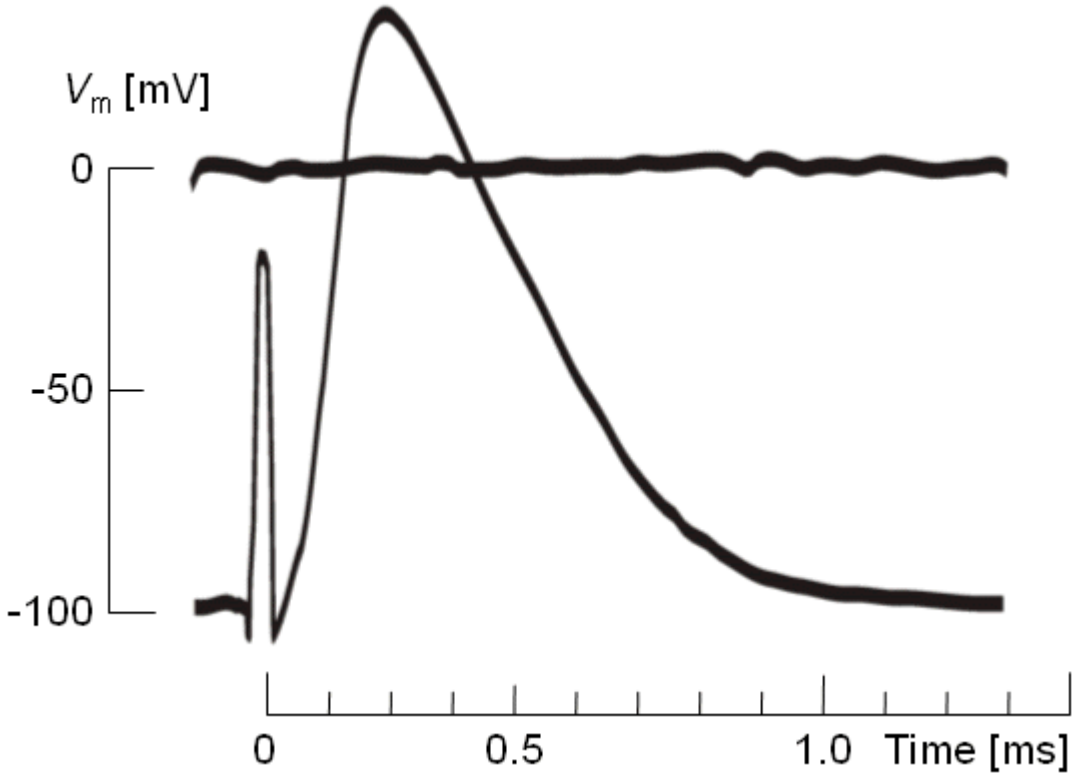


- Nerve cells (neurons)
- Muscle cells (cardiac, squeletal)
- First, cells are interconnected by low-resistance pathways (gap junctions), as a result of which currents flowing in the intracellular space of one cell pass freely into the following cell
- Hodgkin-Huxley model

- (K) Potassium
- (Na) Sodium
- (Cl) Chloride

Depolarization/Repolarization The Action Potential (AP)

Motoneuron: note the stimulus at t=0



Different APs

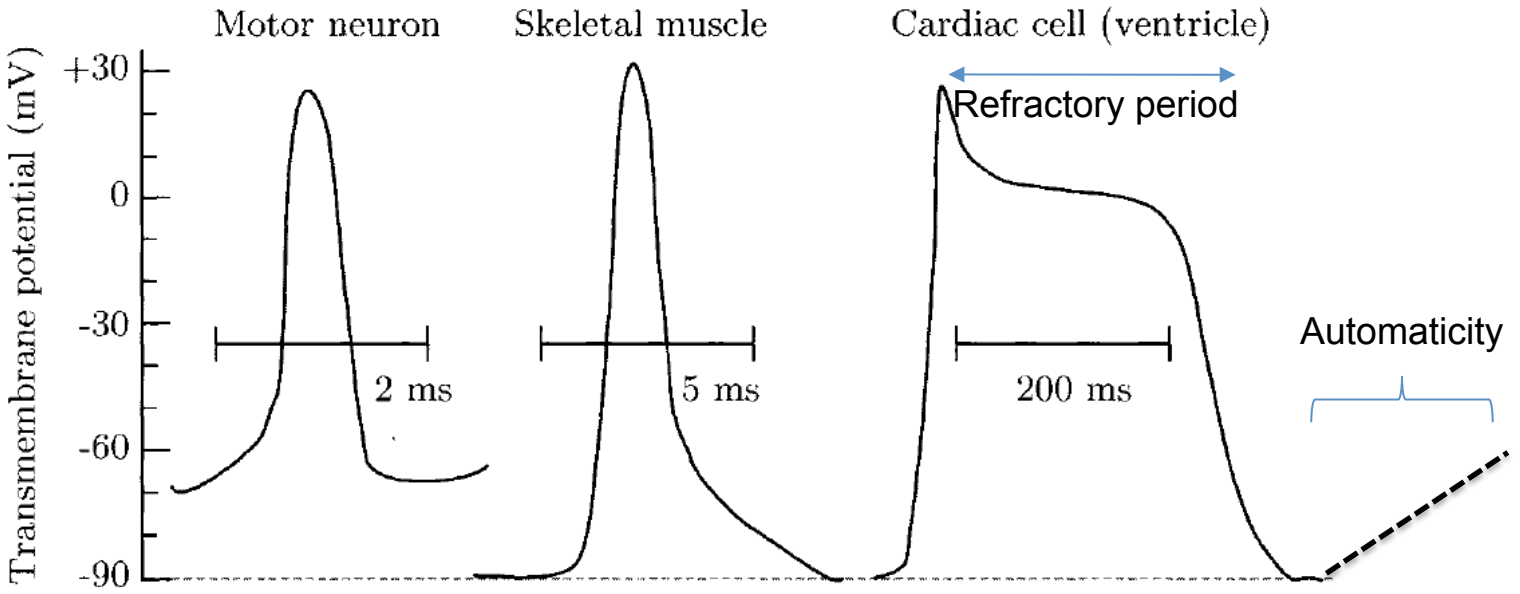
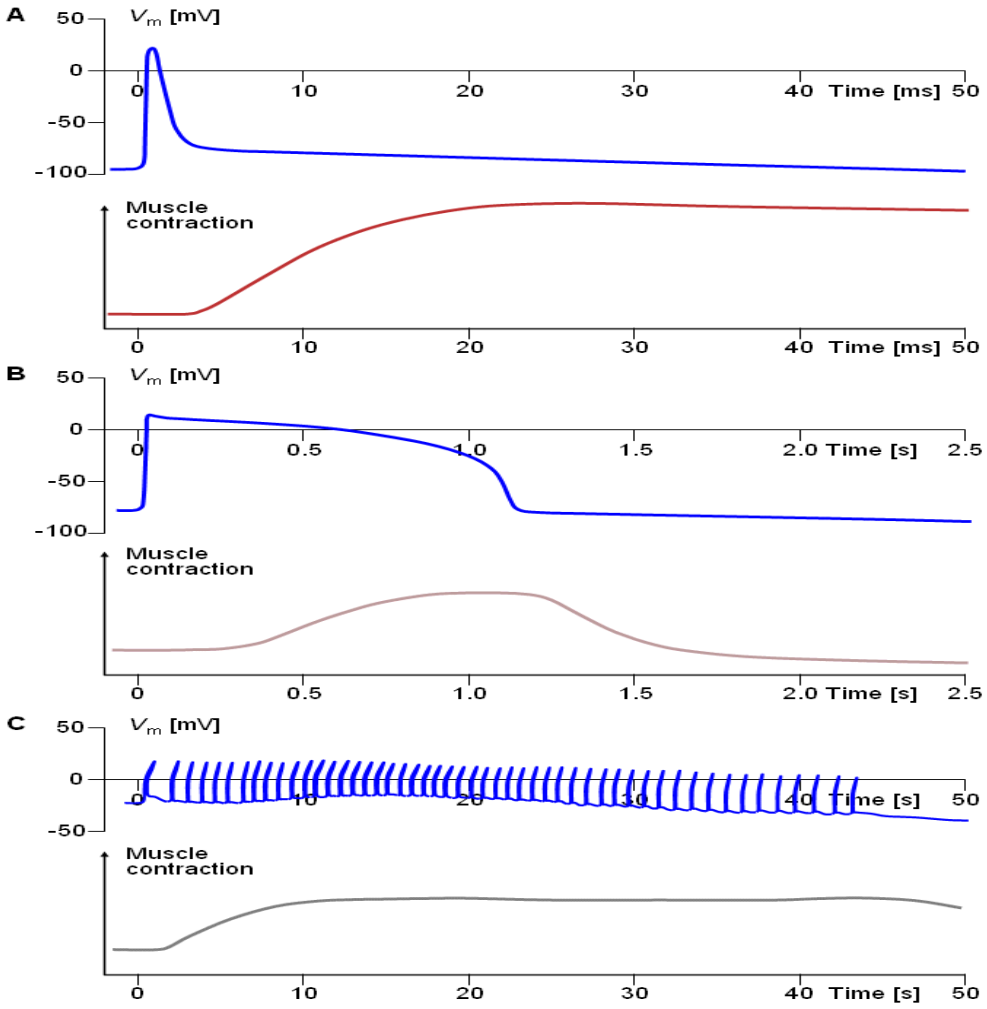


Figure 1.2: Examples of action potentials with shapes that range from the spike-like waveform of a nerve cell (left) to the much more extended waveform of a cardiac cell (right). The transmembrane potential difference was measured by placing one microelectrode inside the cell and another outside. It should be noted that the timescale differs from waveform to waveform.

Different effects of the APs

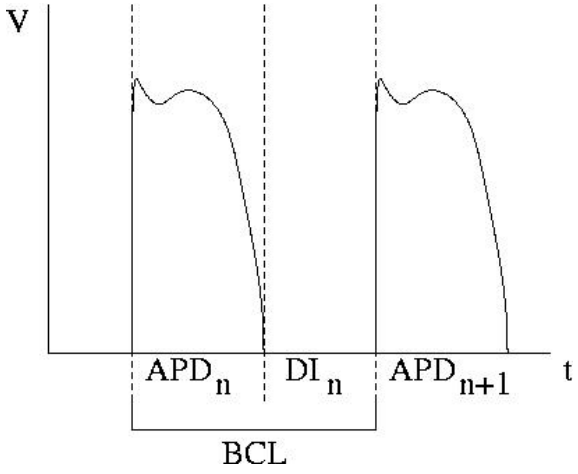


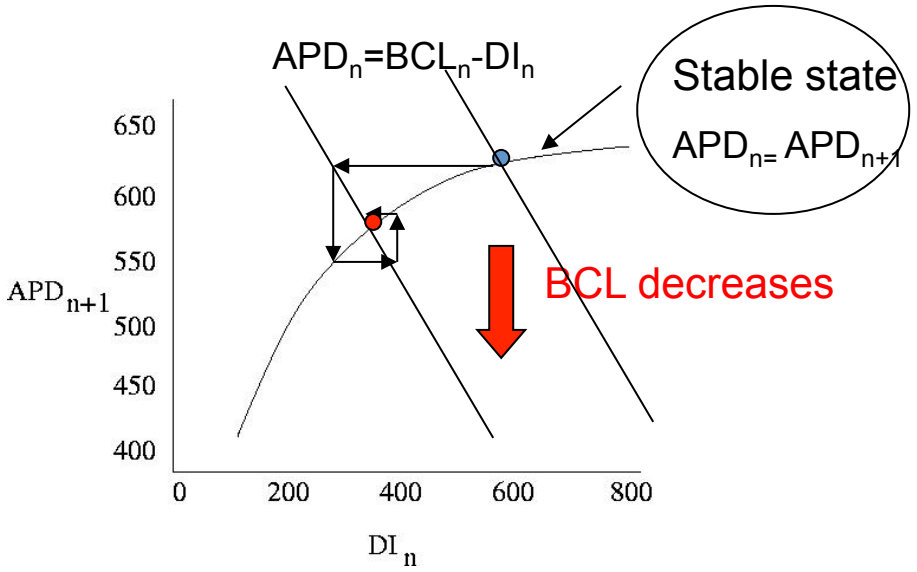
Electric and mechanical activity in:
(A) frog sartorius muscle cell,
(B) frog cardiac muscle cell, and
(C) rat uterus wall smooth muscle cell.

An interesting property of AP

The restitution curve:

- Action Potential Duration (APD)
- Diastolic Interval (DI)
- Basic cycle lentgth (BCL)

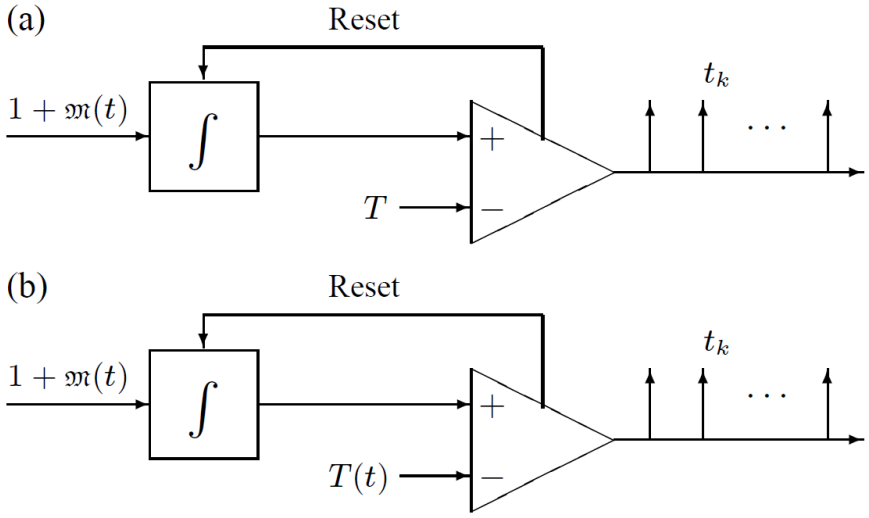




Modelling the autodepolarizing cell

The integral Pulse Frequency Model (IPFM): integrate and reset

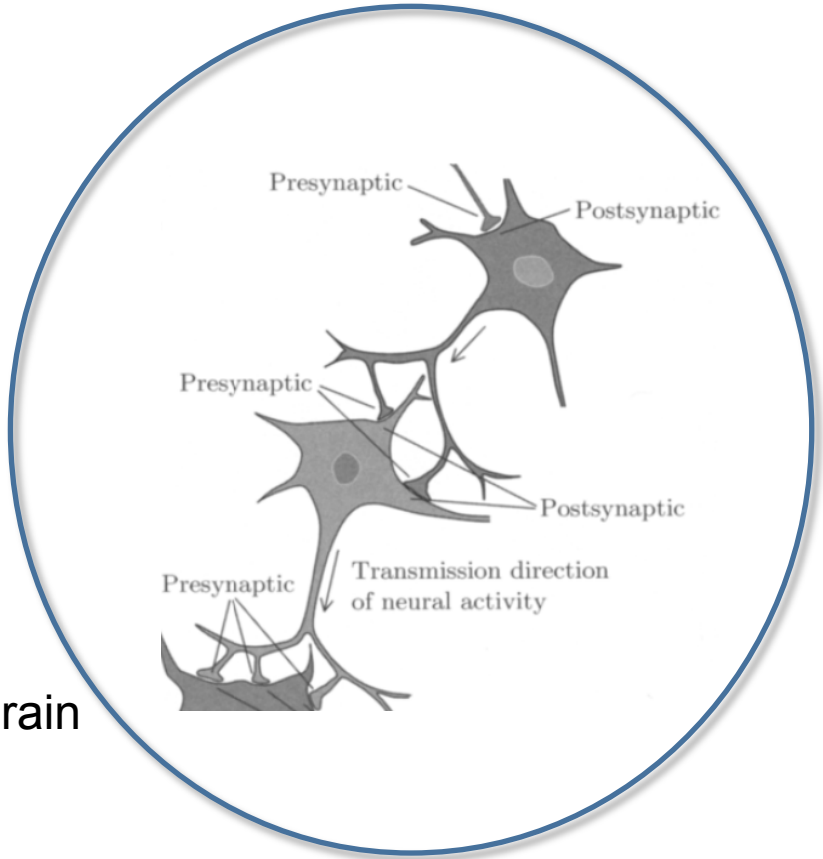
When m(t) is null (m(t) <1) , the rate is constant otherwise the rate is modulated (ANS)
The model can be extended to T(t)



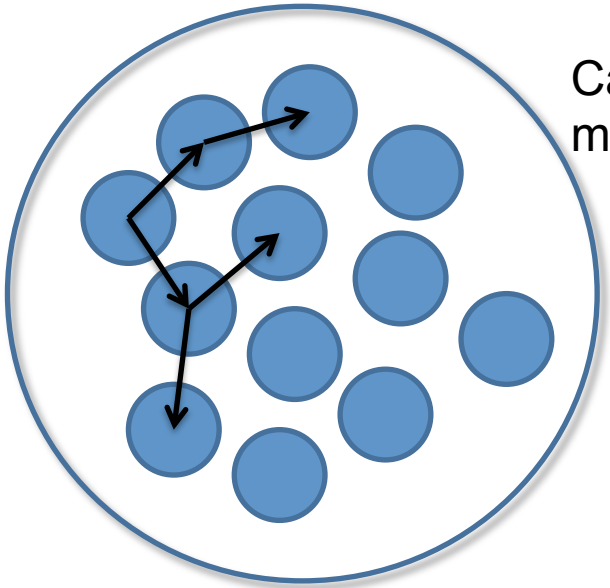
$$k = \int_0^{t_k} \frac{1 + \mathfrak{m}(t)}{T} dt,$$

A colony of cells

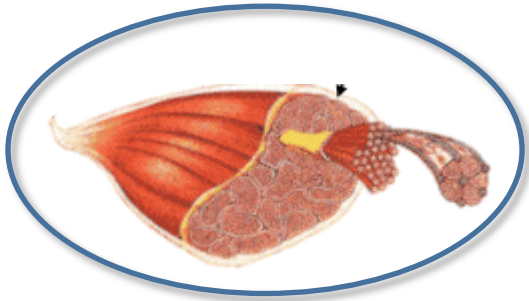
The current created by the initial membrane depolarization triggers an adjacent membrane so that a new action potential results, and so on …



Brain



Cardiac muscle



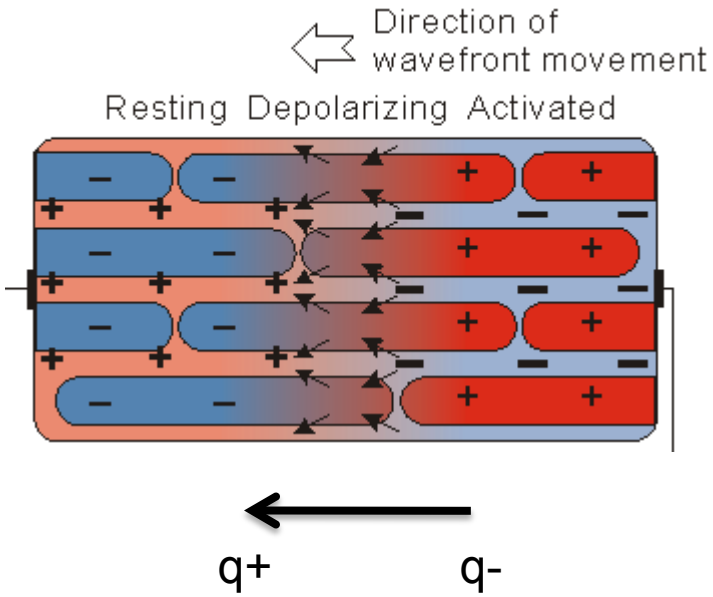
Squeletal muscle

Signal Acquisition

Signal may be acquired :

- In the vincinity of the cell (needle)(high spatial resolution)
- On the body surface (less invasive) -> a volume conductor

During the information propagation (depolarization), potential nearby the wavefront (outside the cells) is equivalent to a dipole



Signal Acquisition

Assume a volume source in a homogeneous medium.

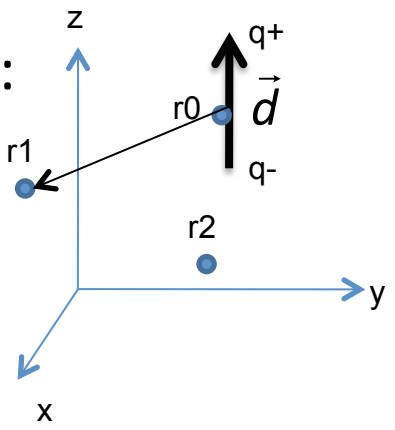
$\vec{p} = q\vec{d}$ is the dipole momentum.

The electrical potential at r1 (far field) is : $\Phi(r1) = \frac{(4\pi\varepsilon_0)^{-1}}{\left\|\overrightarrow{r1-r0}\right\|^3}(\overrightarrow{r1-r0})^T\vec{p}$

If $\overrightarrow{r1-r0}$ is orth. to $\vec{d}$ then potential=0

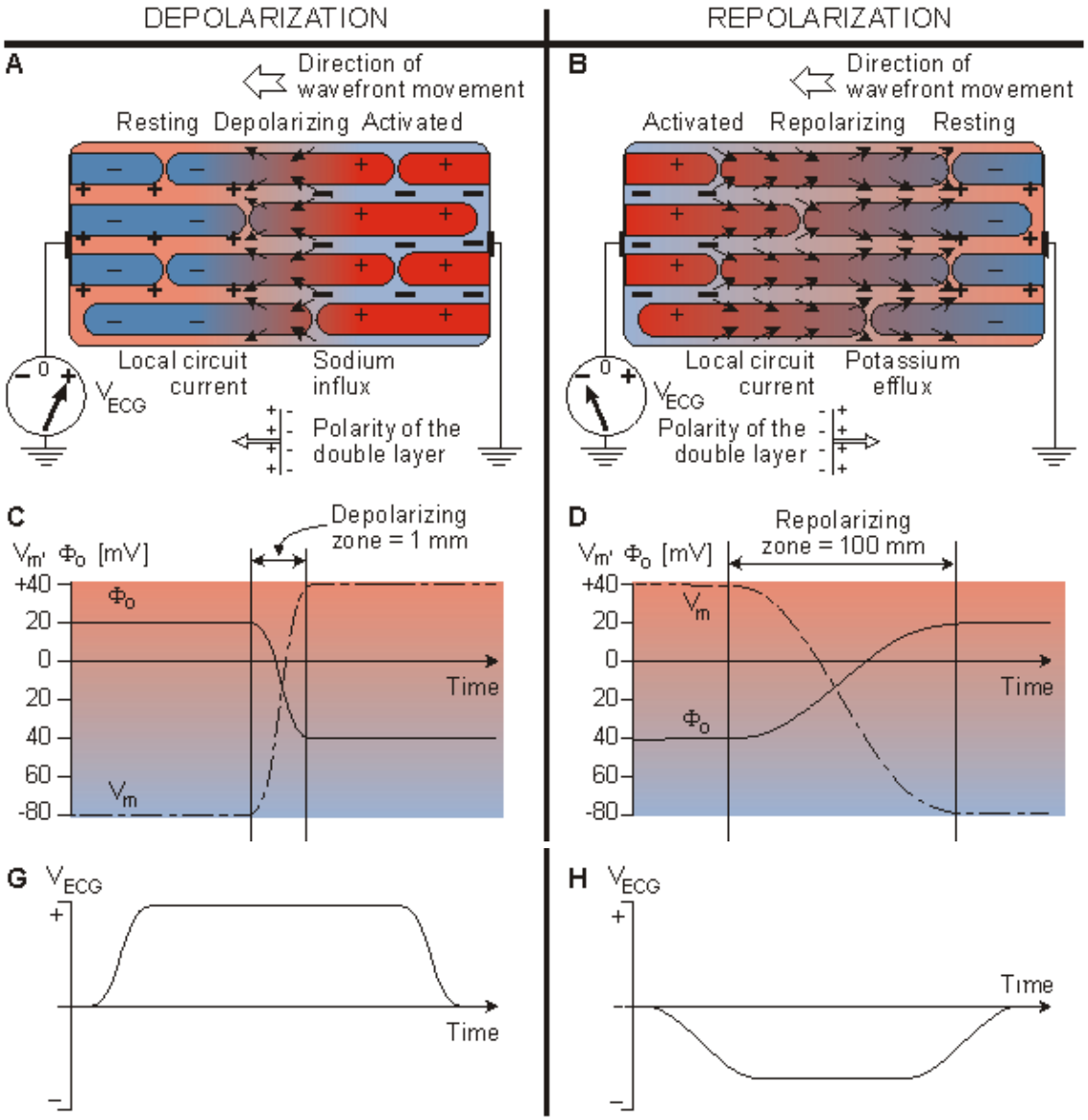
- The potential difference PD between r1 and r2:

$\propto$ Projection of $\vec{d}$ over $\overrightarrow{r1-r2}$



- In practice, one sensor for the reference and one for exploration.

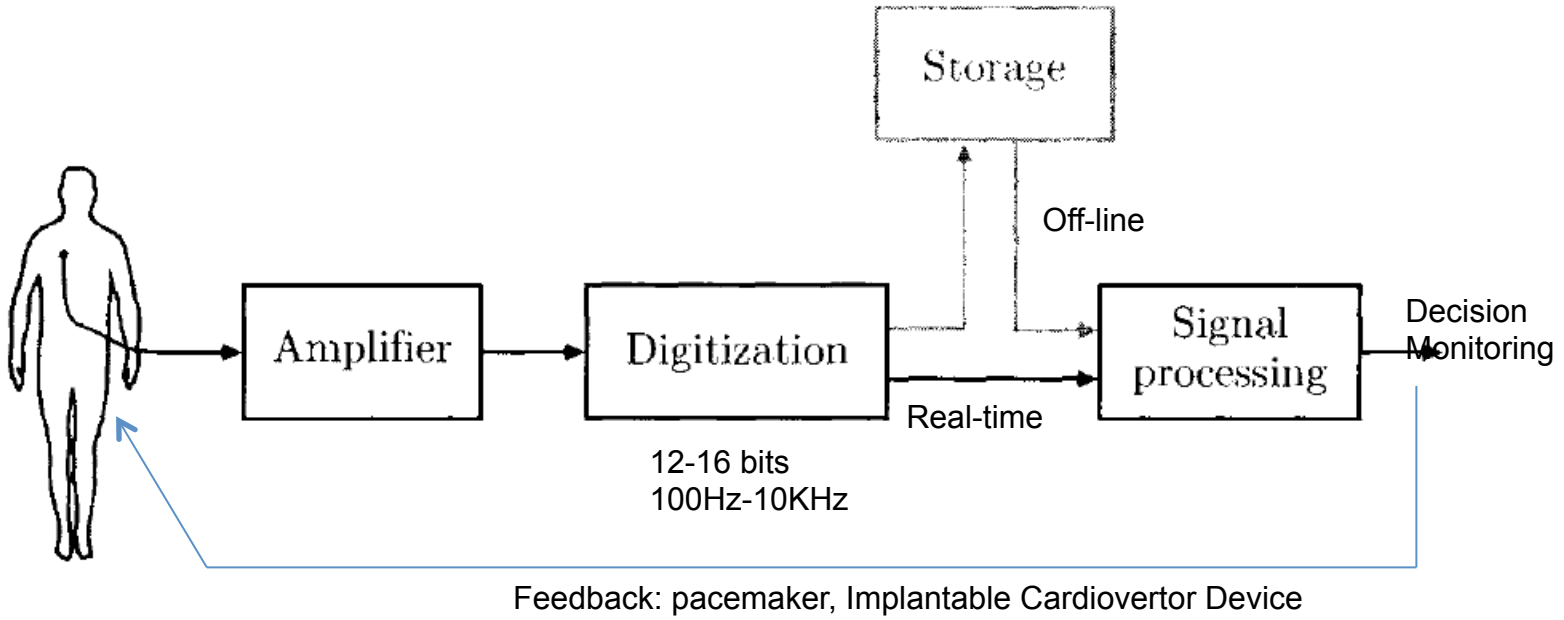
Signal Acquisition



- The medium is a volume conductor
- A voltage potential can be measured within the medium
- Dipoles generated by each cell (Vi-Vo≠0) are null (closed surface)
- The voltage potential characterizes the wavefront propagation

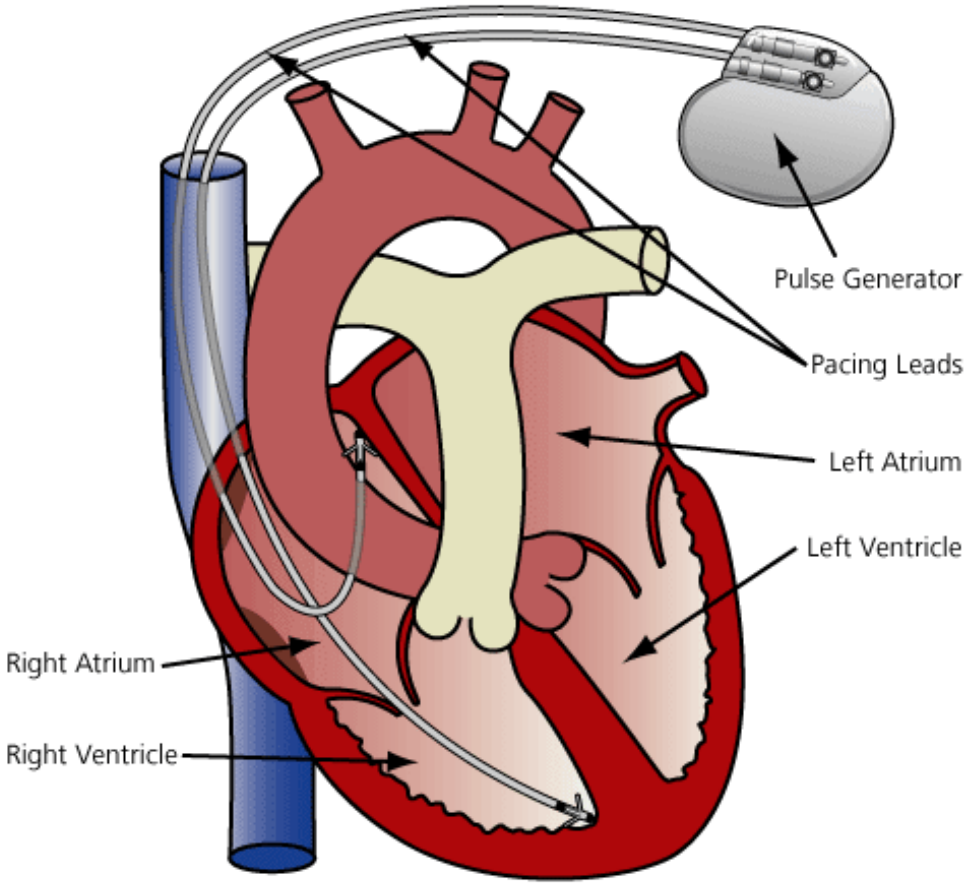
Signal Acquisition

- From the Brain (scalp): Electroencéphalogram EEG or ElectrocorticogramECoG
- From the heart (surface): Electrocardiogram ECG or endocardiogram (EMG)
- Form muscles (surface): Electromyogram sEMG



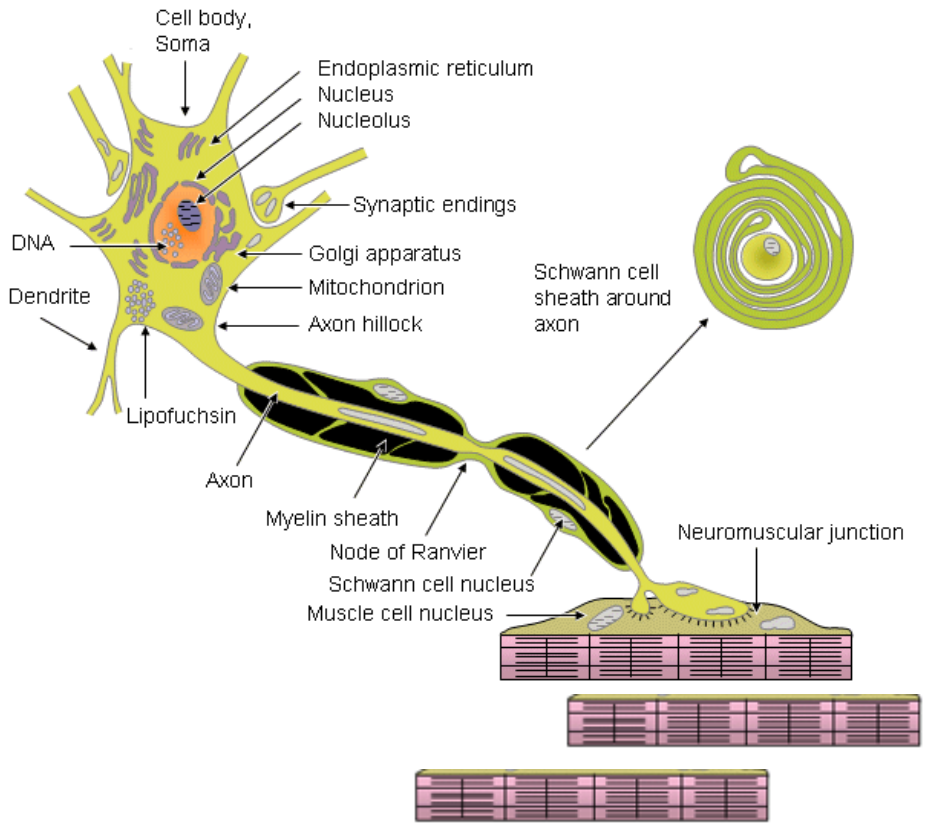
Counterexample: cochlear implant (no biosignal acquisition)

ECG-Pacemaker



See doc The cardiac electrical activity

EMG



Several types of muscles
- squeletal (volontary)
- smooth (inv.) (intestin, body hairs)
- cardiac (inv.)

- An impulse initiated in a motoneuron propagating through the axon reaches a number of muscle fibers (**efferent nerves**). This ensemble is the motor unit (MU)

- Cells are depolarized (AP) and contract, passing from cell to cell along the fiber

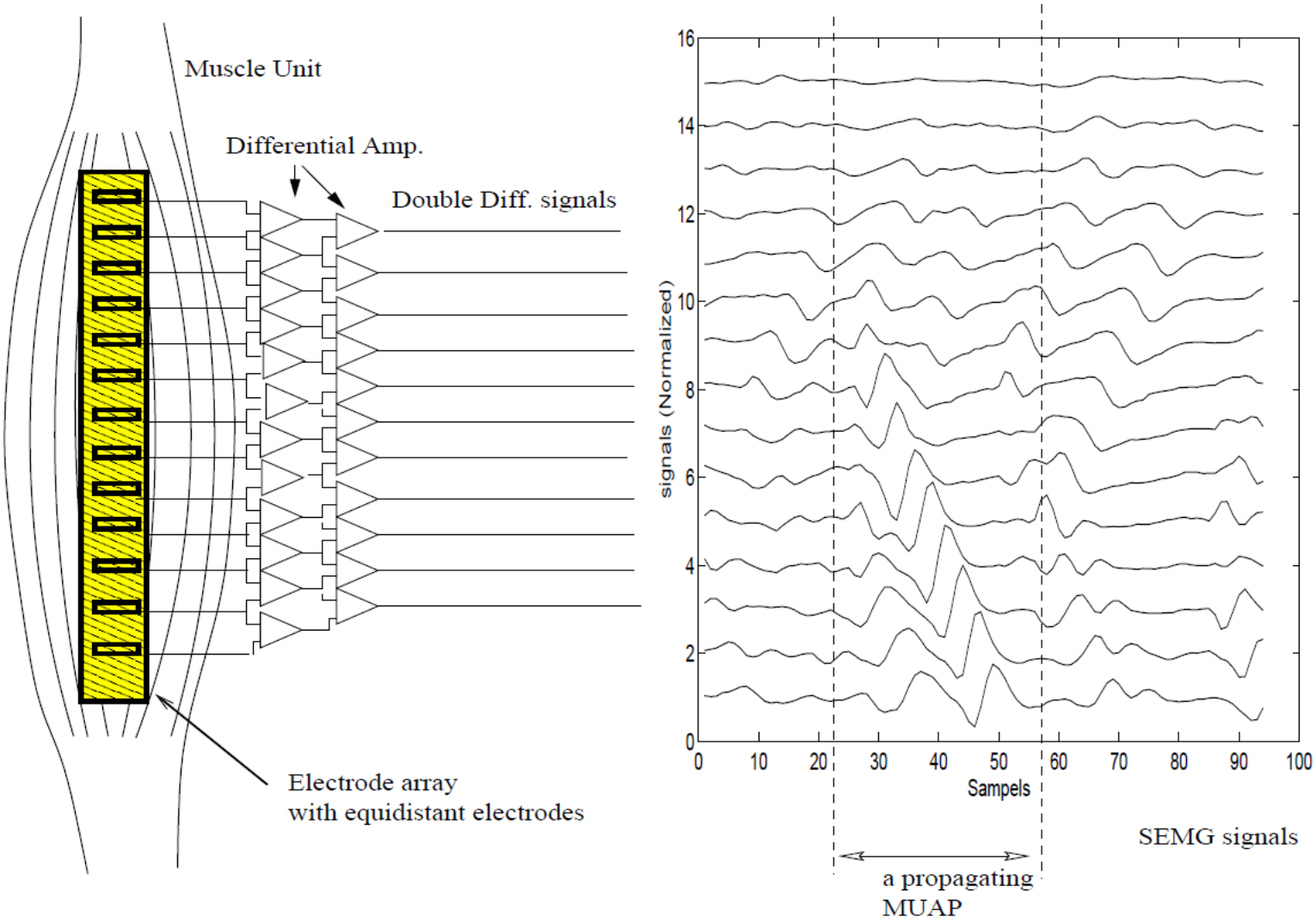
- The spatial sum of each AP is names Motor Unit Action Potential (MUAP)

Rem: a surface electrode records en ensemble of MUAP

To increase the strengh of the contraction, central nervous system recruit more motoneurons (more MU) and increases the firing rate (7Hz to 50 Hz)

- Local (taping-strech receptors) and global (metabolites sensing) feedback (**afferent nerves**): closed loop

EMG-MUAP

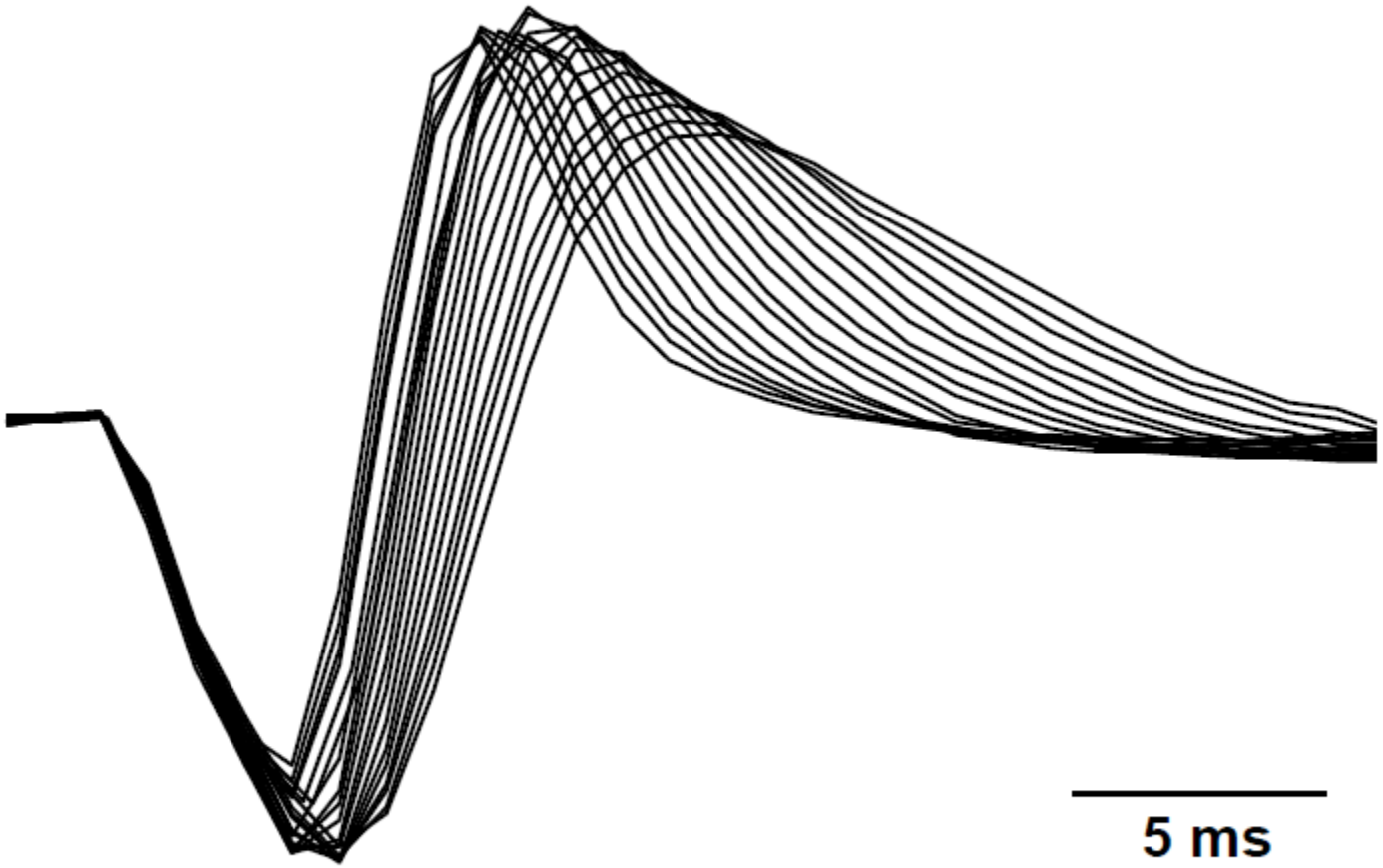

Muscle Unit
Differential Amp.
Double Diff. signals
Electrode array
with equidistant electrodes
signals (Normalized)
Sampels
SEMG signals
a propagating
MUAP

EMG-MUAP

- When a fiber depolarizes : genesis of one particular MUAP (shape) travelling along the fiber
- When it is periodical : series of MUAP at fixed period
- Equivalent to Dirac train convoluted with a single MUAP
- The Spectrum is the multiplication of the Dirac train by the spectrum of the MUAP
- It explains the shape of the EMG Spectrum
- If the MUAP changes (the fiber type) -> the EMG Spectrum changes
- In real life: not periodical at all (with randomness) and many fibers

EMG-M waves

The muscle is electrically stimulated (large number of synchronous AP)



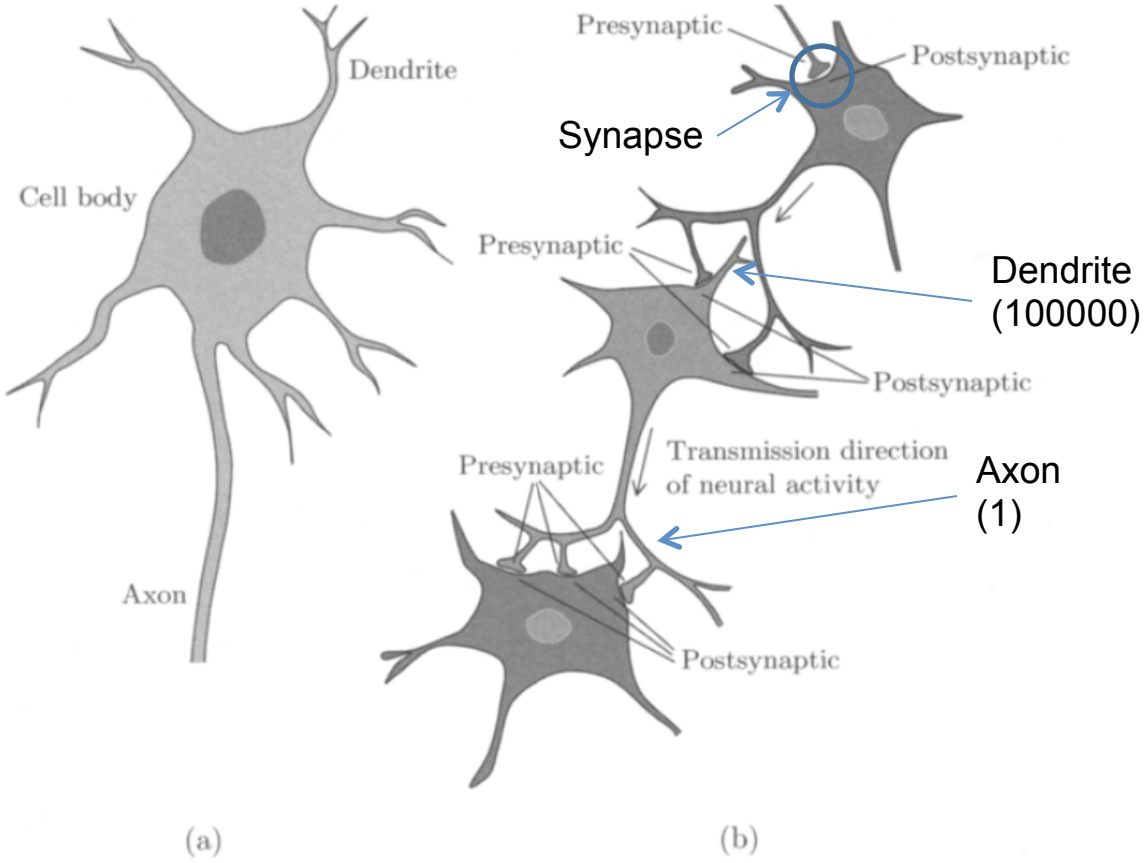
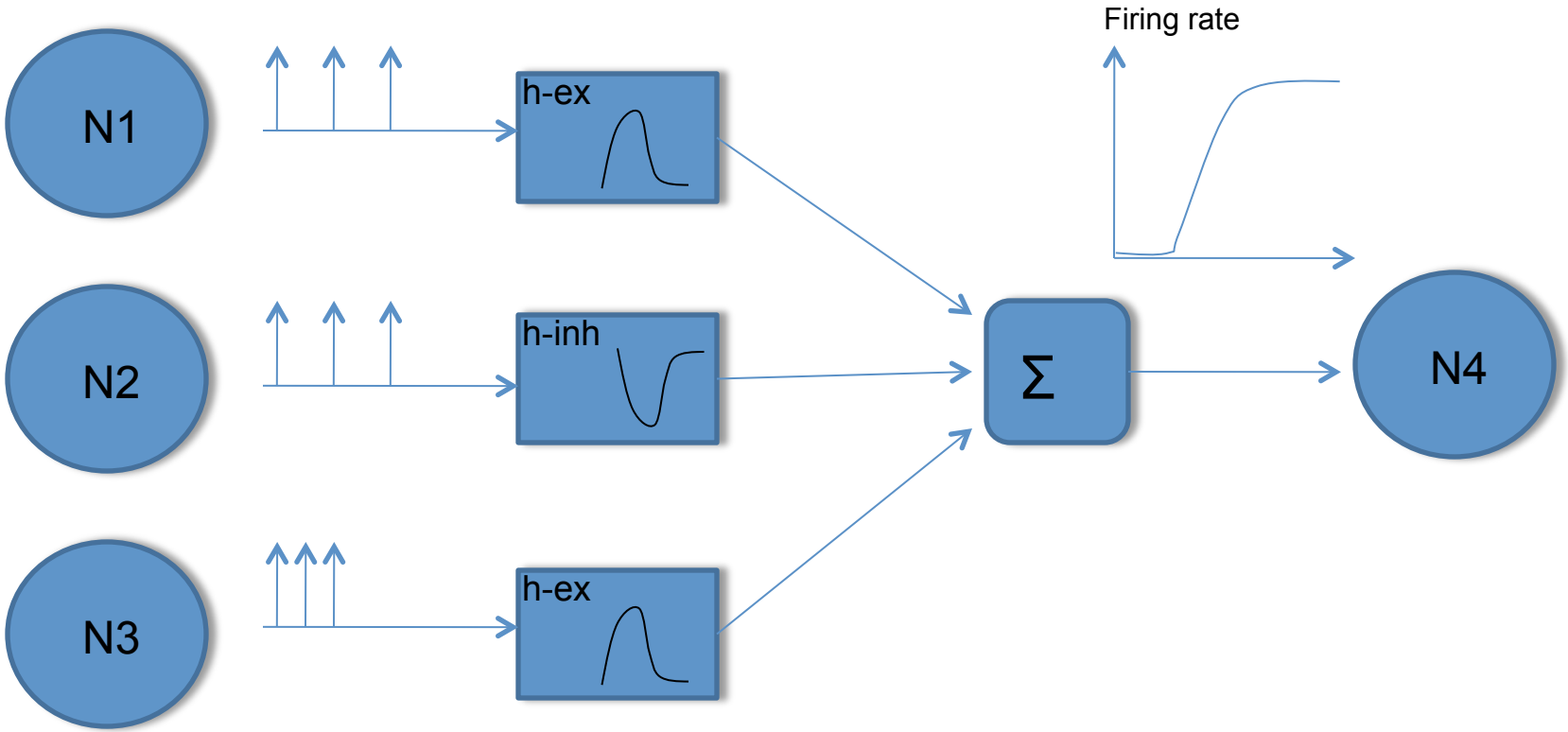


Figure 2.1: (a) An archetypal neuron and (b) three interconnected neurons. A presynaptic neuron transmits the signal toward a synapse, whereas a postsynaptic neuron transmits the signal away from the synapse.

Action on other neurons

A neuron affects other neurons by releasing a neurotransmitter that

- Inhibite (inhibitory state)
- Excitate (excitatory state)
- Modulate (modulatory state)



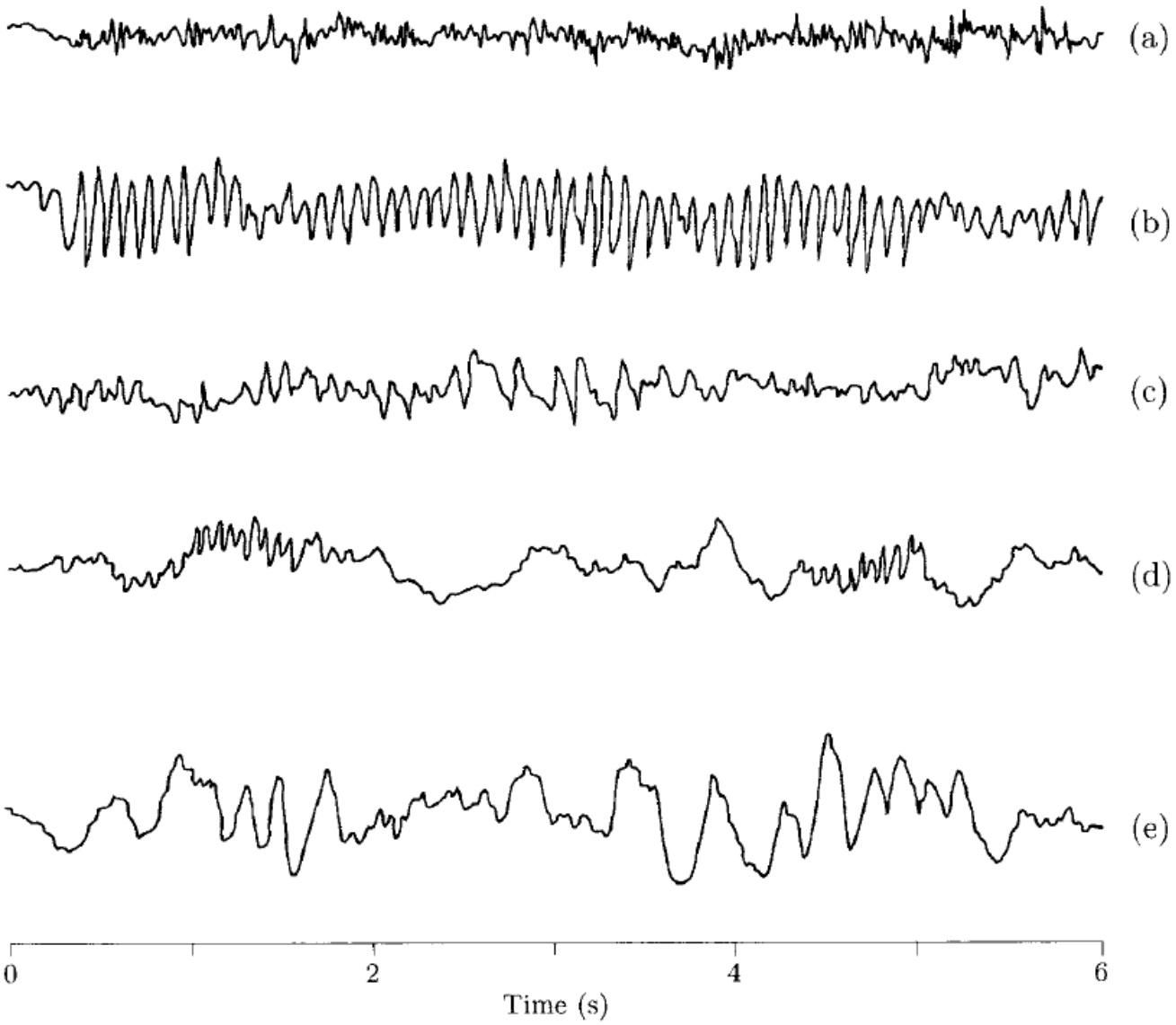


Figure 2.3: Electroencephalographic rhythms observed during various states from wakefulness to sleep: (a) excited, (b) relaxed, (c) drowsy, (d) asleep, and (e) deeply asleep. This example is classical and was originally presented by the famous EEG pioneer H.H. Jasper [12].

Table 2.1: Essential characteristics of the four non-REM sleep stages and REM sleep [17].

Sleep stage	Sleep depth	Waveforms
1	Drowsiness	From alpha dropouts to vertex waves
2	Light sleep	Vertex waves, spindles, K complexes
3	Deep sleep	Much slowing, K complexes, some spindles
4	Very deep sleep	Much slowing, some K complexes
REM	REM sleep	Desynchronization with faster frequencies

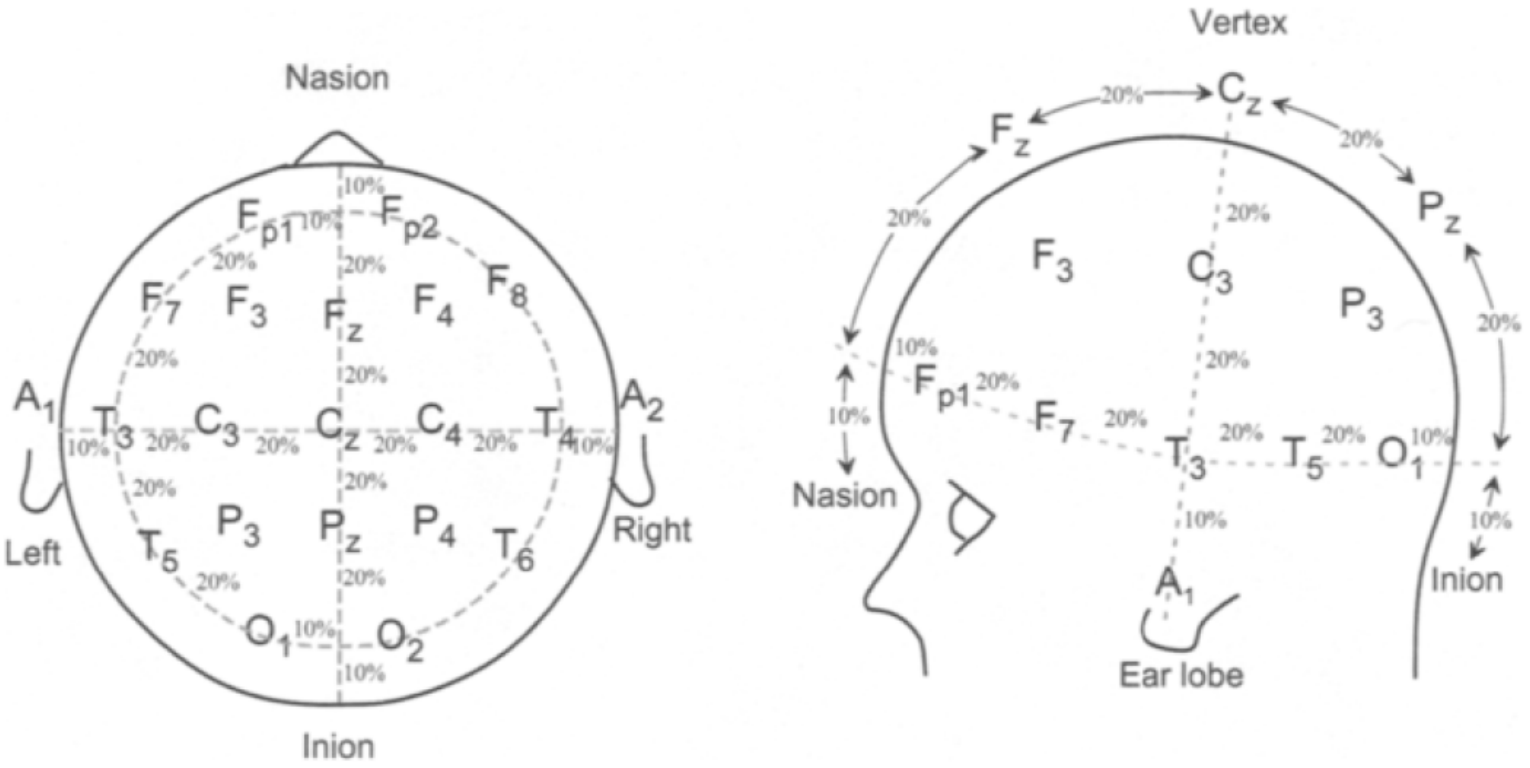


Figure 2.7: The International 10/20 system for recording of clinical EEGs. The anatomical reference points are defined as the top of the nose (nasion) and the back of the skull (inion). The letters F, P, C, T, O, and A denote frontal, parietal, central, temporal, occipital, and auricle, respectively. Note that odd-numbered electrodes are on the left side, even-numbered electrodes are on the right side, and z (zero) is along the midline.

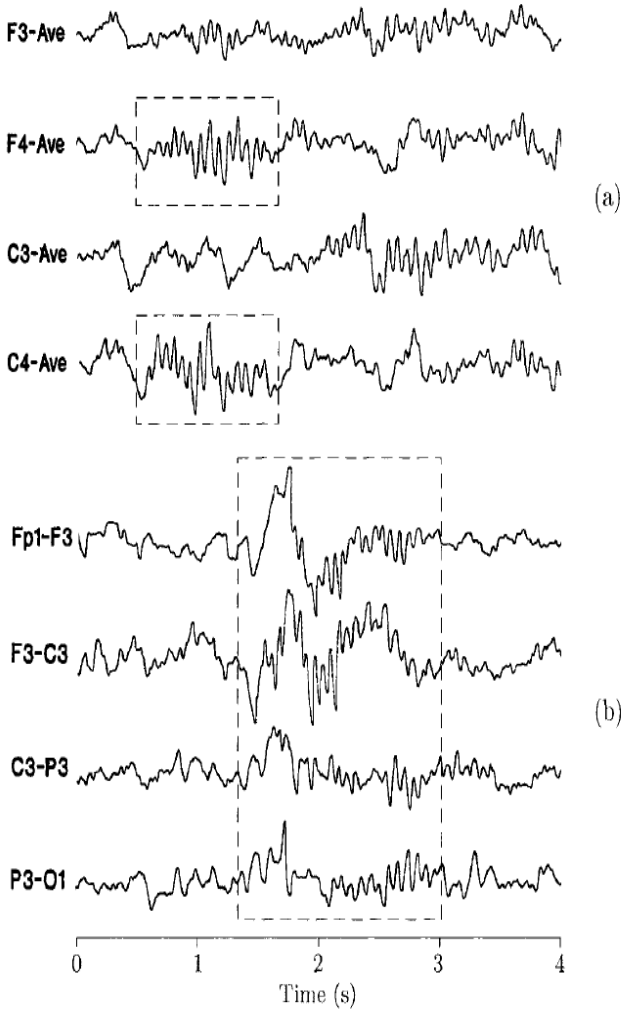


Figure 2.5: Electroencephalographic signals recorded during sleep with (a) sleep spindles and (b) K complexes; note that each K complex is the fusion of a vertex wave and a sleep spindle. (Reprinted from Wong [16] with permission.)

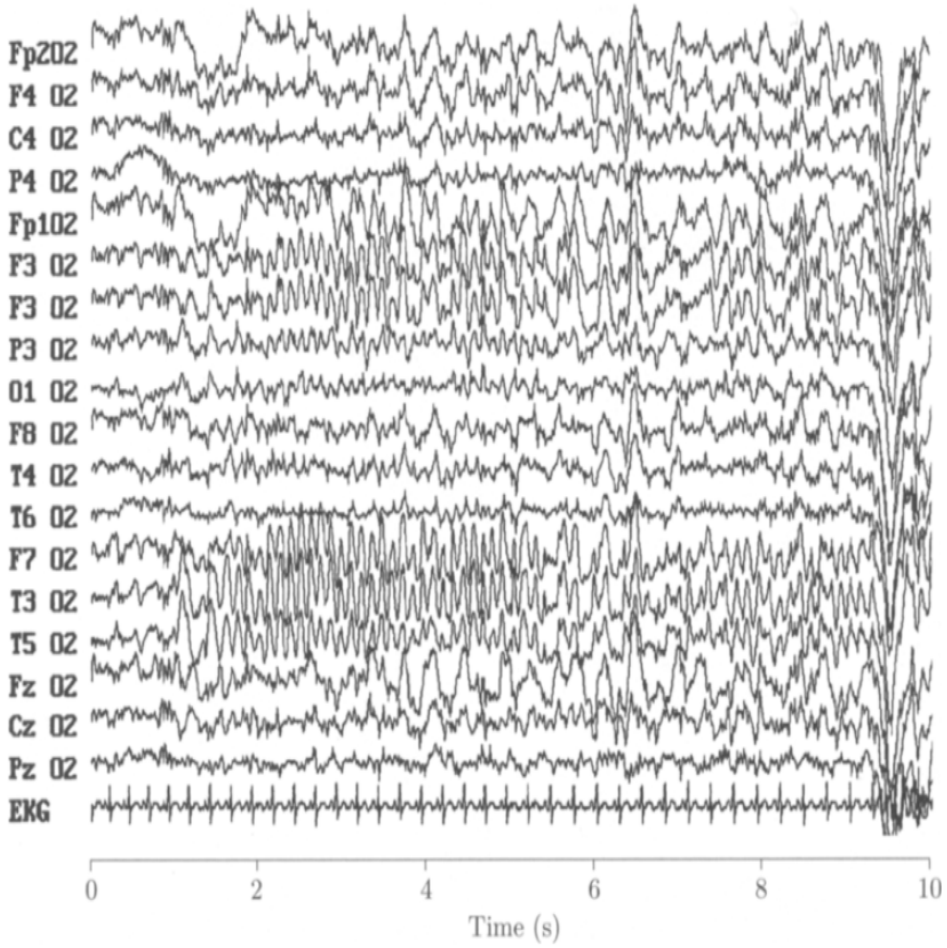
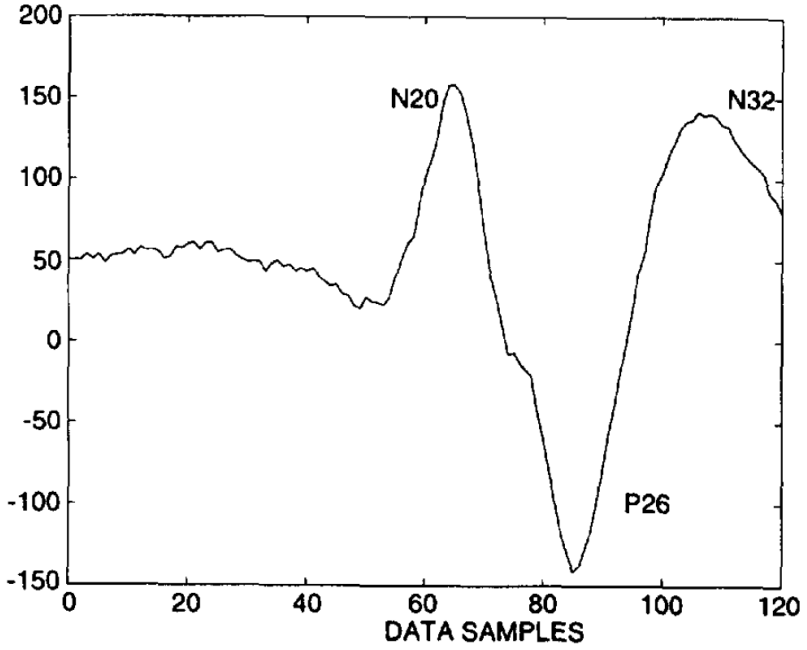
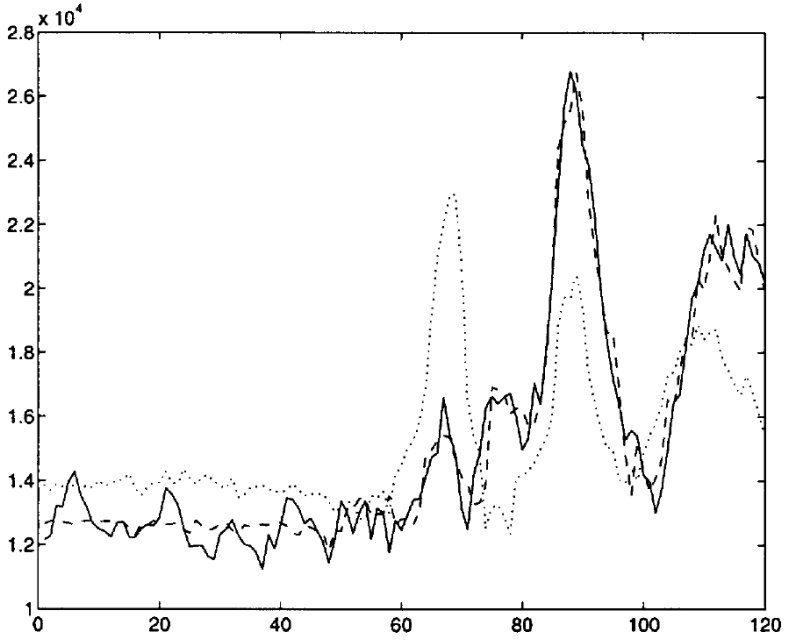


Figure 2.6: A multichannel EEG showing the onset of an epileptic seizure, occurring after the first second. The onset is characterized by an increase in amplitude and a change in spectral content. The seizure is particularly pronounced in certain channels. Note that the ECG is displayed at the bottom (the abbreviations EKG and ECG are synonymous). (Reprinted from Wong [16] with permission.)





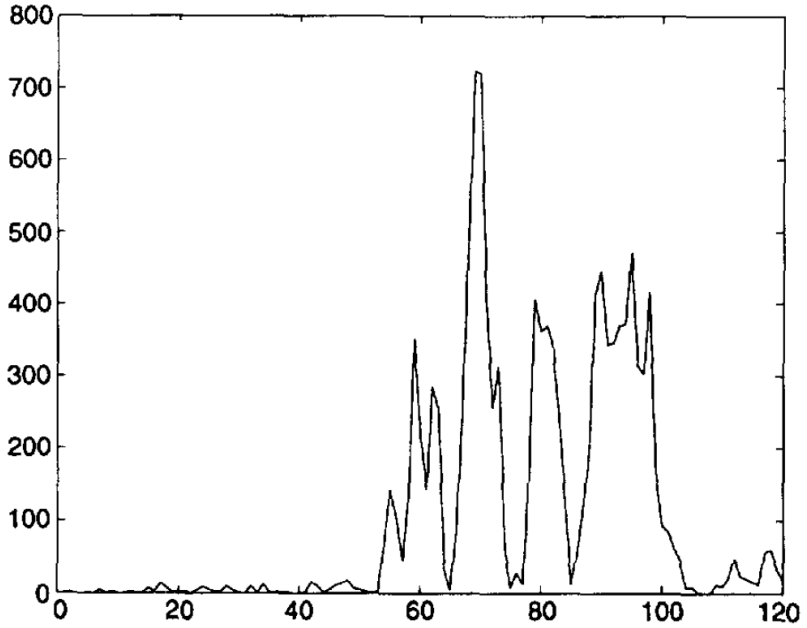


Table 1
Characteristics of the three waves

Wave	N20	P26	N32
$\hat{\sigma}_d$ (ms)	0.17	2.06	2.16
$\hat{\sigma}_p$	0.17	0.49	0.00