Lecture Slides for 22AIE438

Biomedical Signal Processing

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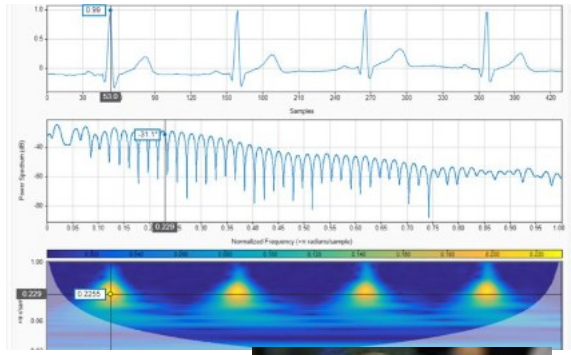
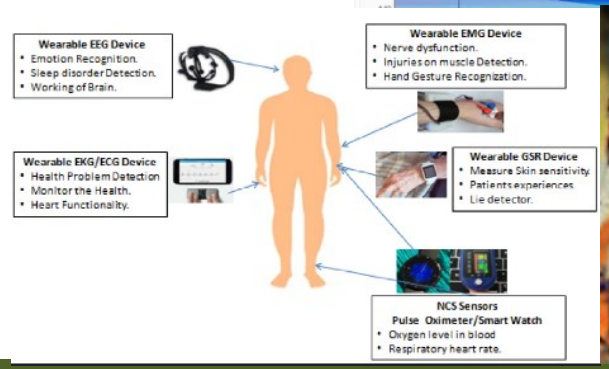




Syllabus

Unit 1

Introduction to Biomedical Signals: Action Potential and Its Generation, Origin and Waveform Characteristics of Basic Biomedical Signals Like: Electrocardiogram (ECG), Electroencephalogram (EEG), Electromyogram (EMG), Phonocardiogram (PCG), Electroneurogram (ENG), Event-Related Potentials (ERPS), Electrogastrogram (EGG), Objectives of Biomedical Signal Analysis, Difficulties in Biomedical Signal Analysis, Computer-Aided Diagnosis.

Unit 2

Biosignal Analysis: Time-domain analysis of Biosignals, Fourier Spectrum of Biosignals, Short Time Fourier Transform and Spectrogram, Discrete Cosine Transform and its Applications, Signal Decomposition based filtering: Wavelet Transform, Hilbert Transform, Empirical Mode Decomposition and Empirical Wavelet Transform.

Unit 3

Introduction to Machine Learning/Deep Learning Approaches for Biomedical Signal Detection and Classification. Performance Measures for Detection and Classification System. Case studies on some recent advances in analysis of biomedical signals.

Unit 1 : An Outline

- Introduction to Biomedical Signals: Action Potential and Its Generation, Origin and Waveform Characteristics of Basic Biomedical Signals Like: Electrocardiogram (ECG), Electroencephalogram (EEG), Electromyogram (EMG), Phonocardiogram (PCG), Electroneurogram (ENG), Event-Related Potentials (ERPS), Electrogastrogram (EGG), Objectives of Biomedical Signal Analysis, Difficulties in Biomedical Signal Analysis, Computer-Aided Diagnosis

Understand underlying principles and characteristics of bio signals

* Notes provided are for reference only. These are not exhaustive contents

Overview

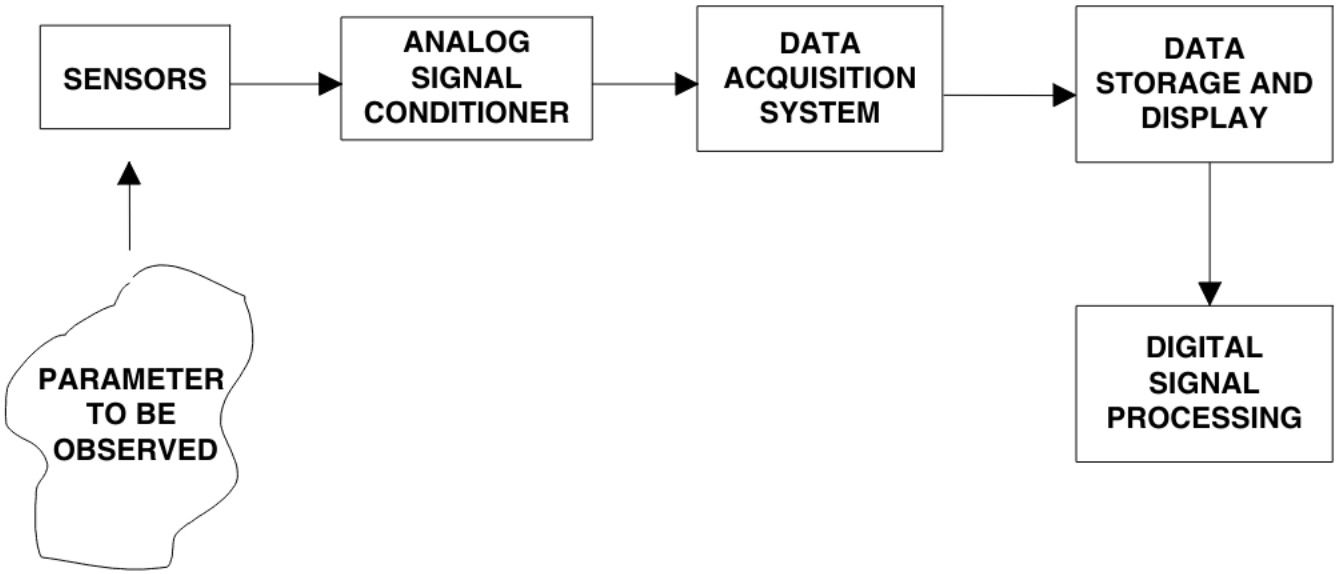


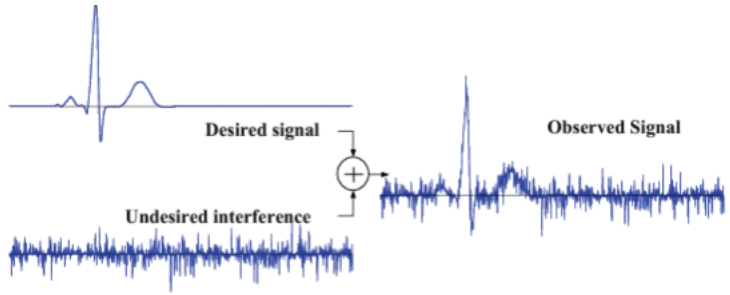
Figure 10.4 Sensors adapt the signal that is being observed into an electrical analog signal that can be measured with a data acquisition system. The data acquisition system converts the analog signal into a calibrated digital signal that can be stored. Digital signal processing techniques are applied to the stored signal to reduce noise and extract additional information that can improve understanding of the

Biological Signals

- Bioelectrical signals, which originate from the electric phenomena taking place on the membrane of cells;
- Bioacoustic which entail the measurement of sounds that are generated by some organs due to fluidic or mechanical movements within the body;
- Biomechanical signals which include measurement of the deflections in position, pace, acceleration, flow rates and pressures;
- Biochemical signals providing information regarding the concentration of substances in body and their pH;
- Body temperature which reflects the metabolic interactions within the body
- other types of biological signals such as bioimpedance and biomagnetic signals, which frequently are not applied due to their associated measurement complexity and limited clinical utility
- **clinical applications of the bioelectrical signals are the most prevalent**

Difficulties in biomedical signal processing

- Variability of features in biomedical signals and systems, which is far higher than that encountered in physical systems or observations.
- Accessibility of the variables to measurement.
- Variability of the signal source. Inter-relationships and interactions among physiological systems.
- Effects of the instrumentation or procedure on the system.
- Physiological artifacts and interference.
- Patient safety.



Objectives of Biomedical Signal Analysis

Information gathering— measurement of phenomena to interpret a system.

Diagnosis— detection of malfunction, pathology, or abnormality.

Monitoring— obtaining continuous or periodic information about a system.

Therapy and control — modification of the behavior of a system based upon the outcome of the activities listed above to ensure a specific result.

Evaluation— objective analysis to determine the ability to meet functional requirements, obtain proof of performance, perform quality control, or quantify the effect of treatment.

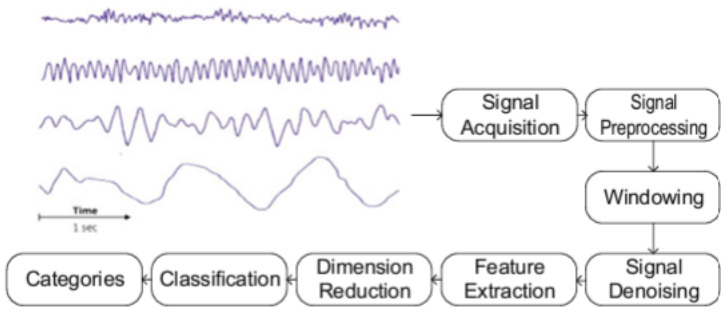


Fig. 1.6 General biomedical signal analysis framework

Introduction to biomedical signals

- Most physiological processes are accompanied by or manifest themselves as signals that reflect their nature and activities
- Discrete vs digital signals?

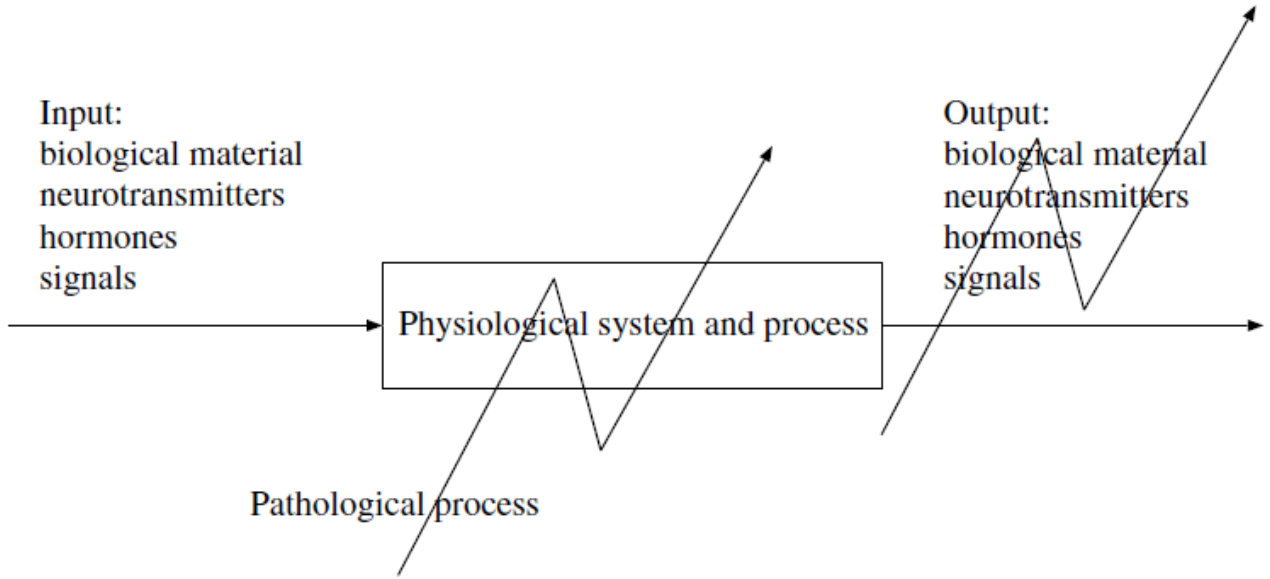


Figure 1.1 Schematic representation of a generic physiological system with various types of possible inputs and outputs. The effect of a pathological process is depicted by the zigzag line across the system and the list of possible outputs.

Biomedical signals

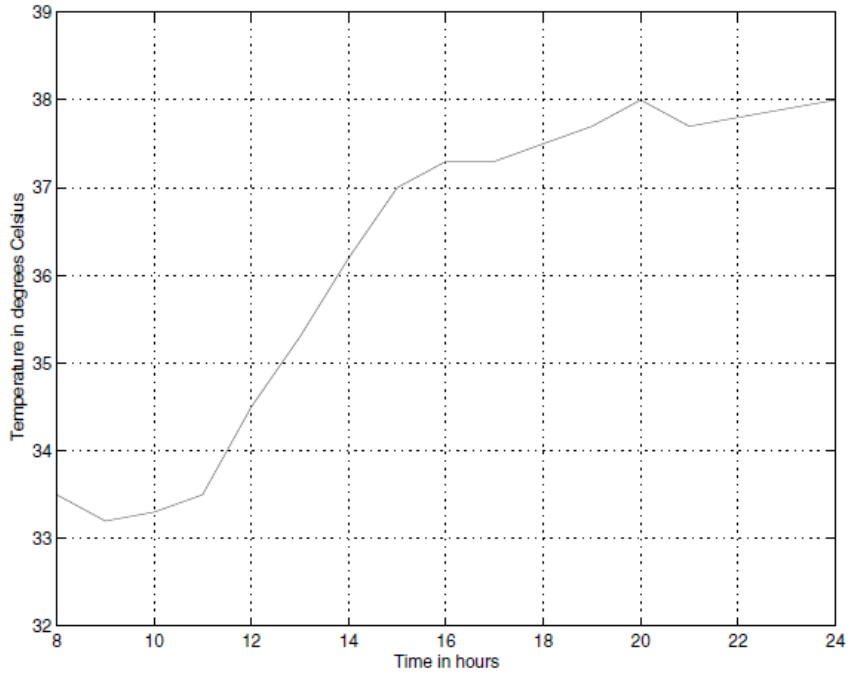
- Example of body temperature as a signal is a simple example of a biomedical signal.

$x = 33.5\,^{\circ}C$

(a)

Time (h)	08:00	10:00	12:00	14:00	16:00	18:00	20:00	22:00	24:00
$x(n)$ ($^{\circ}C$)	33.5	33.3	34.5	36.2	37.3	37.5	38.0	37.8	38.0

(b)

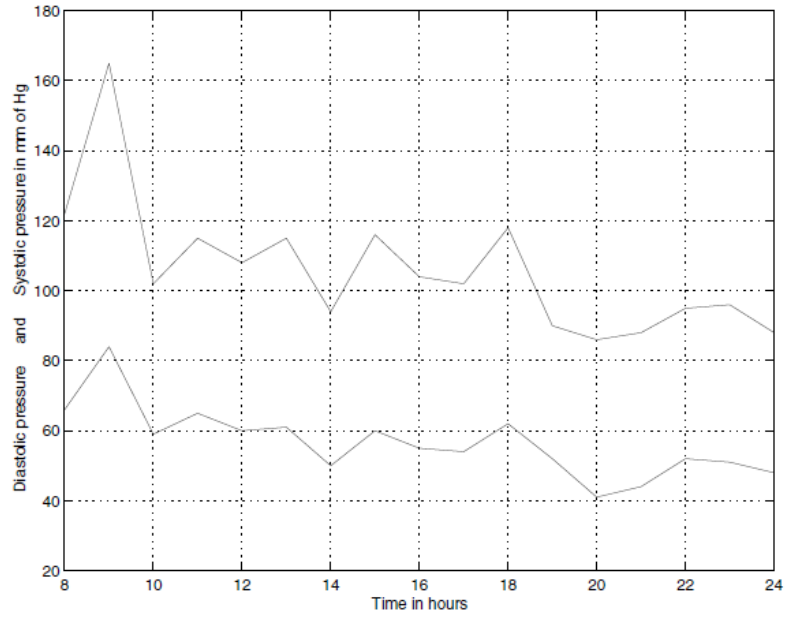


$$\mathbf{x} = \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} = \begin{bmatrix} \text{Systolic} \\ \text{Diastolic} \end{bmatrix} = \begin{bmatrix} 122 \\ 66 \end{bmatrix}$$

(a)

Time (h)	08:00	10:00	12:00	14:00	16:00	18:00	20:00	22:00	24:00
Systolic	122	102	108	94	104	118	86	95	88
Diastolic	66	59	60	50	55	62	41	52	48

(b)

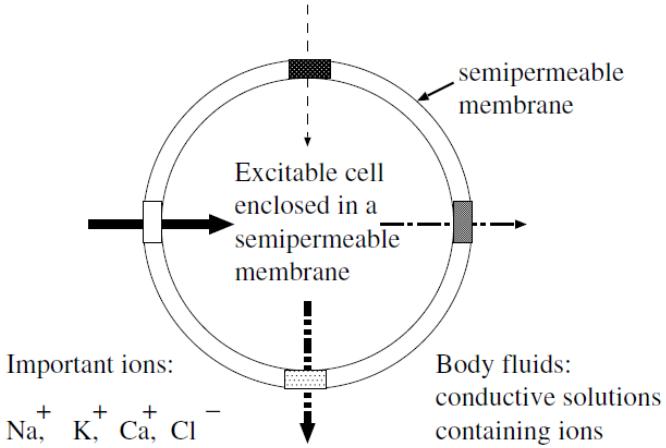


Overview of some bioelectric signals

Bioelectrical Signal	Signal Origin	Frequency Range (Hz)	Typical Amplitude (mV)	Measurement Method
ECG (Electrocardiogram)	Action potentials of heart muscle cells	0.05–250	0.01–5	surface
fECG (Fetal ECG)	Fetal heart activity	0.05–250	0.01–0.02	surface
EEG (Electroencephalogram)	Brain neurons activity	0.1–80	0.005–0.3 0.005–10	surface intracortical
EP (Evoked Potentials)	Brain activity in reaction on external stimuli	30–3000	0.0001–0.02	surface
ENG (Electroneurogram)	Action potentials of peripheral nerves	0.01–1000	0.005–10	interstitial
EMG (Electromyogram)	Action potentials of muscle fibers	0.01–10,000	0.1–10 0.05–0.3	surface
EHG (Electrohysterogram)	Uterus activity during contractions	0.1–3	0.1–5 0.1–1	surface intrauterine
EGG (Electrogastrogram)	Gastric muscles activity	0.02–0.15	0.01–0.5 0.1–10	surface intragastric

Action Potential (AP)

- The action potential is **the basic component of all bioelectrical signals.**
- The AP is the electrical signal that accompanies the mechanical contraction of a single muscle cell when stimulated by an electrical current (neural or external). Action potentials are also associated with signals and messages transmitted in the nervous system with no accompanying contraction.
- The action potential is caused by the flow of sodium (Na+), potassium (K+), chloride (Cl−), and other ions across the cell membrane.
- Action potentials are generated in neurons, skeletal muscle cells, and cardiac muscle cells, also known as cardiomyocytes.
- Different cell types generate different action potentials, depending on the types of ion channels in their cell membranes.



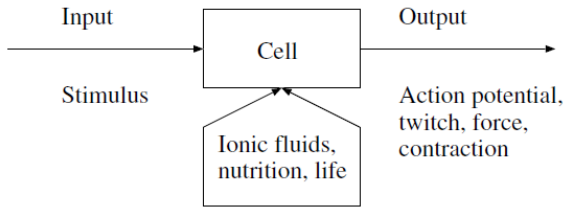
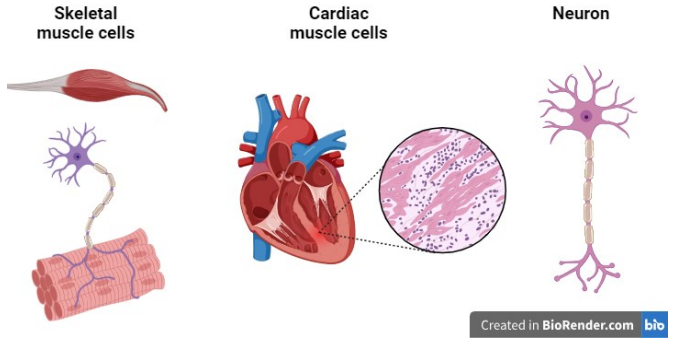
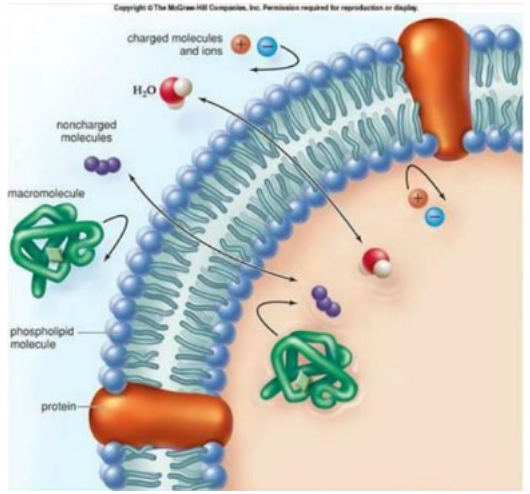


Figure 1.9 Schematic representation of a cell as a system. Upon receiving an input of a stimulus, the cell provides a response that could cause an action potential, a twitch, contraction, or force.

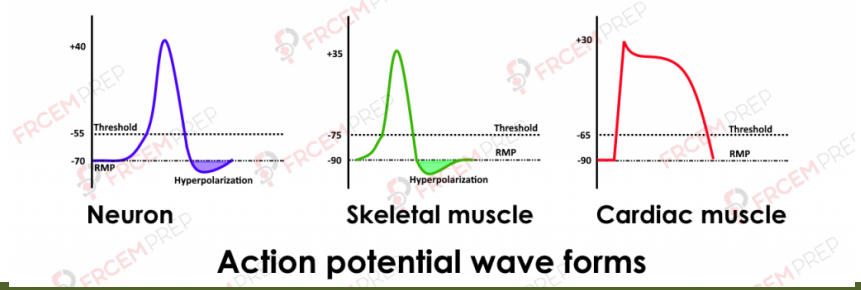




Action Potential (AP)

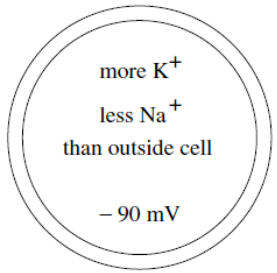
AP is simply a change in the resting membrane potential

- **Resting membrane potential** - All cell membranes have a membrane potential, with excitable tissues exhibiting resting membrane potentials between -60 and -90 mV due to asymmetric distribution of ions, particularly Na+ and K+. It is maintained by the unequal distribution of ions (such as sodium, potassium, chloride, and others) across the cell membrane through ion channels and pumps.
- **Threshold:** APs are triggered when the membrane potential reaches a certain threshold level.
- **Depolarization and repolarization:** During an AP, the membrane potential rapidly depolarizes (becomes more positive) and then repolarizes (returns to resting potential).
- **Absolute Refractory period:** After an AP, there is a brief period where the cell is resistant to firing another action potential.
- **relative refractory period** when another action potential may be triggered by a much stronger stimulus than in the normal situation
- Ion channels: AP involves the opening and closing of voltage-gated ion channels, such as sodium and potassium channels, that mediate the flow of ions across the cell membrane.
- Sodium influx and potassium efflux: During an action potential, there is a rapid influx of sodium ions into the cell, contributing to depolarization, followed by an efflux of potassium ions, contributing to repolarization.
- **All-or-nothing response**: APs either occur fully or not at all, there is no partial depolarization. The action potential is always the same for a given cell, regardless of the method of excitation or the intensity of the stimulus beyond a threshold

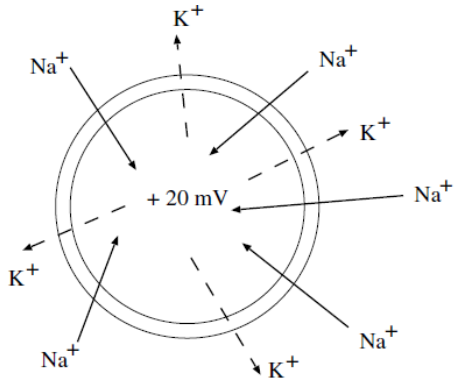


Action potential wave forms

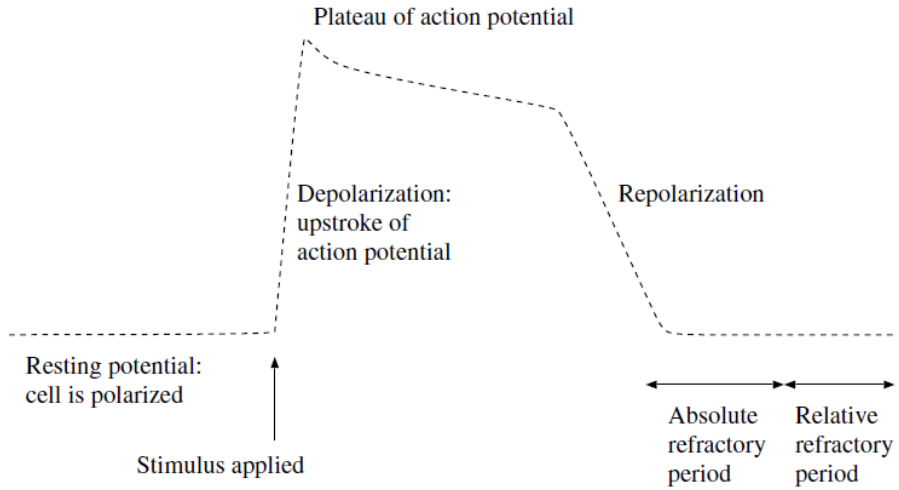
Action potential in cardiomyocytes



At rest: permeability for K^+ 50 to 100 times that for Na^+. The cell is polarized.



Depolarization: triggered by a stimulus; fast Na^+ channels open



Action potential in cardiomyocytes

- Resting Potential: The membrane potential of -90mV is maintained due to the presence of K+ leakage channels.

Depolarization:

- Phase 0: Rapid influx of Na+ ions through voltage-gated Na+ channels, causing a sharp depolarization to around +20-30mV.

Plateau Phase:

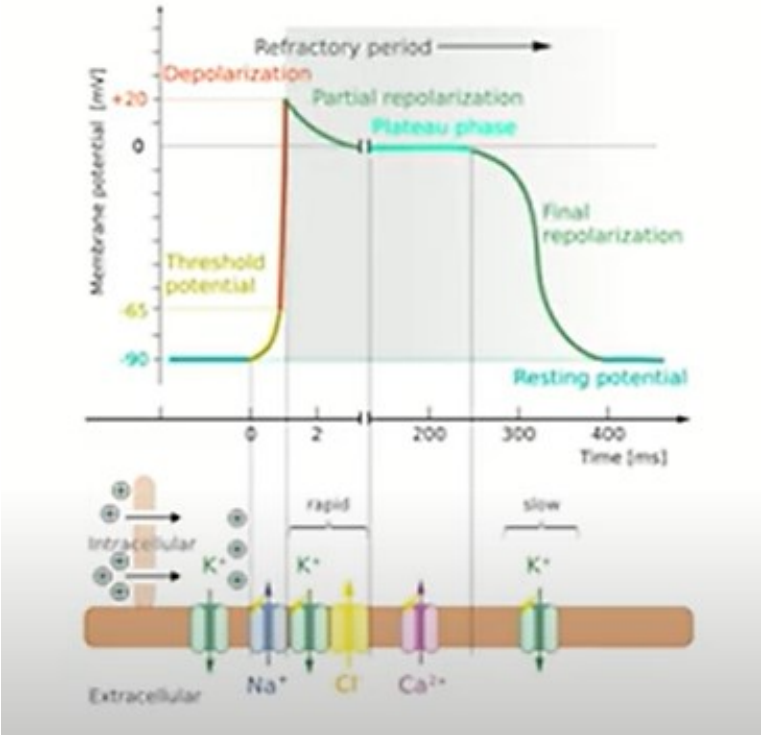
- Phase 1: Brief initial repolarization due to transient K+ channels opening.
- Phase 2: Plateau phase maintained by a balance between Ca2+ influx via L-type Ca2+ channels and K+ efflux.

Repolarization:

- Phase 3: Delayed rectifier K+ channels open, leading to K+ efflux and cell membrane repolarization.

Resting Phase:

- Phase 4: Return to resting membrane potential through the activity of Na+/K+ pumps and K+ leakage channels.
- This sequence of events ensures proper cardiac muscle contraction and relaxation, contributing to the overall function of the heart.



Electrocardiogram (ECG)

- The ECG is the electrical manifestation of the contractile activity of the heart
- Recorded with surface electrodes on the limbs or chest
- The heart is a four-chambered pump with two atria for collection of blood and two ventricles for pumping out of blood
- heart rate (HR) or cardiac rhythm is controlled by specialized pacemaker cells that form the sinoatrial (SA) node
  - resting or filling phase of a cardiac chamber →diastole
  - contracting or pumping phase → systole
- The action potential of the SA node propagates through the rest of the heart, causing a particular pattern of excitation and contraction

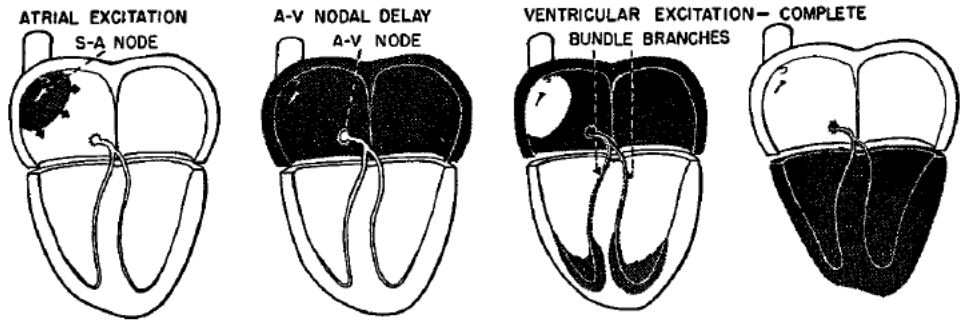
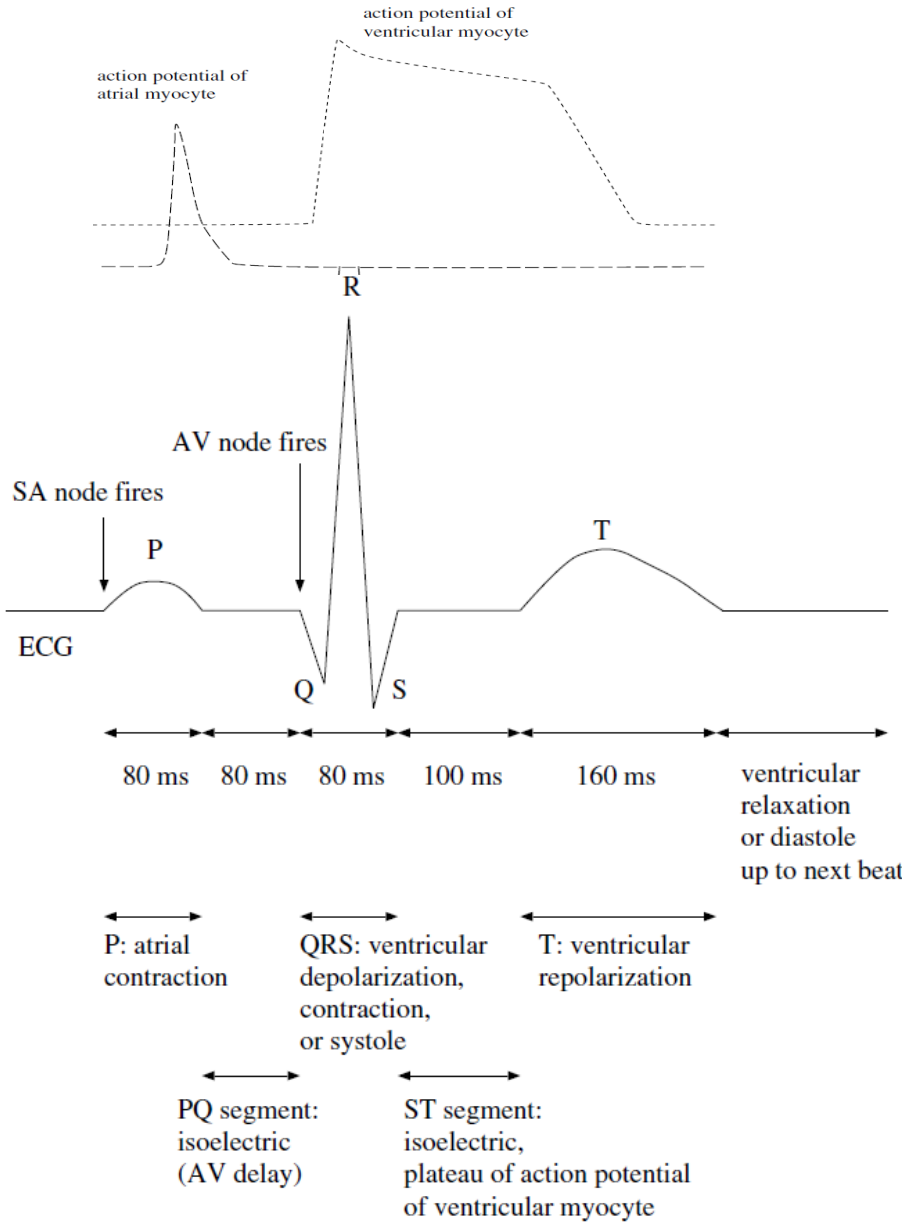


Figure 1.23 Propagation of the excitation pulse through the heart. Reproduced with permission from R.F. Rushmer, *Cardiovascular Dynamics*, 4th edition, ©W.B. Saunders, Philadelphia, PA, 1976.

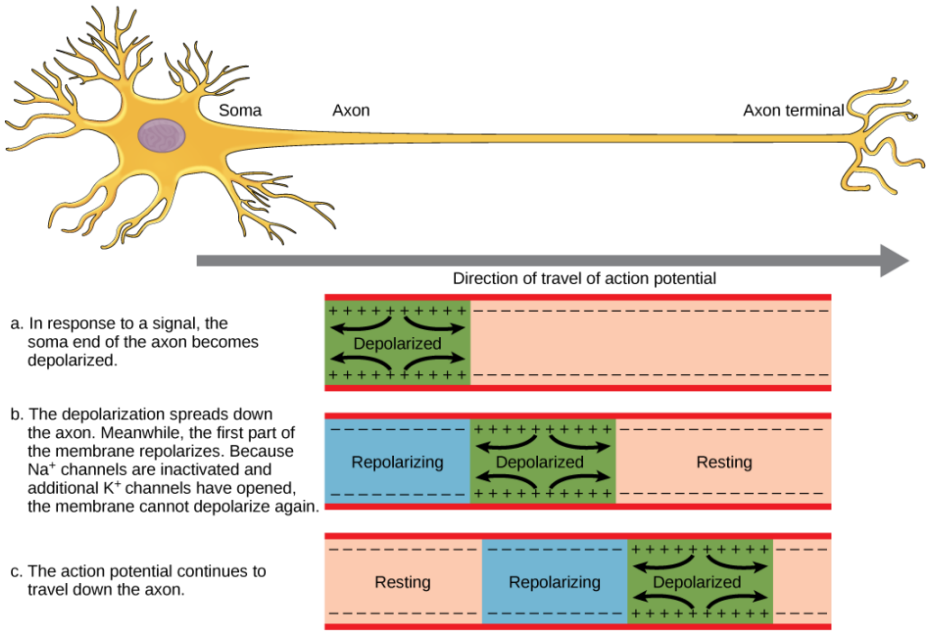
ECG waveform

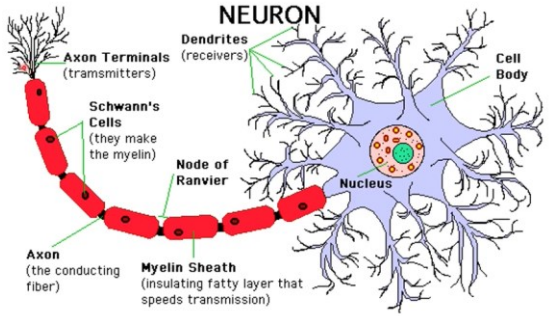
- The SA node fires.
- Electrical activity is propagated through the atrial musculature at comparatively low rates, causing slow-moving depolarization (contraction) of the atria. This results in the P wave in the ECG. Due to the slow contraction of the atria and their small size, the P wave is a slow, low-amplitude wave, with an amplitude of about 0.1 – 0.2 mV and a duration of about 60 – 80 ms.
- The excitation wave faces a propagation delay at the atrioventricular (AV) node, which results in a normally isoelectric segment of about 60–80 ms after the P wave in the ECG, known as the PQ segment. The pause assists in the completion of the transfer of blood from the atria to the ventricles.
- The AV node fires.
- The His bundle, the bundle branches, and the Purkinje system of specialized conduction fibers propagate the stimulus to the ventricles at a high rate.
- The wave of stimulus spreads rapidly from the apex of the heart upwards, causing rapid depolarization (contraction) of the ventricles. This results in the QRS wave of the ECG — a sharp biphasic or triphasic wave of about 1 mV amplitude and 80 ms duration
- The plateau portion of the action potential causes a normally isoelectric segment of about 100–120 ms after the QRS, known as the ST segment. This is because ventricular muscle cells possess a relatively long action potential duration of 300 – 350 ms.
- Repolarization (relaxation) of the ventricles causes the slow T wave, with an amplitude of 0.1 – 0.3 mV and duration of 120 – 160 ms

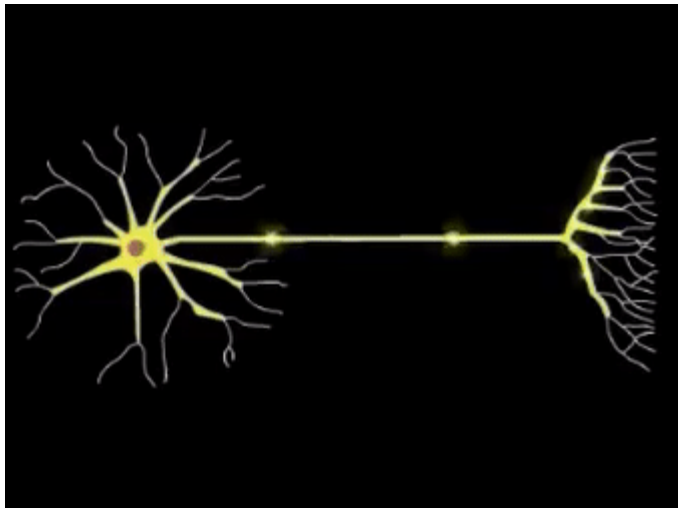


Nerve action potential

- The action potential is the unit of neural information.
- The all-or-none or one-or-zero property of the action potential ensures that the signal does not suffer from degradation and contamination while traveling the length of a nerve.
- Aps transmitted by nerves can be carried across several tens of centimeters in the human body. The action potential is therefore a temporal as well as a spatial event.
- As neighboring regions sequentially undergo potential changes and return to rest, the action potential is seen to propagate spatially. Overall, the action potential is a spatiotemporal event.

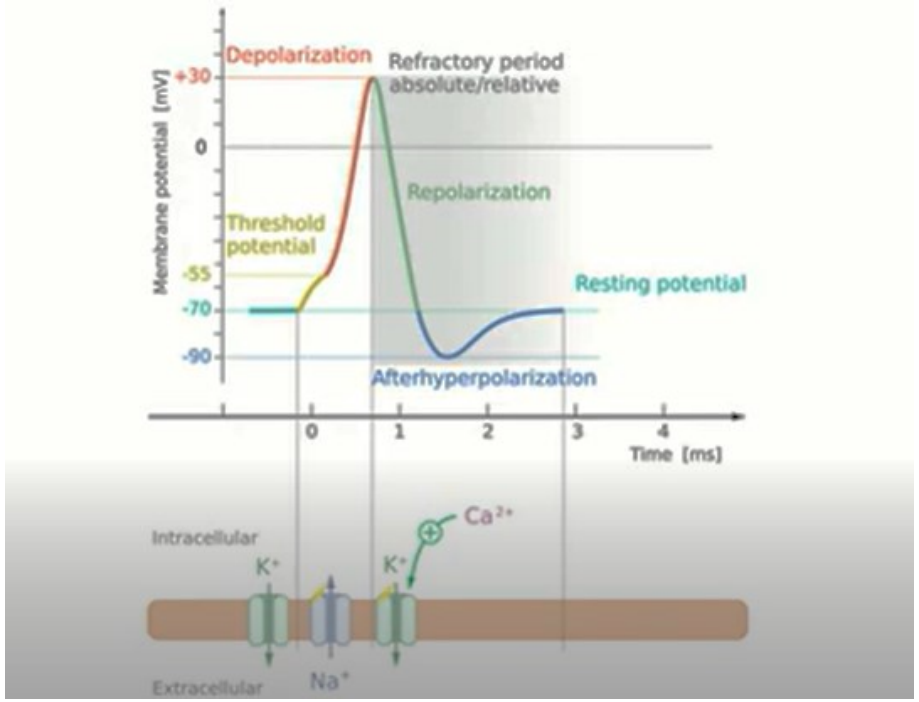






Neuron action potential

- The resting potential of approximately -70 millivolts is maintained primarily by the transport of potassium ions.During the resting membrane potential there are:
  - More sodium ions (Na+) outside the neuron
  - More potassium ions (K+) inside the neuron
- **Initiation of Action Potential**
  - Trigger: Opening of sodium channels
  - Ion Movement: Na+ enters the cell
  - Voltage Change: Membrane potential becomes less negative
- **Threshold and Depolarization**
  - Threshold Potential: ~-55 mV
  - Voltage-Dependent Sodium Channels: Open
  - Rapid Influx: More Na+ into the cell
  - Maximum Potential: ~+30 mV
  - Closure of Potassium Channels Effect: Increases positive charge inside cell
  - Action Potential Peak: Reached at ~+30 mV
- **Repolarization**
  - Potassium Efflux: K+ exits the cell
  - Membrane Potential: Decreases
  - End Point: ~-90 mV
- **Restoration to Resting Potential**
  - Refractory Period: Ends
  - Potassium Channels: Close
  - Resting Potential: Re-established at ~-70 mV

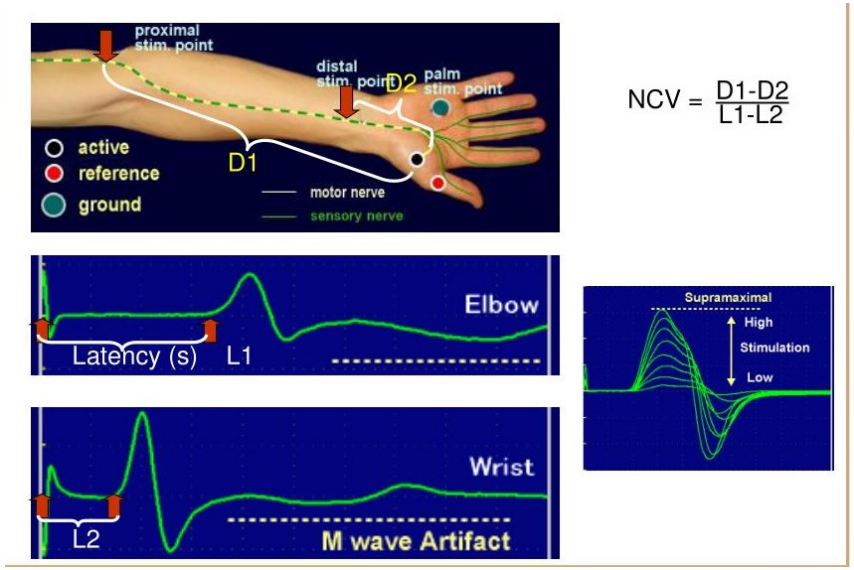


Electroneurogram (ENG)

- ENG is an electrical signal observed as a stimulus and the associated nerve action potential propagate over the length of a nerve.
- It may be used to measure the velocity of propagation (or conduction velocity) of a stimulus or action potential in a nerve
- ENGs may be recorded using concentric needle electrodes or silver–silver-chloride electrodes (Ag − AgCl) at the surface of the body.
- The conduction velocity in a peripheral nerve may be measured by stimulating a motor nerve and measuring the related activity at two points that are a known distance apart along its course.
- Typical values of propagation rate or nerve conduction velocity are
  - 45 − 70 m/s in nerve fibers;
  - 0.2 − 0.4 m/s in heart muscle;
  - 0.03 − 0.05 m/s in time-delay fibers between the atria and ventricles.
  - Neural diseases may cause a decrease in conduction velocity.
- ENGs have amplitudes of the order of 10 μV and are susceptible to power-line interference and instrumentation noise.
- Once initiated by a stimulus, the action potential propagates along the whole length of a fiber without decrease in amplitude by progressive depolarization of the membrane

ENG

- The conduction velocity in a peripheral nerve may be measured by stimulating a motor nerve and measuring the related activity at two points that are a known distance apart along its course.
- In order to minimize muscle contraction and other undesired effects, the experimental limb is held in a relaxed posture and a strong but short stimulus is applied in the form of a pulse of about 100 V amplitude and 100−300 µs duration.
- The difference in the latencies of the ENGs recorded over the associated muscle gives the conduction time. Knowing the separation distance between the stimulating and recording sites, it is possible to determine the conduction velocity in the nerve
- The three traces in the figure indicate increasing latencies with respect to the stimulus time point, which is at the left margin of the plots.



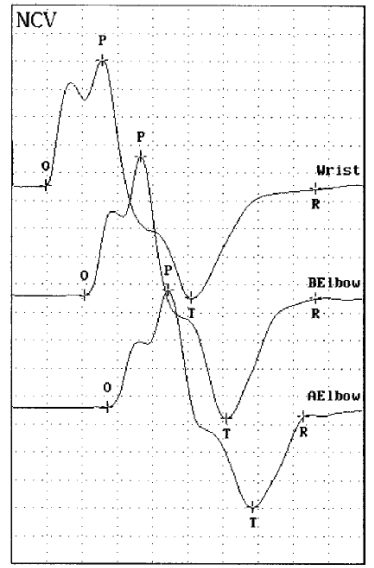
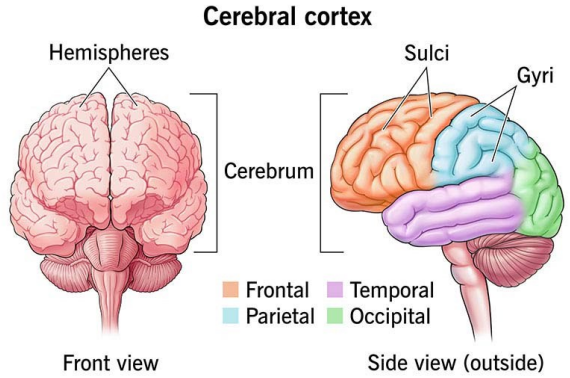
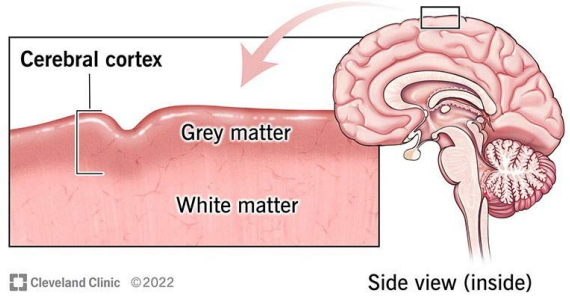


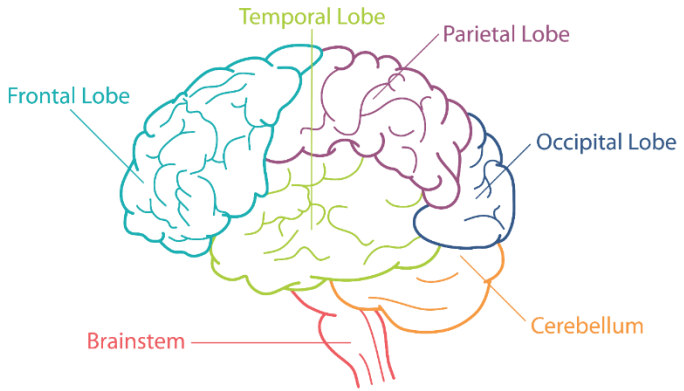
Figure 1.11 Nerve conduction velocity measurement via electrical stimulation of the ulnar nerve. The grid boxes represent 3 ms in width and 2 μV in height. AElbow: above the elbow. BElbow: below the elbow. O: onset. P: Peak. T: trough. R: recovery of baseline. Courtesy of M. Wilson and C. Adams, Alberta Children's Hospital, Calgary.

Electroencephalogram (EEG)

- EEG (popularly known as brain waves) represents the electrical activity of the brain
- The outer surface of the cerebral hemispheres, known as the cerebral cortex, is composed of neurons (gray matter) in convoluted patterns, and separated into regions by fissures (sulci).
- Beneath the cortex lie nerve fibers that lead to other parts of the brain and the body (white matter).
- EEG techniques include the use of needle electrodes and nasopharyngeal electrodes, recording the electrocorticogram(ECoG) from an exposed part of the cortex, and the use of intracerebral electrodes.
- The scalp EEG is an average of the multifarious activities of many small zones of the cortical surface beneath the electrode.
- The International Federation of Societies for Electroencephalography and Clinical Neurophysiology recommended the 10–20 system of electrode placement for clinical EEG recording







EEG

- EEG signals exhibit several patterns of rhythmic or periodic activity. The commonly used terms for EEG frequency (f) bands are:
  - Delta (δ): $0.5 \leq f < 4$ Hz;
  - Theta (θ): $4 \leq f < 8$ Hz;
  - Alpha (α): $8 \leq f \leq 13$ Hz; and
  - Beta (β): $f > 13$ Hz.
  - the gamma rhythm is defined as activity in the range 30 – 80 Hz.
- EEG rhythms are associated with various physiological and mental processes
  - The alpha rhythm is the principal resting rhythm of the brain
  - gamma rhythm is considered to be related to responses induced by various types of sensory input or stimuli, active sensory processes involving attention, and short-term memory processes
  - Theta waves appear at the beginning stages of sleep;
  - delta waves appear at deep-sleep stages.
  - High-frequency beta waves appear as background activity in tense and anxious subjects.

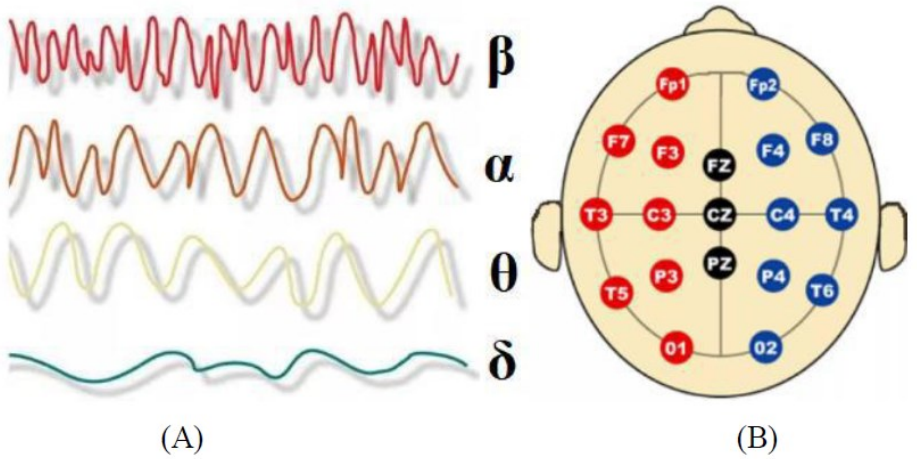


Figure 2.1: A - brain rhythms (β, α, θ, γ), B – the international system of placement of electrodes "10-20".

EEG

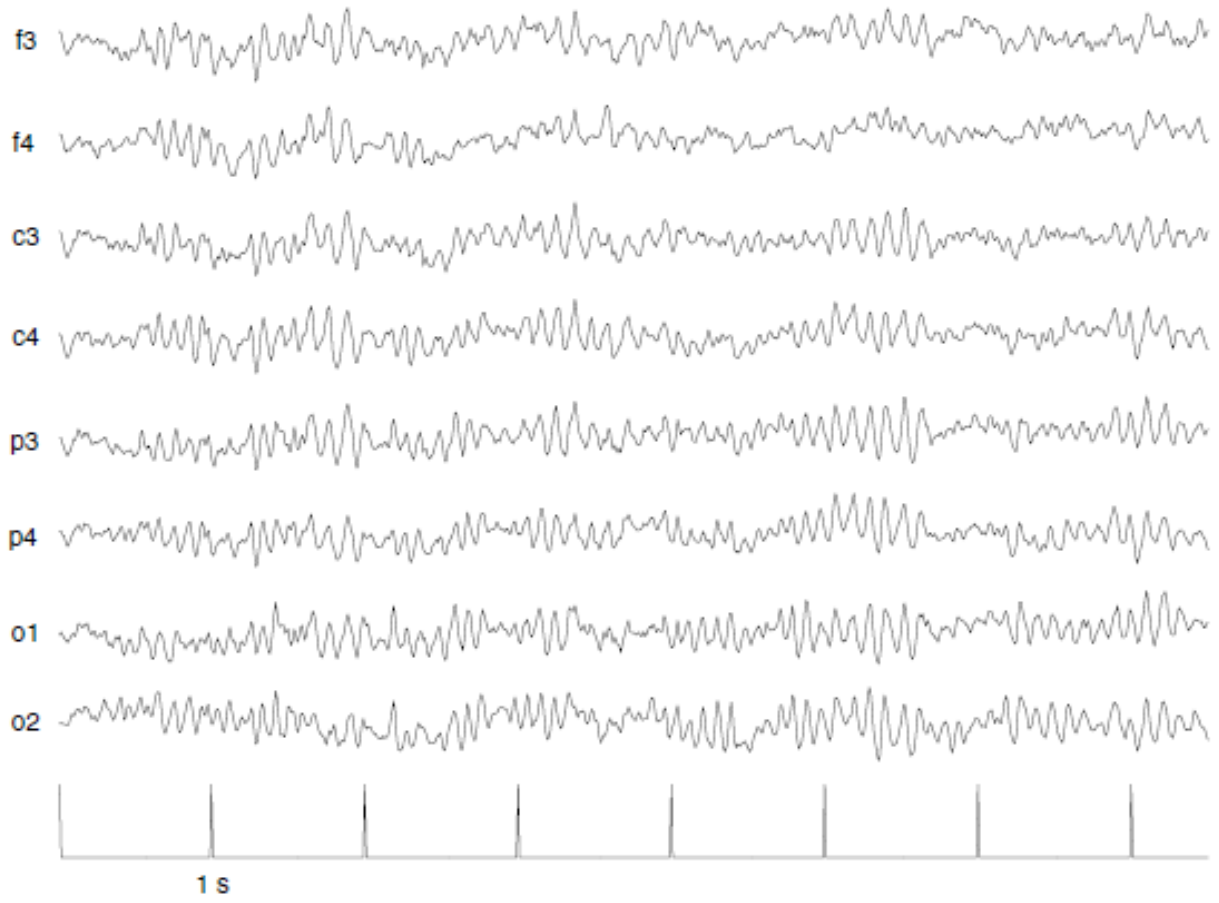


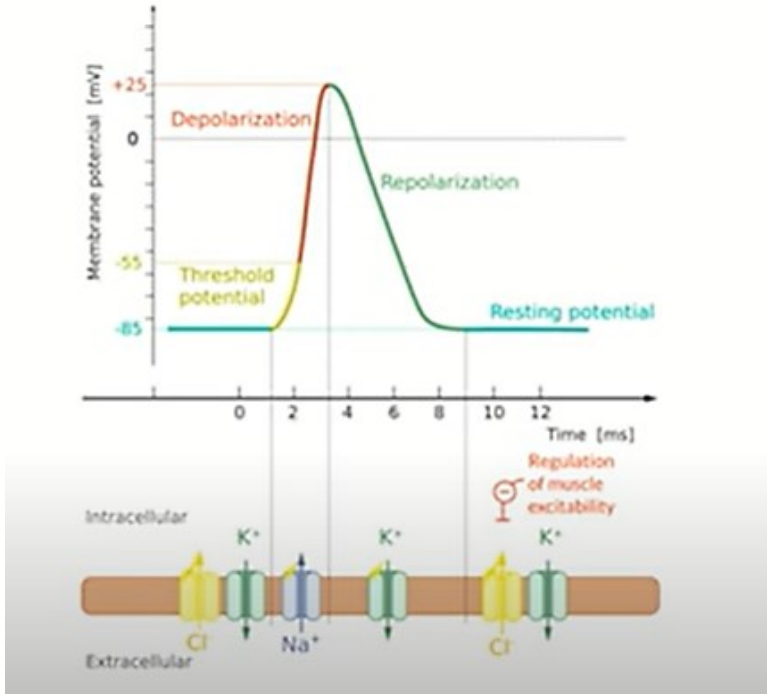
Figure 1.39 Eight channels of the EEG of a subject displaying alpha rhythm. See Figure 1.37 for details regarding channel labels. Data courtesy of Y. Mizuno-Matsumoto, Osaka University Medical School, Osaka, Japan.

Event-related potentials (ERPs)

- event-related potential is more general than and preferred to the term evoked potential, and includes the ENG or the EEG in response to light, sound, electrical, or other external stimuli.
  - Short-latency ERPs → Depend mainly on the physical characteristics of the stimulus.
  - Longer-latency ERP → Influenced more by the conditions of stimulus presentation.
- Latency: The time between the stimulus and the response; important for determining the speed of neural processing.
- Amplitude: The strength of the electrical signal; can indicate the degree of neural engagement or response.
- Polarity: Positive (P) or negative (N) deflections, named based on their polarity and timing (e.g., P300, N400).
- Averaging Technique: To improve the signal-to-noise ratio (SNR), multiple ERP trials are averaged to enhance the signal and reduce background noise.

Action potential in skeletal muscle cell

- In the default state, chloride and potassium channels are open in the skeletal muscle cell membrane, termed the sarcolemma.
- Together, the channels generate a resting potential of approximately -85 millivolts which is significantly lower than that of neurons.
- The neuron releases acetylcholine, which binds to ligand-gated sodium channels in the sarcolemma.
- Through these channels, sodium flows down its concentration gradient into the skeletal muscle cell and the membrane potential increases.
- Once the threshold potential is reached, the voltage-gated sodium channels in the sarcolemma also open.
- Even more sodium ions flow into the cell, leading to depolarization with a membrane potential of around +25 millivolts.
- Additionally, there's delayed voltage-dependent potassium channel opening. The efflux of potassium ions down their concentration gradient repolarizes the sarcolemma.
- Because of the highly negative resting potential, repolarization doesn't lead to afterhyperpolarization, as is the case in neurons.



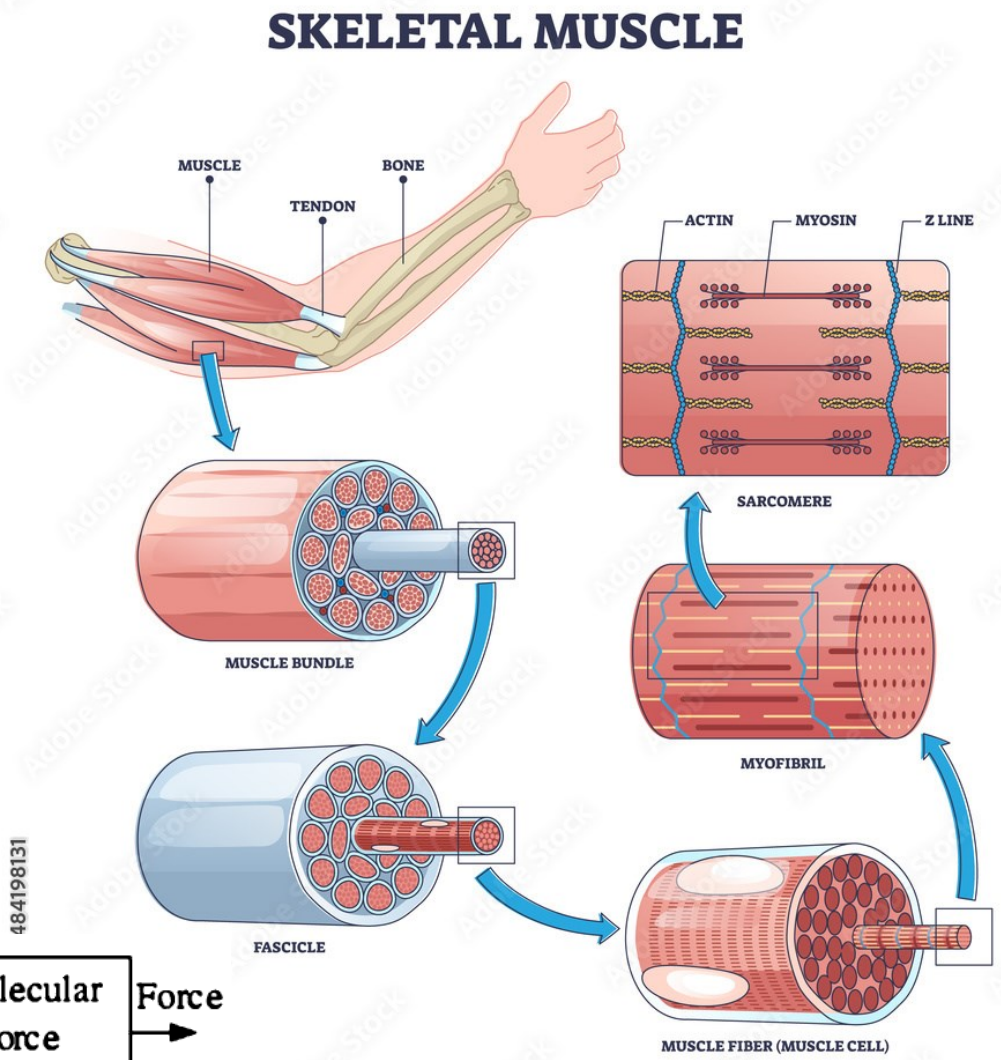
Action potentials in skeletal muscle cells involve ion transport, with chloride and potassium channels generating a resting potential, and acetylcholine-induced sodium influx triggering depolarization and repolarization via potassium efflux.

Action potential in skeletal muscle cell

- The short refractory period in skeletal muscle action potentials serves to prevent muscle fiber from immediately contracting again after it has just contracted. This brief period of time, during which the muscle fiber cannot respond to a new stimulus, allows the muscle fiber to reset and prepare for the next contraction.
- Thus, the refractory period helps to ensure that muscle contractions are coordinated and effective, allowing the muscle to function optimally in performing its physiological functions.

EMG

- Signal Transmission: Skeletal muscle action begins with activity in the central nervous system, producing action potentials in peripheral nerves (motor neurons) connected to the muscle.
- Neuromuscular Junction: The signal is transferred across the neuromuscular junction (N-M junction) by neurotransmitters (acetylcholine) and initiates action potentials in the muscle fibers.
- Depolarization and Contraction: The muscle action potential moves as depolarization along the muscle fiber membrane
- Sarcomere: The basic contractile element in skeletal muscle is the sarcomere, approximately 2.5 µm long, capable of a 25% range of movement, producing force in millinewtons.
- Muscle Fiber Composition: Several thousand sarcomeres make up a muscle fiber, which can be several centimeters long with a 25% range of movement.



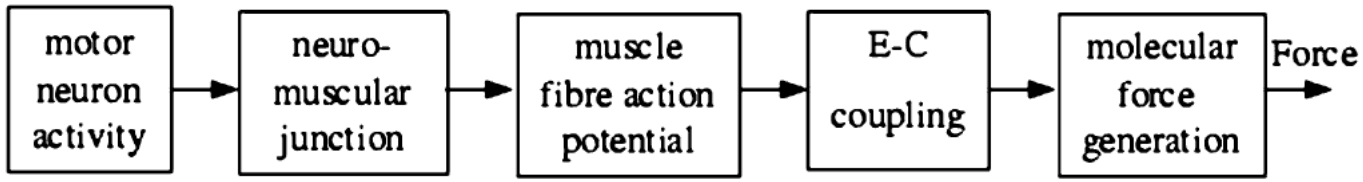
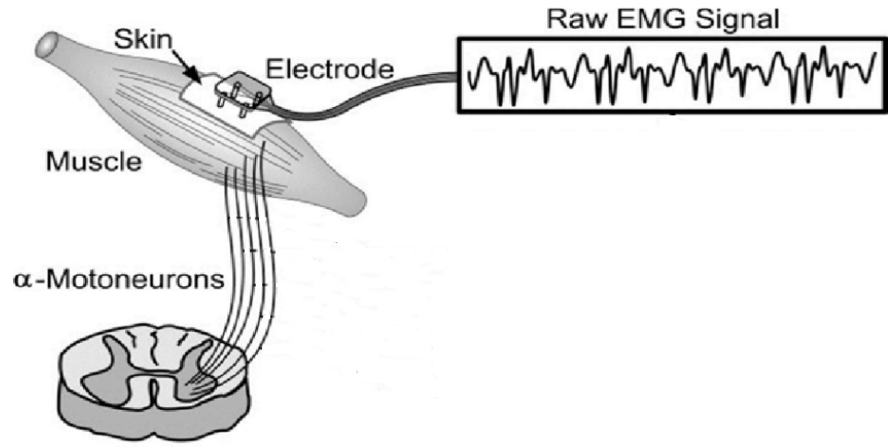


Fig. 10.1 Sequence of events in muscle force generation

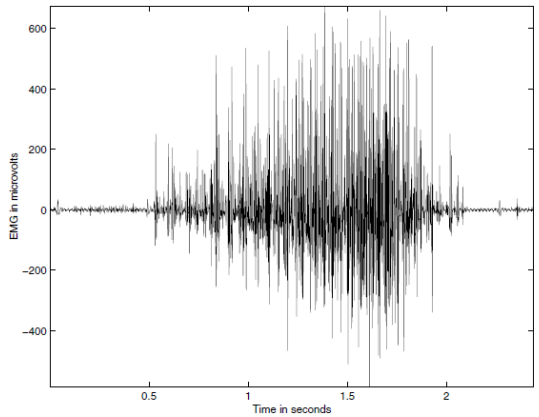
EMG

- Motor Units: Several hundred muscle fibers make up a motor unit, providing an appreciable fraction of a Newton in force. Multiple motor units compose a whole muscle, amplifying the force.
- Synchronous Activation: All fibers within a motor unit are activated simultaneously. Single-Motor-Unit Action Potential (SMUAP): The electrical signal from the contraction of a motor unit is the summation of the action potentials of all its fibers.
- Innervation Ratio: The number of muscle fibers per motor neuron varies:
  - Gross Movement: Muscles involved in large force or gross movements have hundreds of muscle fibers per motor unit.
  - Fine Movement: Muscles involved in precise or fine movements have fewer fibers per motor unit.
  - Mechanical Output: Muscle contraction results from the stimulation and contraction of several motor units.



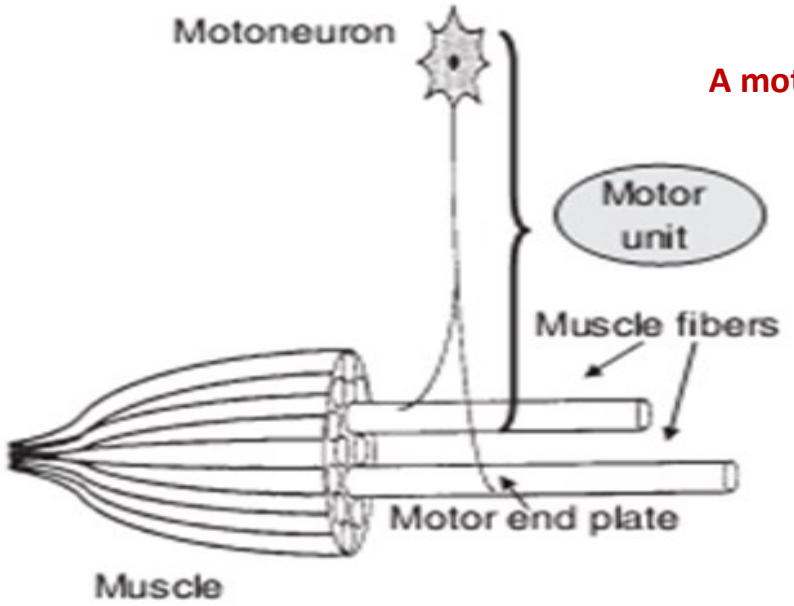
Surface EMG signal and its constituent Motor Unit Action Potentials

De Luca et al., 2006

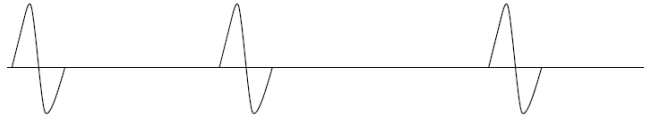


EMG

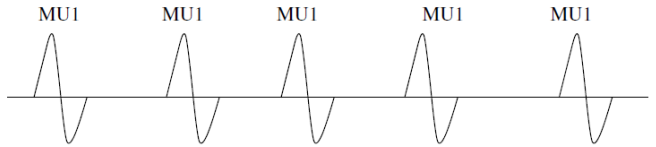
- An EMG signal indicates the level of activity of a muscle, and may be used to diagnose neuromuscular diseases such as neuropathy and myopathy.
- The shape of SMUAPs is affected by disease



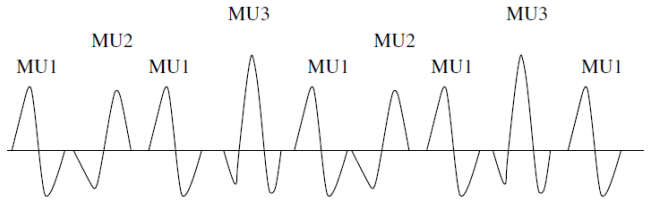
A motor unit



(a) At the beginning with low effort, only motor unit MU1 is firing at a low rate.



(b) At a slightly higher level of effort, with temporal recruitment, the firing rate of MU1 is increased. No other motor unit has been recruited yet.



(c) At an even higher level of effort, with spatial recruitment, new motor units MU2 and MU3 have been brought into action. MU1 continues to fire at the same rate as in (b).

Schematic representation of spatiotemporal recruitment of motor units and the resulting EMG signals. To keep the illustration simple, it is assumed that the MUAPs do not overlap.

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