MEDICAL UNIVERSITY – PLEVEN
FACULTY OF MEDICINE

DIVISION OF PHYSICS AND BIOPHYSICS

LECTURE 9

# BIOELECTRICITY

The living cell as an electric source. The electrocardiogram. The electroencephalogram. Other bioelectric measurements. The electronic pacemaker

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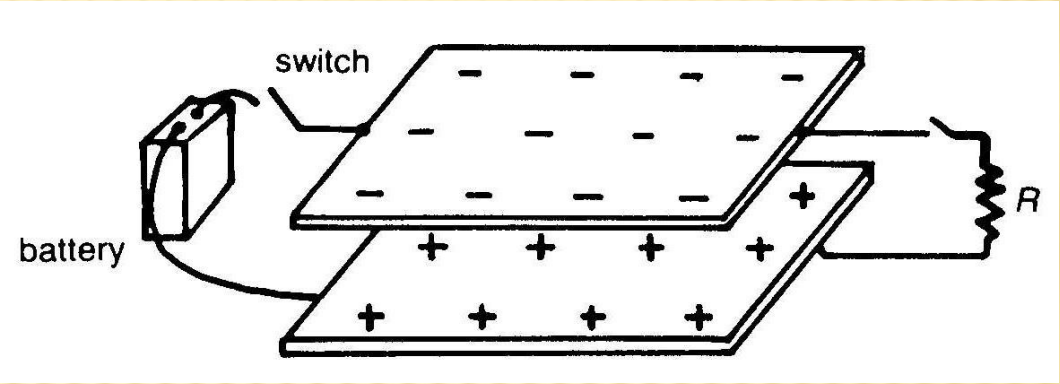
*Bioelectricity refers to electrical phenomena in living tissues :*

- small electric currents are generated in tissue
- the conduction of electricity is important in the functioning of nerves
- the external measurement of electrical signals generated by the body is the basis for diagnostic techniques, such as the ECG and EEG
- the pacemaker is an instrument which simulates normal bioelectric potentials when the body is not capable of producing them

# THE LIVING CELL AS AN ELECTRIC SOURCE

The membrane of the living cell can maintain a potential difference between the inside and outside of the cell. This is analogous to the capacitor.




If the right hand switch were closed, the system would "depolarize" or discharge through the resistance.

If unlike charges are placed on the parallel conducting plates, a voltage will exist between the plates. Energy is required from a battery or other source to establish this unequal charge distribution (polarized capacitor).

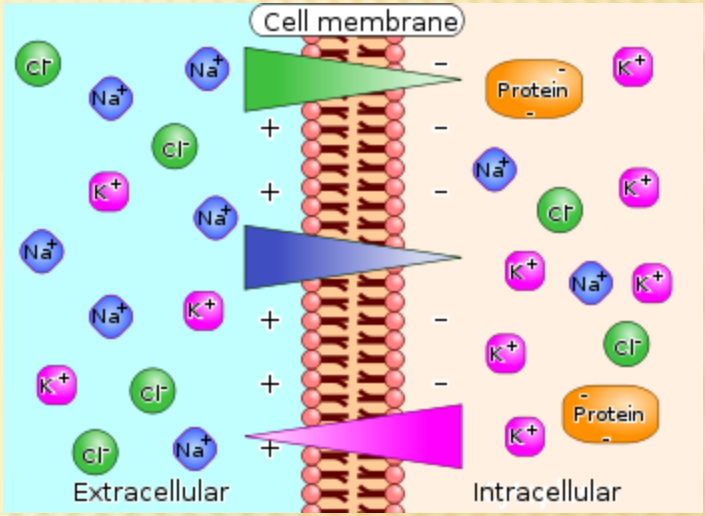
If the battery switch is opened after charging the plates, the charge will remain at rest on the plates since there is no available discharge path.

Because of the mutual repulsion of like charges and the attraction toward the unlike charge on the opposite plate, the charge has potential energy and would "depolarize" or discharge through the resistance *R* if the right-hand switch were closed.

A living cell in its normal or "rest" state maintains a voltage (referred to as the "membrane potential" or "resting potential ") of about 70 to 90 mV between the inside and outside of the cell.

The inside of the cell is (-) with respect to the outside.

$K^+$, $Na^+$, and $Cl^-$ are the major key to the origin of bioelectricity.




Their movements through the membranes are governed by:

(1) the concentration gradient
(2) the electrical potential gradient
(3) the permeability of the membrane to the particular ion.

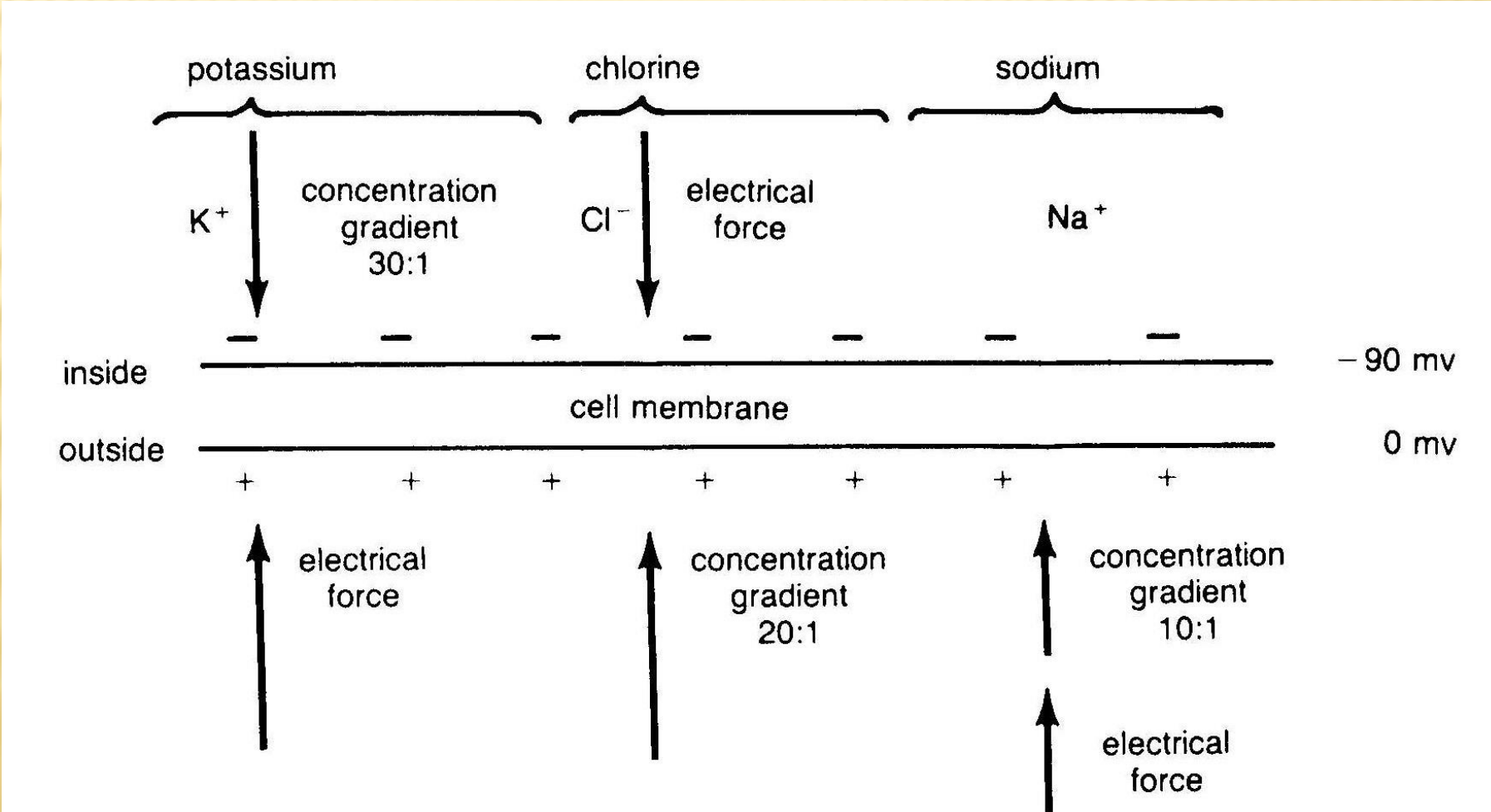
Large concentration gradients exist across the membrane for each of the three ions.

$K^+$ ions are more concentrated inside the cell by a factor of roughly 30 to 1. $Na^+$ and $Cl^-$ ions are more concentrated outside, with concentration ratios of roughly 10 : 1 for $Na^+$ and 20 : 1 for $Cl^-$.

If the cell wall is uncharged, $K^+$ begins to diffuse outward through the permeable membrane because of the large concentration gradient.

- After a brief diffusion period, on the order of ms, a stable equilibrium voltage is established and no further net diffusion occurs.

This voltage may be calculated from a model (Nernst potential). The calculated value agrees with $Cl^-$ since they migrate only by passive diffusion. The $K^+$ gradient is a few % larger than predicted. [$K^+$ ] in the cell is increased by some active transport mechanism or "potassium pump."



Both the concentration and the electrical gradients tend to move $Na^+$ ions into the cell but the membrane **permeability** to $Na^+$ is **very low** during the rest state. Some $Na^+$ penetrates the membrane, but the "sodium pump" removes it. The pump must work against both the electric and diffusion influences to maintain the rest potential.

It is these active "pump" mechanisms that distinguish the living cell membrane from a nonliving one.

The word "pump" is used to indicate that the process requires energy from the cell's metabolic process. It is analogous to the battery energy needed to charge the plates of the capacitor.

**THE ACTION POTENTIAL.** When a membrane of a nerve cell is sufficiently stimulated, it "fires" or releases some of the stored energy.

The interior potential of the cell quickly rises from about **-90 mV** to about **+20 - +30 mV.** The process is called *depolarization.* The *repolarization* process begins immediately and builds the interior potential back to the -90 mV resting potential.

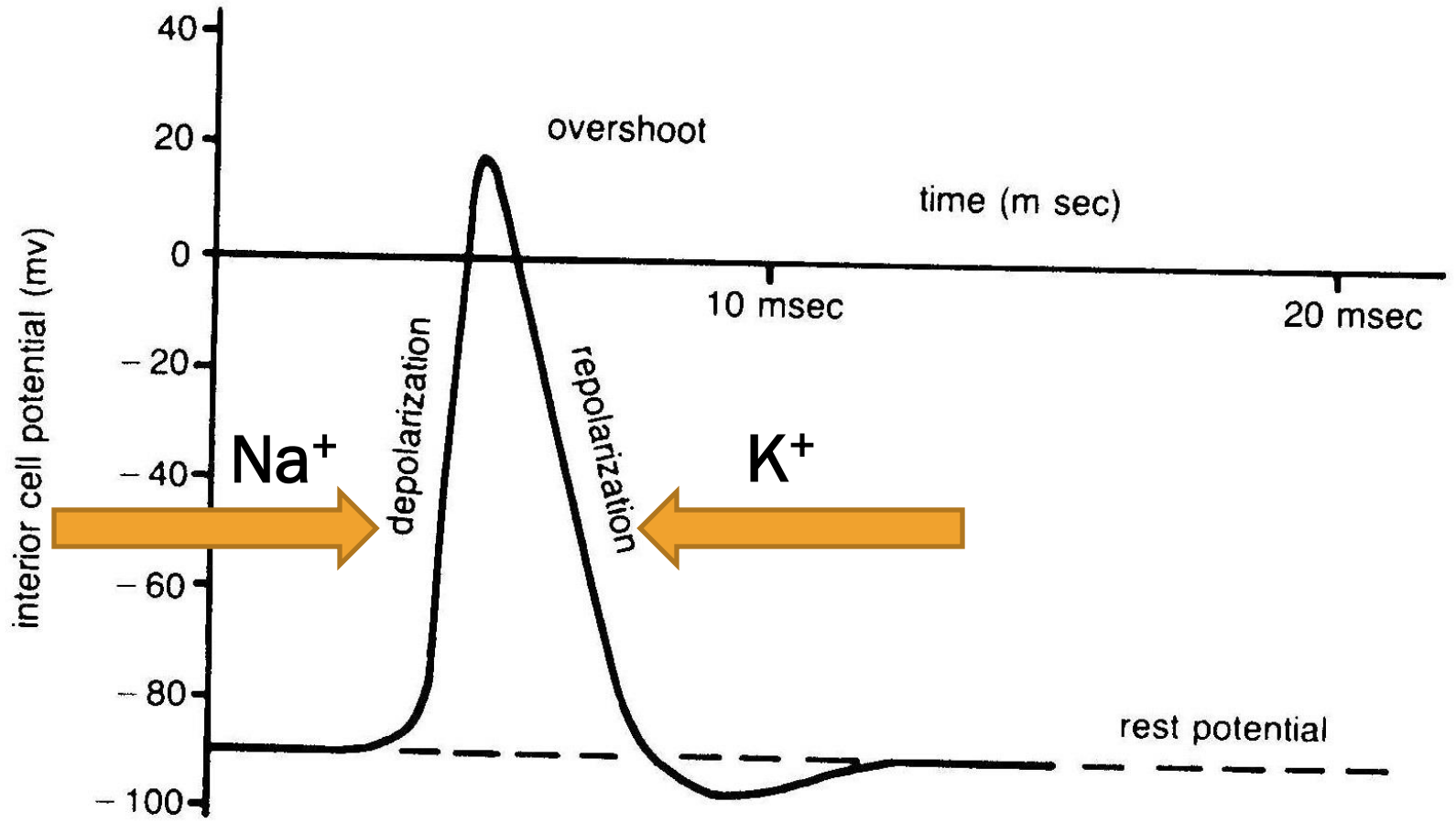
**Def. The voltage pulse produced by the depolarization-repolarization process is referred to as the action potential.**

The depolarization process is closely related to the conduction of $Na^+$ ions into the cell.

During depolarization the cell membrane becomes permeable to $Na^+$, driving the potential positive.

Once the influx starts, it is self-sustaining until it is counteracted by the outward migration of $K^+$. The lowered electrical force allows $K^+$ to migrate outward.

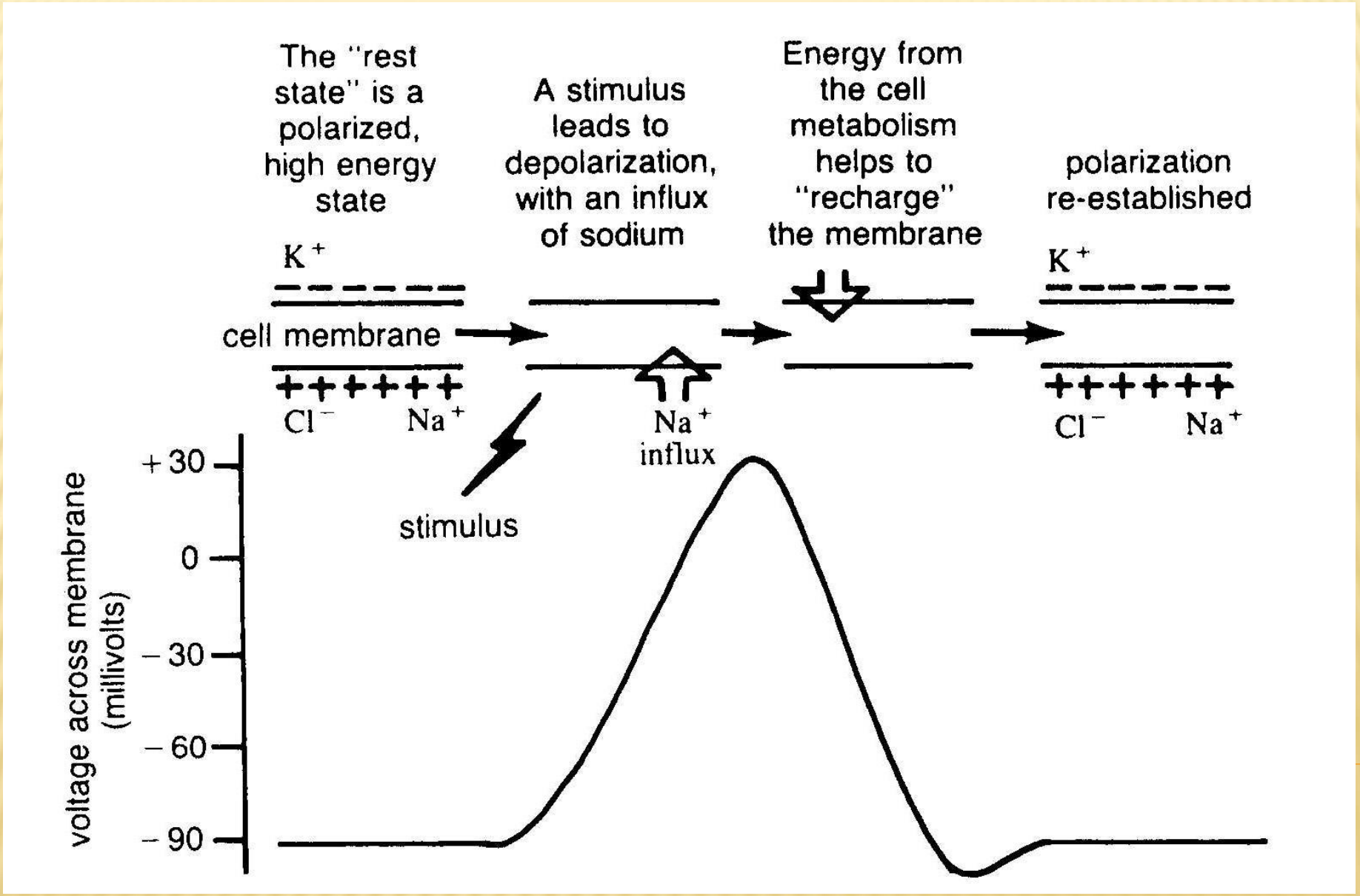
With energy supplied by the cell, $K^+$ diffusion takes control for the repolarization or "recharging" of the cell membrane when the membrane's permeability to $Na^+$ is turned off.


40
20
0
– 20
– 40
– 60
– 80
– 100
interior cell potential (mv)
overshoot
time (m sec)
10 msec
20 msec
depolarization
repolarization
Na+
K+
rest potential

In response to a strong, continued stimulus, several hundred action potentials per second can be generated.

In large cells, such as nerve cells with long extensions called axons, an action potential can be generated in one part of a cell and transmitted to other parts.

This involves the **successive stimulation** of neighboring membrane areas so that the depolarization-repolarization pulse propagates through the cell.


The "rest state" is a polarized, high energy state
A stimulus leads to depolarization, with an influx of sodium
Energy from the cell metabolism helps to "recharge" the membrane
polarization re-established
K+
cell membrane
Cl−
Na+
Na+ influx
stimulus
voltage across membrane (millivolts)
+30
0
−30
−60
−90

# THE ELECTROCARDIOGRAM (ECG)

It is a direct measurement of voltages produced by the body and therefore does not involve a transducer.

The action potentials produced in the heart result in measureable voltages at the skin which can be monitored by external electrodes. These are the largest action potentials measured on the body, producing voltages of 1 mV between leads.

ECG signal is much easier to record and measure than the much smaller signals associated with the electroencephalogram (EEG) and other bioelectric measurements.

The pumping cycle of the heart is initiated by electrical impulses generated in a small specialized spot in the right atrium - sinoatrial node (SA node).

It constitutes the natural "pacemaker" of the heart. Data from the nervous system external to the heart can cause the SA node to respond to increased or decreased demand for blood.

In the absence of external information, the SA node has its own rhythm which normally controls the heart rate.

The series of electrical impulses from the SA node can be thought of as self-stimulated action potentials. When an action potential of the SA node has been completed, the SA node spontaneously "fires" again and repeats the sequence.

# Conduction system of the heart

1. The action potential from the SA node is the first step in an electrical conduction process.

2. The SA node stimulates atrial contraction, and the impulses travel to the atrioventricular node (AV node).

3. The consequent depolarization of the AV node causes electrical impulses to travel to the myocardium (heart muscle) via a special conducting system composed of a bundle of fibers known as the bundle of His.

# Conduction system of the heart

4. The conducting system branches to go to the individual ventricle via smaller conducting systems known as the Purkinje fibers. This system provides for simultaneous stimulation of all parts of the ventricles so that they contract sharply for effective pumping action.

The normal heart action is thus dependent upon the generation and conduction of electrical impulses over specified paths within a small time period.

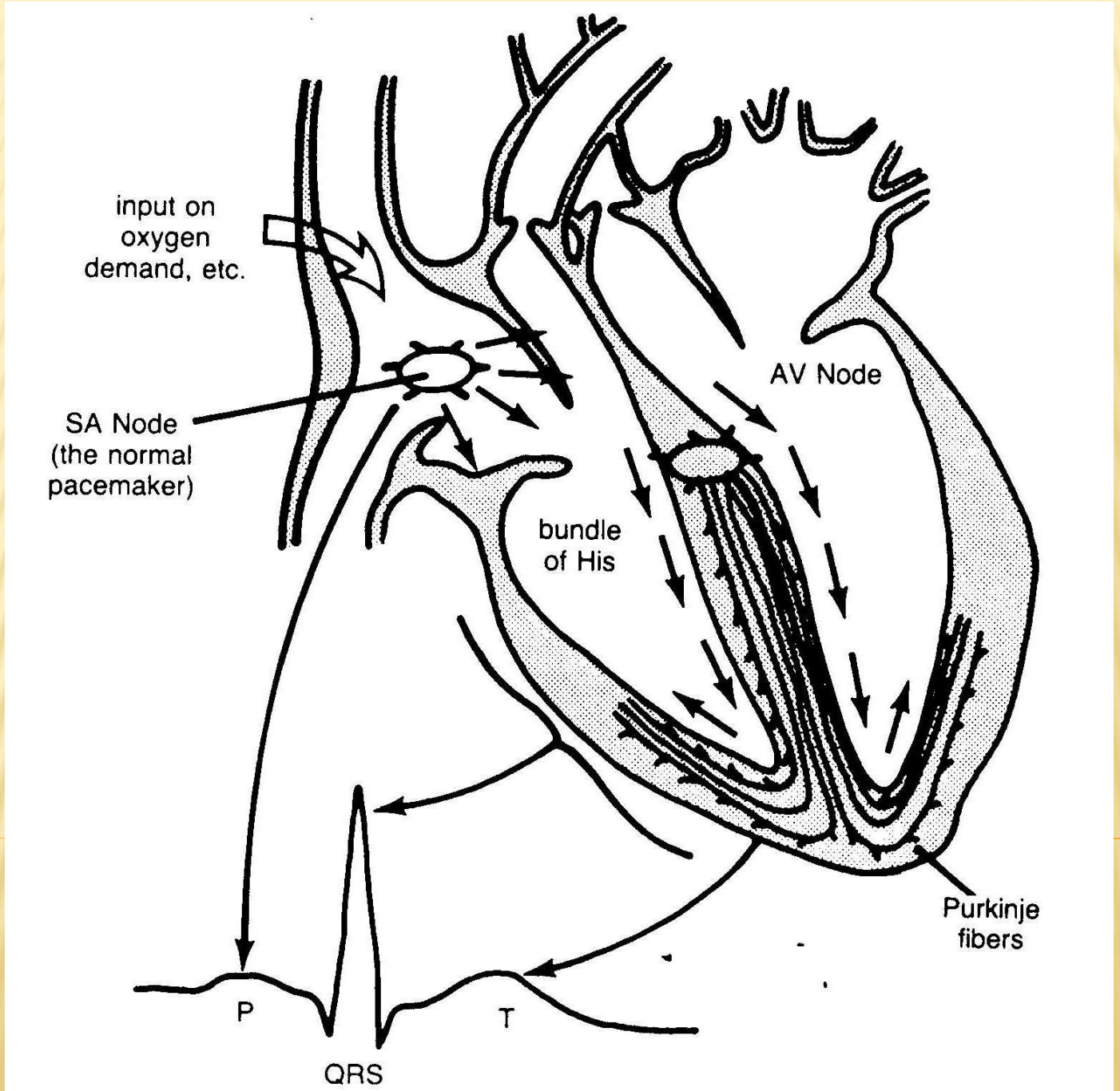
Since these electrical impulses are also conducted to the surface of the skin, the ECG offers a means for monitoring the action of the heart.

The size, shape, and time sequence of the impulses reaching the skin provide a large amount of diagnostic data. The various components of the ECG pattern are labeled **P, Q, R, S,** and **T**.

P wave — associated with the depolarization of the SA node. The resultant action potential normally requires from 120 to 220 ms to travel to the AV node.

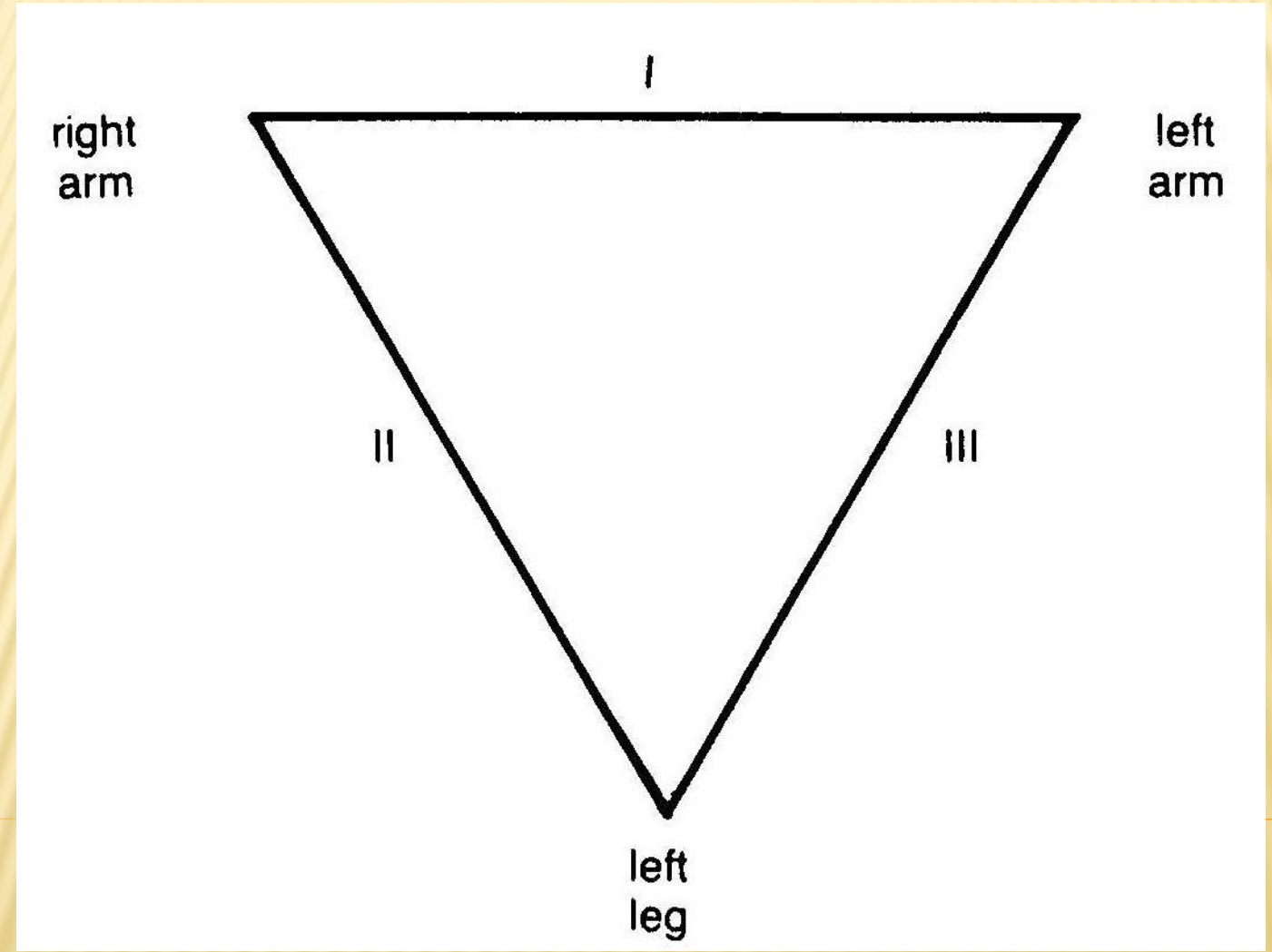
QRS complex — associated with the subsequent depolarization of the AV node and conduction to the ventricles.

T wave — associated with the repolarization of AV node and ventricular conduction system.


input on
oxygen
demand, etc.
SA Node
(the normal
pacemaker)
AV Node
bundle
of His
Purkinje
fibers
P
T
QRS

The usual diagnostic tests use electrodes which make electrical contact with the skin. If the electrodes are placed on the chest, the signals obtained are larger and less likely to have large amounts of electrical "noise" superimposed upon them.

The most common technique involves electrodes on the right and left arms and left leg. These three electrodes form an effective triangle known as the Einthoven triangle. The standard bipolar ECG's are made by measuring the voltage between pairs of these leads. **This gives three standard ECG traces labeled I, II and III.**

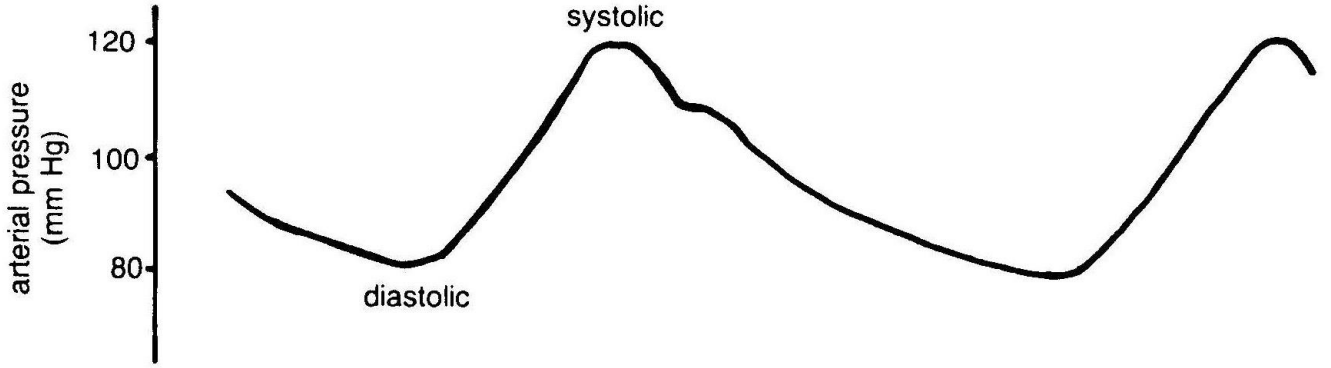

I
right
arm
left
arm
II
III
left
leg

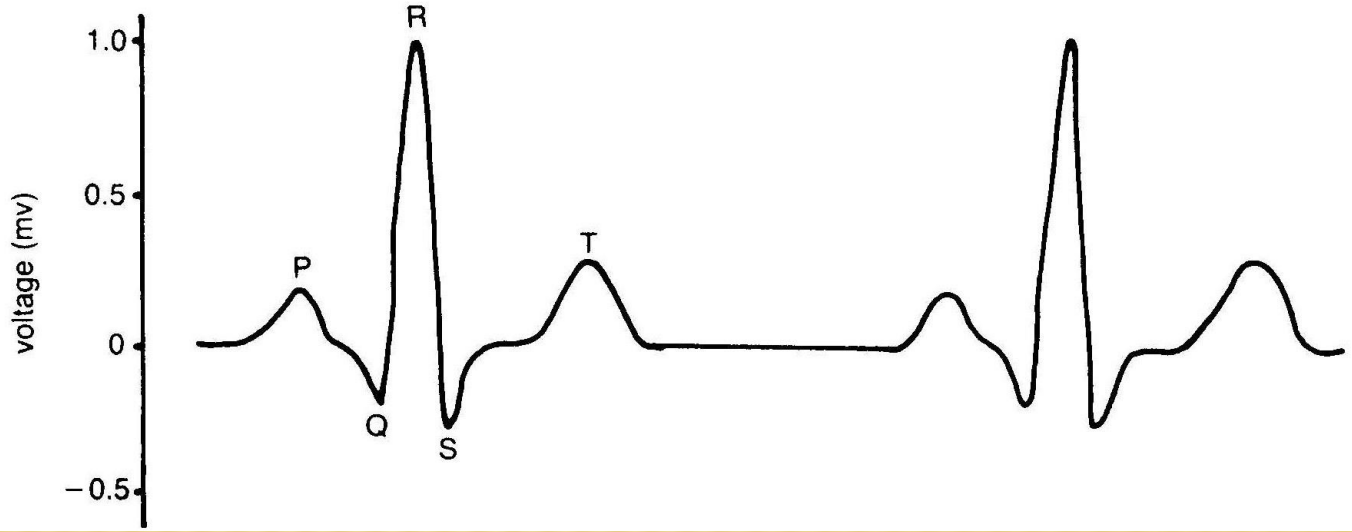
Multiple ECG measurements are made because the transmission of the action potentials in the heart is a directional or vector process.

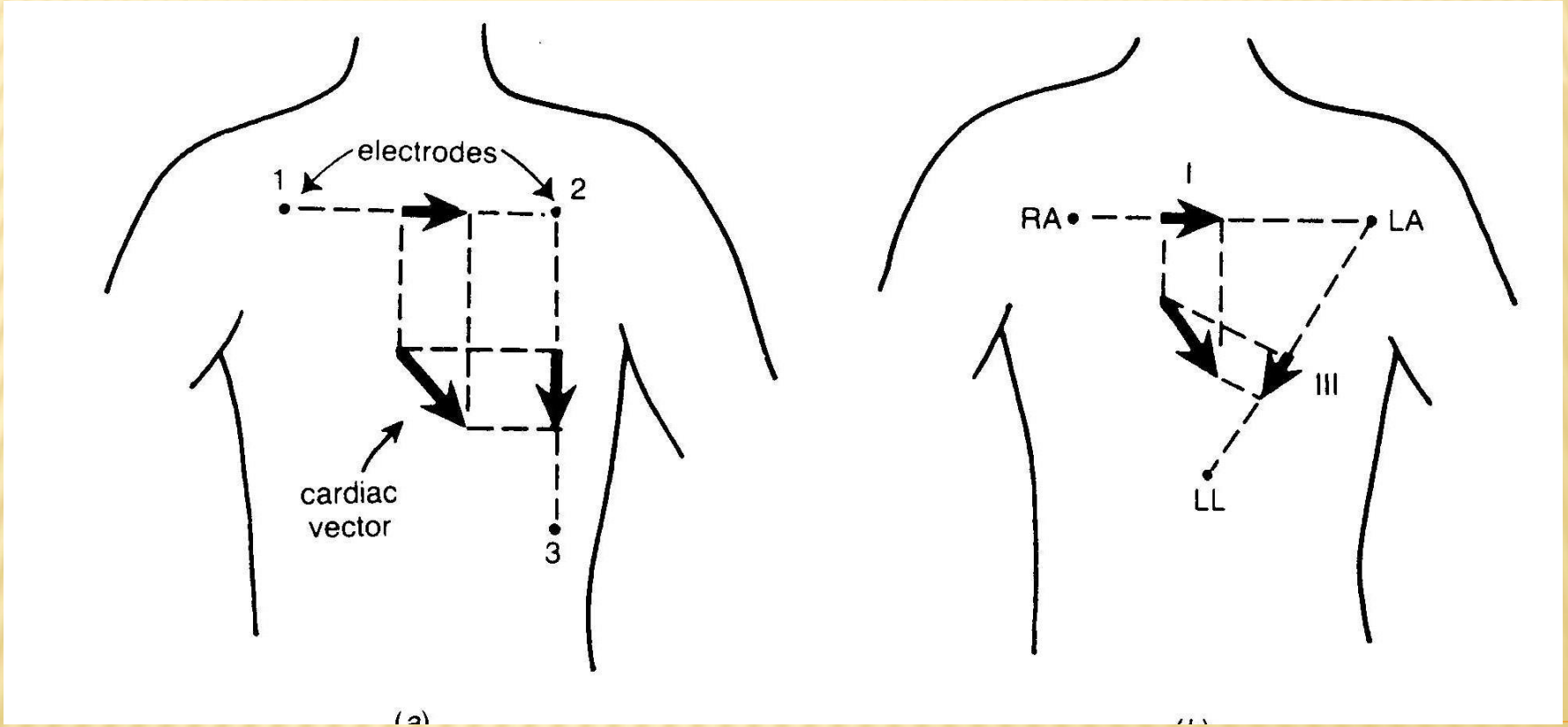
The cardiac vector is associated with the electric field vector produced by the instantaneous charge distribution in the heart during this conduction process.

The measurement of the action potential with a given pair of electrodes gives an indication of one component of the vector.

Two independent measurements yield the components of the vector along two directions, and the orientation and relative magnitude of the vector can be deduced.


systolic
120
100
80
arterial pressure
(mm Hg)
diastolic


R
1.0
0.5
P
T
0
Q
S
−0.5
voltage (mv)


electrodes
1
2
cardiac
vector
3
I
RA
LA
III
LL

# THE ELECTROENCEPHALOGRAM (EEG)

It is a recording of electrical signals produced by the brain.

Electrodes are placed on the scalp. The voltages measured are on the order of 50μV.

The signals must be amplified by factors of several thousand to be recorded. This makes the problems of electrical noise much more severe than with the ECG.

The EEG signals cannot be correlated with specific brain activity as precisely as the ECG pulses can be related to the heart cycle.

The signals are composed of periodic oscillations of varying frequencies. The frequencies are divided into bands.

The alpha waves are associated with the relaxed but alert state.

During sleep the alpha waves decrease, and the presence of delta waves indicates deep sleep. The delta waves are strong and dominant when the patient is in a comatose state.

Further interpretation can be made in terms of the size and shape of the waveforms. The EEG has been of considerable value in diagnosing epilepsy, tumors, certain forms of drug addiction, ect.

# THE ELECTRONIC PACEMAKER

The SA node is the natural pacemaker, but when it is disabled or if the conduction system which carries the stimulating impulses to the ventricles is blocked, the synchronous action of the heart is destroyed.

The artificial pacemaker is a battery-powered device which generates electrical stimuli at a predetermined rate.

Typically these pulses will be on the order of 10 V with duration of a few ms and a repetition rate of 60 to 70/min.

The electrodes make contact with the myocardium, and the arrival of an electrical impulse of sufficient size will cause the entire heart to contract.

More sophisticated pacemakers operate on a standby basis and become functional only if the normal rhythm falls below a certain rate.

The cardiac pacemaker is the most successful example of an artificial implanted device. The pacemaker is implanted subcutaneously in the abdominal region.

The major problem is the provision of a power supply which will last for long periods of time.

Most present pacemakers are powered by small mercury batteries which last 2 to 4 years. When the batteries are exhausted, the pacemaker must be replaced by a surgical procedure.

It would be desirable to have a power source which would last 10 to 20 years. Active research is being carried out to develop a suitable long-lived power source.

The types of power sources which show promise as alternatives to the mercury batteries are nuclear fuel sources, piezoelectric sources, biogalvanic sources, and radio frequency power transmitters.

The nuclear fuel element produces Q at the junctions of a large number of thermocouples which produce the needed voltage.

The piezoelectric sources are powered by crystals, which produce a voltage when subjected to deformation forces. These devices are implanted in positions such that the expansion of the aorta or the heart provides the necessary deformation.

The bio-galvanic sources make use of the fact that body fluids are electrolytes and can form part of a "battery" if suitable electrodes are supplied. The body can supply the necessary energy to operate the source as long as the electrodes of the biogalvanic source remain intact.

Radio frequency (RF) transmitter method - the battery and electronic package are outside the body.

The necessary impulses are generated in the form of high frequency signals which are transmitted to an implanted receiver attached to the cardiac electrodes. This receiver detects the transmitted pulse and applies it to the heart.

Alternatively, the transmitted power can be used to recharge a battery for operation of the pacemaker.

# Review questions

1. How does the electrochemical gradient for sodium ions across the resting cell membrane differ from that for the potassium and chlorine ions ?

2. Once a cell membrane has been stimulated and the sodium influx has started, what causes the potassium ions to start diffusing outward ?

3. After a nerve cell has “fired” or produced an action potential, why is there a waiting period before it can fire again ?

4. How do the action potentials of the heart get to the surface of the skin to produce the electrocardiogram signals ?