

# A TEXT BOOK OF MEDICAL INSTRUMENTS

S. Ananthi



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# **A TEXT BOOK OF MEDICAL INSTRUMENTS**

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## PREFACE

The field of medical diagnostic instruments has developed very well during the past 25 years with the impact the Electronics Engineering has provided to it. Today, more and more of Electronic & Instrumentation Engineering students have taken to work on the development of either better Instruments using the Technology or of new instrumental techniques for better and non-invasive diagnostics. In the U.S.A., graduate students from India are now being taken to work in this area for research projects in the Universities and hospitals. Side by side, medical graduates also are now taking interest in learning about the developments in Electronics so that they can use its components and circuits for making better use in Medical Technology.

Therefore, today, most Engineering graduate and Science post-graduate courses have included the subject in the curriculum. It is now well understood that for a technology researcher to interact with the hospital surgeons and seniors in projects of medical instrumentation, he or she should have a good knowledge of the principles of early-day medical instruments, physiology basics and medical terminology.

This book has therefore subdivided the realm of medical instruments into the same sections like a text on physiology and introduces the basic early-day methods well, before dealing with the details of present-day instruments currently in use. Some principles of diagnosis are also included in order that a new researcher could understand the requirements of the Physician rather than blindly proceed in his developments using his knowledge of circuitry, software and methods of signal processing. Further, medical diagnostic practice has been conservative in preserving the acumen the Physicians have imbibed from their seniors. For example, in the ECG, the very same trace occupying just 2 mm–3 mm with a chart paper is the vital (QRS) component in diagnosis, though, at present, the same information can be presented in a much better time-scale with greater detail. Because ECG diagnosis is still based on this standard record, a researcher intending to produce a new algorithm for a detection of typical pathology (automatically) would need to know the principles of pathological detection from the ECG in current use. That is why, the book has spent some pages on such aspects as well.

After covering the several instruments under the different heads of Physiology, the later-day instruments like the CT scanner, the MRI, Ultrasound and lasers are included. These deserve typically separate volumes on their own, but even here, the essentials are covered both from the medical and technical angles.

Particular importance has been given to safety aspects as has been widely made known through several papers in the IEEE magazines, in a separate chapter. A chapter on possible further developments and another on signal processing examples have been included to the advantage of a medical reader intending to exploit the technological developments.

A final chapter on the use of computers for medical data management and the use of the Web at large concludes the book.

In a book of this kind, meant to be of use for the student who gets himself introduced to medical instruments for the first time, a large number of books, journals and manufacturers'

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material had to be referred to. Today, the subject is growing at a very fast pace and newer methods in surgery and diagnostics are coming up every day. The book could cover only such material as are current and it is up to the reader to keep himself abreast of the developments by looking into the useful journals for example, the IEEE issues. A little work done by the author's own Biomedical and Engineering group has been included in the chapter on New developments.

It is hoped that the book will meet the needs of all these who take to the study of this subject either in a course or for research applications, both in medical and in electronic technology.

I have to express my thanks to my erstwhile Professors. K. Padmanabhan, K. Chandrasekharan and V. Mohan for their guidance. Particularly I wish to express my thanks to my husband Mr. S. Rajendran, to my brother-in-law Mr. S. Udayakumar, to Mr. R. Vijayarajeswaran of VI Microsystems and to Mr. P. Swaminathan for their interaction and help in this preparation. I am to record also the tolerance and appreciation exhibited by my sons R. Pradeep and R. Babu when their mother was found busy spending her time late into the night on her computer for this preparation for quite some months.

**Dr. S. Ananthi**

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# Chapter 1

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## Electrophysiological Measurements

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### 1. INTRODUCTION

From the biological cell, electrical potentials are generated and it is due to the electrolytes inside and outside of the cell. A bioelectric potential may be defined as the difference in potential between the inside and the outside of a cell; there exists a difference in potential existing across the cell wall or membrane. A cell consists of an ionic conductor separated from the outside environment by a semi permeable or selectively permeable cell membrane. Human cells may vary from 1 micron to 100 microns in diameter, from 1 millimeter to 1 meter in length and have a typical membrane thickness of 100 Angstrom units. Bioelectricity is studied both from the viewpoint of the source of electrical energy within the cell and also from the viewpoint of the laws of electrolytic current flow relative to the remote ionic fields produced currents by the cell. We make measurements external to a group of cells while these cells are supplying electrolytic current flow.

#### 1.1. Cell Potential Genesis

Experimental investigations with microelectrodes have shown that the internal resting potential within a cell is approximately  $-90$  mV with reference to the outside of the cell.

$$\text{The equation for resting potential is } e = \frac{RT}{F} \log_e \left( \frac{c_2}{c_1} \right)$$

where  $R$  = Gas constant =  $8.31436$  Joule mole $^{-1}$  deg $^{-1}$

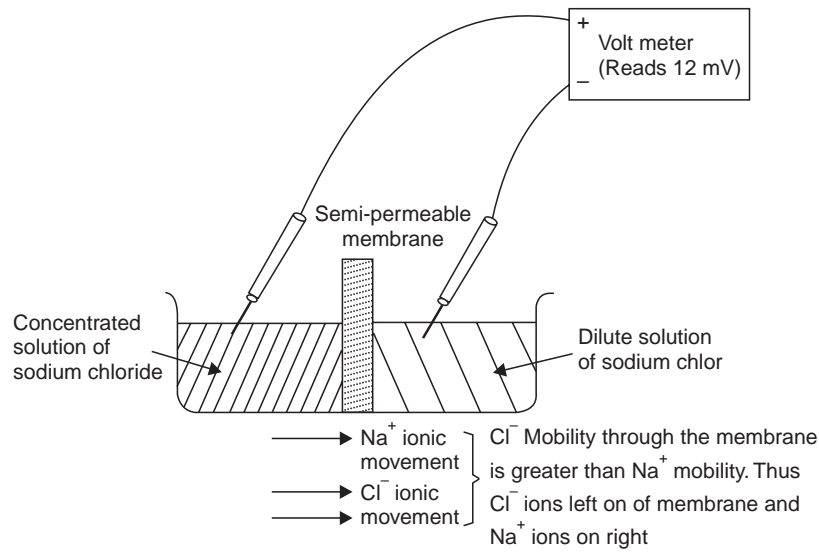
$T$  = Temperature, °kelvin

$F$  = Faraday constant =  $96488$  coulomb/gm-equivalent.

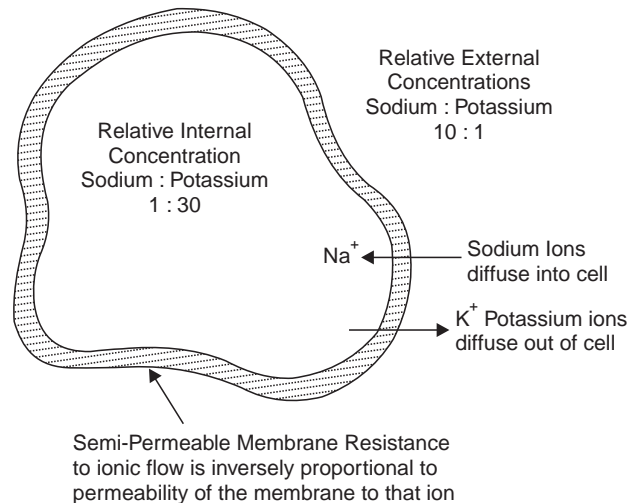
( $c$  means concentration, 1 for inside and 2 for outside.)

This potential changes to approximately  $+20$  mV for a short period during cell depolarisation. Cell activity results from some form of stimulation. The Hodgkin – Huxley excitation by stimulus theory was initially postulated (Nobel Prize winners) during the 1950's. This theory is briefly described as follows :

The interior of a cell primarily contains concentrations of sodium and potassium ions. These concentrations within a cell differ markedly from the concentrations of these ions in the space outside the cells (Fig. 1.1). Elementary ionic theory states that, under suitable conditions, any uneven distribution of ionic concentration in an aqueous solution will result in a potential difference between the regions of different concentration. If, for example, solutions containing unequal concentrations of ions are separated by membrane semi permeable to these ions, a potential will be found to exist (Fig. 1.2).



**Fig. 1.1** Shows the potential generated ionic concentration difference between two solutions.



**Fig. 1.2** Shows typical concentration of sodium and Potassium ions within the cell.

## 1.2. Chemical Gradient

This potential, which is referred to later as the chemical gradient, is given by the Nernst relations : ( $T = 293^{\circ}\text{K}$ )

### 1.2.1. Nernst Relation

$$\text{Potential (mV)} = 61.6 \log_{10} \frac{\text{concentration one side of membrane}}{\text{concentration, other side of membrane}}$$

or for univalent ionic solutions, the Nernst relation simplifies to :

$$\text{Potential (mV)} = 61.6 \frac{U - V}{U + V}$$

where  $U$  = Mobility of the negative ions (anions) through the membrane

$V$  = Mobility of the positive ions (cations) through the membrane

Referring to Fig 1.2, for a 10 : 1 activity (concentration) ratio at 37°C, the relative mobilities of chloride and sodium ions are 65.4 and 43.6 respectively. Applying these values to the Nernst relation gives :

$$\text{Potential (mV)} = \frac{65.4 - 43.6}{61.6 \times 65.4 + 43.6} = 12 \text{ mV}$$

This can be confirmed with a voltmeter as shown in Fig. 1.2. This potential will, of course, run down as diffusion proceeds, unlike that of a living cell.

### 1.3. Net Gradient

The ionic current produced by ion movement through a semi-permeable membrane depends on the permeability of the membrane and also on the “gradient” that forces the ion through the membrane. This gradient, referred to as the net gradient, consists of both a chemical gradient and an electrical gradient. A chemical gradient is formed due to a difference in concentration producing a potential gradient as given by the Nernst relation. An electrical gradient is formed as a result of a potential that may exist across the membrane due to some other source.

### 1.4. Cell Concentrations

Experimental investigation have shown that a marked difference in concentrations of both sodium and potassium ions exists across a cell membrane. In mammalian nerve cells as shown in Fig. 1.1. the concentration of potassium ions is in the vicinity fluid external to the cell. On the other hand, sodium ions are approximately 10 times more concentrated in the fluid external to the cell than in the fluid within the cell.

### 1.5. Cell in Resting State

Consider a cell in its resting or polarized state (Fig 1.3a). In this state the membrane is moderately permeable to potassium ions, that is, potassium ions can pass fairly readily through the membrane as the membrane offers medium resistance. This membrane is, however, almost impermeable to sodium ions and, thus, offers a high resistance to the passage of these ions. A large net gradient affects the movement of sodium ions into the cell. This net gradient consists of a chemical gradient produced by the 10 to 1 concentration difference between sodium ions on each side of the membrane and a 90mV electrical gradient produced by the standing potential within cell.

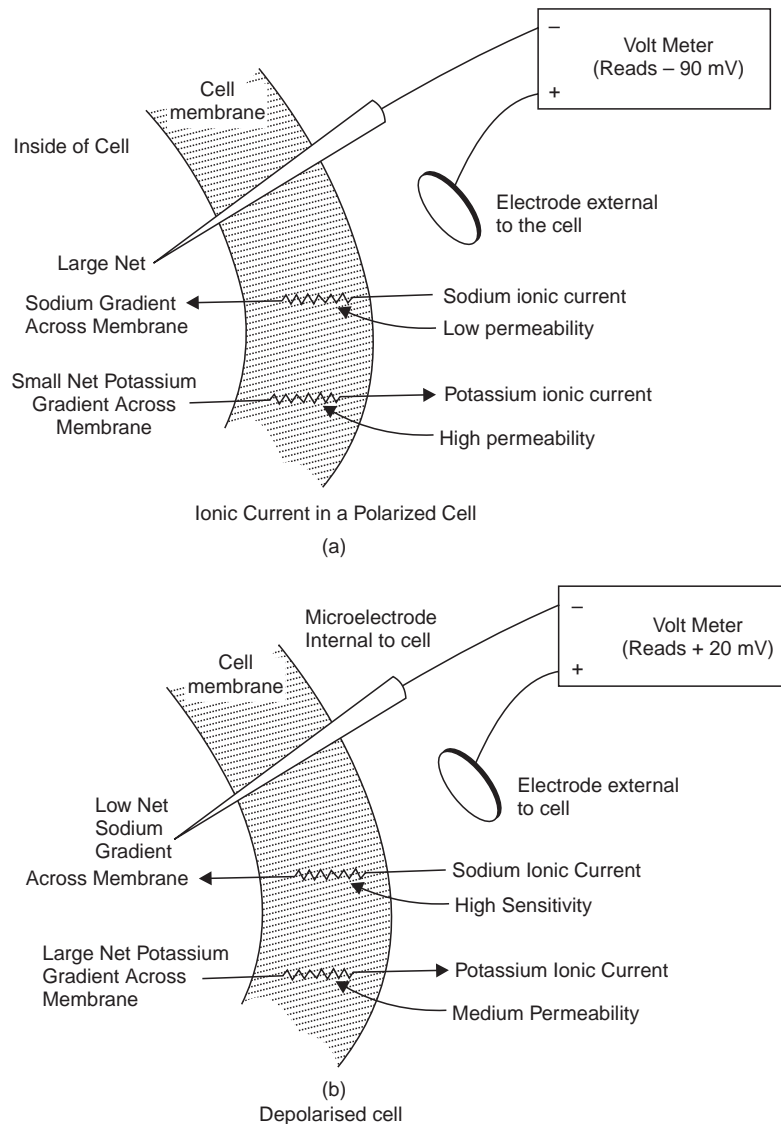


Fig. 1.3

### Net Gradient

The net gradient affecting the movement of potassium ions out of the cell is considerably less than the net sodium gradient. This gradient consists of a large chemical gradient due to the 30 to 1 concentration difference across the membrane; however, this chemical gradient is opposed by the electrical gradient produced by the 90 mV standing potential within the cell. Thus, although the membrane is almost impermeable to sodium ions, the net sodium gradient is high. Conversely, although the membrane is moderately permeable to potassium ions, the net potassium gradient is low. The net result is that the sodium and potassium currents are equal; the sodium current balances the potassium current with a resultant current of zero. Since the net current through the membrane is zero, the cell's internal potential will not change and will remain at its -90 mV resting level.

Indeed, this  $-90$  mV resting level is determined by the internal cell potential required for sodium and potassium current balance.

### Cell Condition after a Stimulus

If the cell receives a stimulus from an outside source, the characteristics of the membrane at the point of stimulation will change and, thus, the ionic currents will also change. After stimulation, the membrane permeability to potassium ions is unaltered but the permeability to sodium ions is increased. A much lower resistance is offered to the flow of sodium ions, thus increasing the sodium ionic current. This increased sodium ionic current causes more positive ions to pass into the cell than are passing out of the cell, causing the internal cell potential to drop from  $-90$  mV in an attempt to achieve sodium current and potassium current balance.

### Cell Depolarization

As this potential decreases, the net sodium gradient across the membrane decreases and the net potassium gradient across the membrane increases, causing the currents to decrease and increase, respectively. This process continues until current balance is again obtained, at which time the internal cell potential is  $+20$  mV. The cell is then referred to as being in a depolarized state.

### Cell Repolarization

By the time the cell has fully depolarized the characteristics of the membrane have begun to revert back to their pre-stimulus state. This causes the sodium ionic current to be considerably lower than the potassium ionic current ; the internal cell potential thus begins to go negative with the process continuing until the  $-90$  mV resting potential of the cell is once again obtained.

### Electrical Analog of the Cell

An electrical analogy to a cell membrane is shown in Fig. 1.4. This circuit cannot strictly be referred to as an equivalent circuit as the electronic current flow in an electrical circuit and the ionic current flow through a cell membrane cannot be said to be equivalent. After assigning resistance values inversely proportional to the relative permeability of the membrane and assuming potassium and sodium concentration ratios, then the intracellular potential for both a polarized cell and a depolarized cell can be determined. The values assumed are analogous to actual values found in a cell.

Assume :

Relative values for  $R_K$ ,  $R_{Na}$  and  $R_D$  are 1 K, 150 K and 0.35 K respectively.

Potassium ion concentration ratio of 30 : 1 inside to outside.

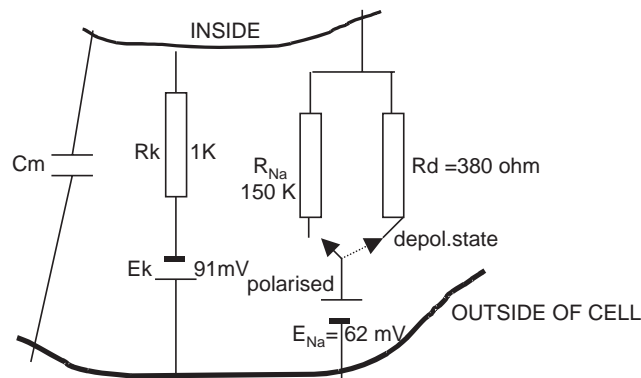
Sodium ion concentration ratio of 10 : 1 outside to inside.

Then,

$$E_k = 61.6 \log \frac{30}{1} = 91 \text{ mV} - \text{by Nernst relation}$$

$$E_{Na} = 61.6 \log \frac{10}{1} = 62 \text{ mV} - \text{in opposite polarity to } E_k - \text{Nernst}$$





**Fig. 1.4.** The Electrical analog circuit of the membrane is shown.  $C_m$  = membrane capacitance,  $E_{Na}$ ,  $E_k$  are the Sodium potassium Nernst potentials,  $R_k$ ,  $R_{Na}$ , the permeability of membrane to K and Na ions flow through membrane,  $R_d$  is the permeability of membrane to Na ion flow in depolarizing condition.

For a polarized cell :

$$\text{Net potassium current} + \text{net sodium current} = 0$$

$$\frac{\text{Net potassium gradient}}{R_k} + \frac{\text{net sodium gradient}}{R_{Na}} = 0$$

$$\frac{\text{Potassium Chemical gradient} + \text{Potassium Electrical gradient}}{R_k}$$

$$+ \frac{\text{Sodium Chemical gradient} + \text{Sodium Electrical gradient}}{R_{Na}} = 0$$

$$\frac{E_k + E_c}{R_k} + \frac{-E_{Na} + E_c}{R_{Na}} = 0$$

$$\frac{91 \times 10^{-3} + E_c}{1 \times 10^3} + \frac{-62 \times 10^{-3} + E_c}{150 \times 10^3} = 0$$

Solving

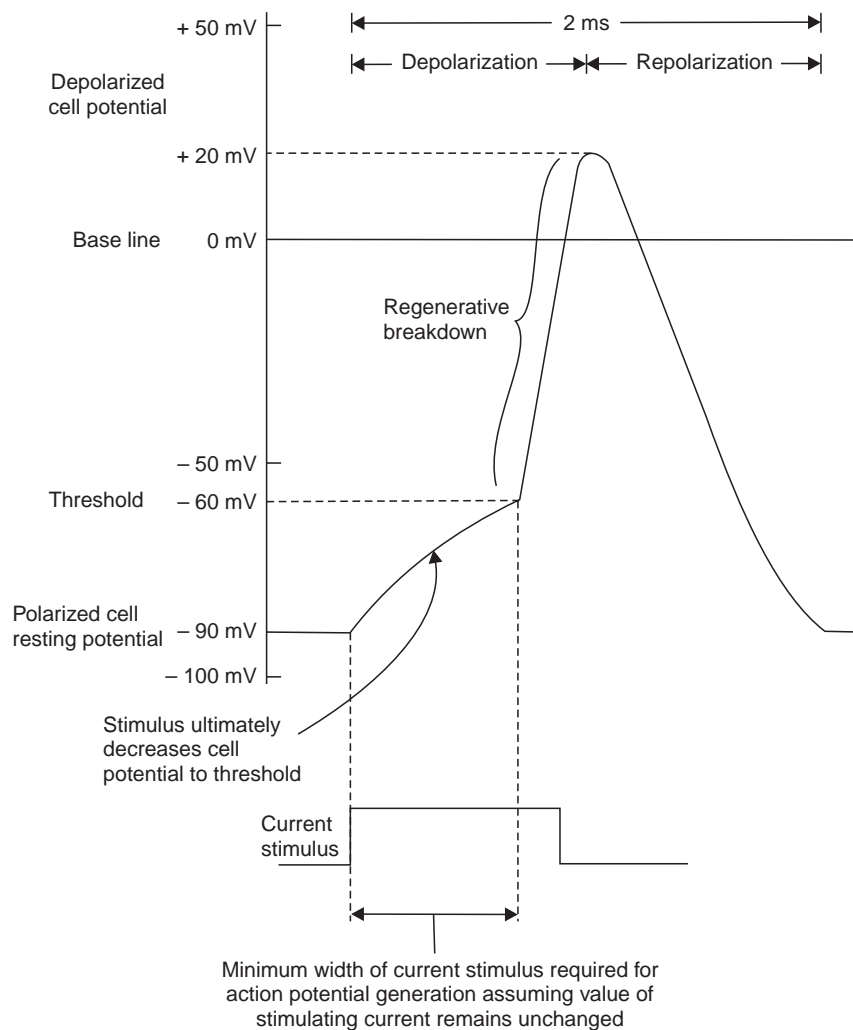
$$E_c = 90 \times 10^{-3} = -90 \text{ mV (polarized)}$$

Similarly, for a depolarized cell,  $R_{NA}$  is replaced by  $R_D$  (0.35 K)

$$E_c = +20 \text{ mV (Depolarized)}$$

## 1.6. Action Potential from a Cell

Suppose a microelectrode were inserted into the cell as shown in Figs. 1.3a and 1.3b and a stimulus were applied to the cell, the output of the microelectrode would appear as shown in Fig. 1.5. this waveform is known as the "Cell action potential". It should be noted that the currents involved in bioelectricity are unlike the currents involved in electronics. Bioelectric currents are due to positive and negative ion movement within a conductive fluid. As these ions possess finite mass and encounter resistance to movement within the fluid their speeds are limited. The cell action potential, thus, shows a finite "rise time" and "fall time".



**Fig. 1.5.** Shows the Cell action Potential (Internally recorded with Micro-electrode).

### Sodium Potassium Pump Phenomenon

The ionic concentration gradient across the cell membrane is maintained by virtue of metabolic energy expended by the cell in “Pumping” ions against the ionic gradient formed by the differing ionic concentration between the inside and outside of the cell. This action has been referred to as the “Sodium – potassium pump”.

### Threshold of Stimulus Causing Action Potential

A cell may be stimulated, or caused to depolarize and then repolarize, by subjecting the cell membrane to an ionic current. This current may be produced by other cells, it may be produced by ionic currents existing as nerve impulses, or it may be artificially produced by some external current stimulus. A cell will be stimulated when sufficient positive ions are added to the inside of the cell to cause its resting potential to be decreased from its - 90 mV level to approximately - 60 mV. Once this threshold level is reached, the cell depolarizes without

requiring the addition of any further positive ions to the inside of the cell from the stimulus source. Unless a stimulus above a certain minimum value is received, known as the stimulus threshold, the cell will not be depolarized and no action potential will be generated. The stimulus required to exceed the threshold, the threshold may be exceeded by a short, high – current pulse or by a longer, lower – current pulse .

### **Refractory Period after excitation**

Since the energy associated with the action potential is developed from metabolic processes within the cell itself and not from the stimulus, a finite period of time, known as the refractory finite period of time, known as the refractory period, is required for metabolic processes within the cell to return the cell to its pre-stimulus state. This refractory period has been observed in most cells found in the nervous system. This refractory period has two parts : The first in which no stimulus, however strong, will cause depolarization (the absolute refractory period) and the second when depolarization occurs only if the stimulus is of more than normal threshold strength (the relative refractory period).

## **1.6. The Resultant Externally Recorded Action Potential**

We have previously discussed the depolarizing and repolarizing action of cells and the resulting potential existing within the cell. As stated earlier, this potential may be recorded with a microelectrode ; however, in most bioelectric measurements, this potential is recorded by electrodes external to the actual cell.

### **External Electrodes**

These external electrodes typically would record the net action of many hundreds of cells, but for the time being, we will consider only a single cell. When recording with external electrodes, an action potential is produced between these electrodes during periods of current flow ; that is to say, no potential exists when cells are either in their depolarized or repolarized state. A potential exists only while the cell is changing from one state to another. As the external action potential is generated by the external current that flows during cell activity, the shape of the action potential is related to the variation of this current with time.

### **External Action Potential**

The external potential field rises to its maximum value sometime during the regenerative breakdown phase of the membrane. The external action potential that is recorded from the cell is somewhat similar to a mathematical time derivative of the trans-membrane potential. This potential is detected with maximum amplitude when one electrode is placed as near as possible to the active area and the other electrode is located in a completely inactive or remote area. It is detected with reduced amplitude as the electrodes are placed closer to each other so they intercept smaller elements of potential difference.

### **Depolarization Current**

In a single polarized cell, the inside of the cell is negative with respect to the outside environment, which may be regarded as a reference. As stated previously, the net ionic current flow across the membrane is zero; thus, ionic current flow to and from the cell is zero. If these conditions are altered due to the presence of a stimulating current through the cell membrane,

then regenerative membrane breakdown will occur and the cell will depolarize. During the depolarization process the net current through the membrane is not zero; there is a net positive ionic current into the cell through the cell membrane. This current may be detected as a potential difference between two electrodes placed in the vicinity of the cell with the potential difference being produced across the finite resistance of the fluids external to the cell.

This current continues until the cell is fully depolarized, thus, the potential will appear between the two electrodes while the cell is undergoing depolarization. For the short time that the cell exists in a depolarized state, the net current through the membrane is once again zero, thus, no potential will appear between the electrodes.

### **Repolarization Current**

Almost immediately after depolarization, the cell begins to repolarize again. During repolarization, positive ionic current flows from the cell membrane, that is, in the opposite direction to ionic current flow during depolarization. During this period of current flow, a potential will be detected between the electrodes and, since this current is in the opposite direction to the depolarization current, the potential produced between the electrodes during repolarization will be of the opposite polarity to the potential produced during depolarization. The area included by the depolarization and the repolarization potential waveforms is the same since the quantity of current involved in each process is the same. It should be noted that the process described above is somewhat theoretical as it describes the external action potential generated by single cell. In the following discussion we show that single cell depolarization invariably results in depolarization of the adjacent cells and, hence, this externally recorded action potential will be the net summation of the results obtained from these cells.

## **1.7. Externally Recorded Action Potential from a Group of Cells, the Travelling Wave of Depolarization**

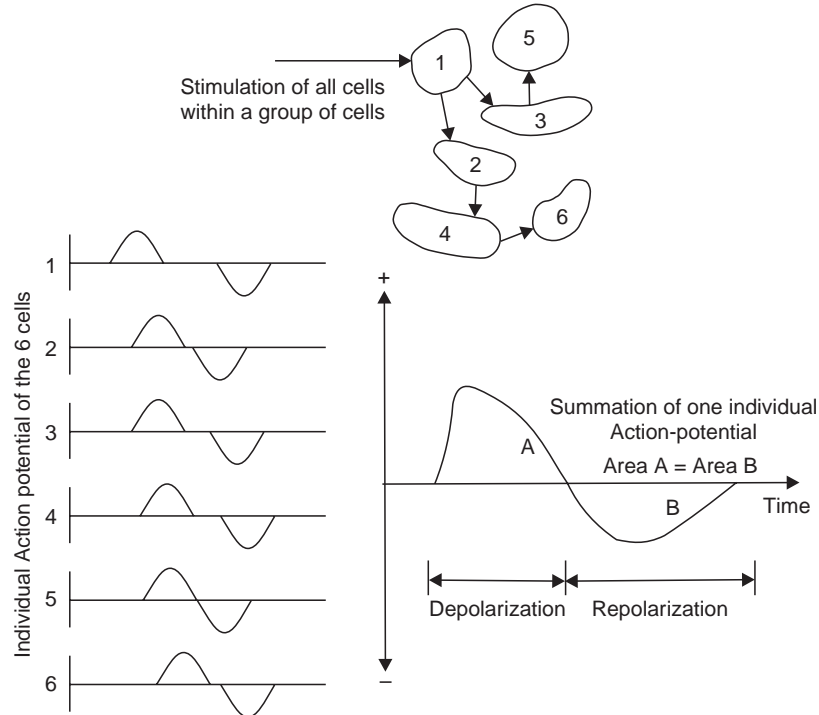
### **Synchronous Depolarization**

The preceding discussion must be modified to allow for many cells in close proximity to one another and to allow for the appreciable length of many of these cells. Consider a group of cells in close proximity to one another, under certain conditions of stimulation, these cells may all depolarize at the same time (synchronous depolarization) ; however, the repolarization process is random. Repolarization of the individual cells will occur at different times. The resultant externally recorded action potential is shown in Fig 1.6. Once again the area included under each wave is the same since the quantity of current involved in each process is the same.

### **Asynchronous Depolarization**

Under other conditions of stimulation, the group of cells described previously will not all depolarize at the same time (asynchronous depolarization). The stimulation may result in one cell depolarizing; the action of this cell depolarizing will then act as a stimulus on its adjacent cell causing it to depolarize also. This chain reaction would proceed until all cells in a particular area have depolarized. The resultant externally recorded action potential would appear as shown in Fig 1.6. In practice, combinations of synchronous and asynchronous depolarization occur in a group of cells.

### Travelling wave within cells



**Fig. 1.6.** Shows the stimulation is not synchronous and the potential externally seen.

In the same way as the depolarization of one cell causes adjacent cells to depolarize, depolarization of a localized area of an individual cell will cause depolarization of other parts of the same cell. Thus, the depolarization process will appear to travel along the length of the cell causing a travelling wave of depolarization as shown in Fig. 1.8.

As most bioelectric potentials are recorded as external cell action potentials, the results obtained are a summation of the action of many cells. The action potential wave form may be modified by the number of cells, the shape of these cells, and the type of stimulation applied.

The cell already passing a wave cannot respond to a second stimulus – it has become refractory. But there is a variation in excitability, as at point 3 units in time, a smaller response can depolarise once again, while at a point in time  $t_4$ , a greater stimulus is required.

The experiments on action potential measurement are usually done on the Squid's axon, which is a large nerve fiber. It is originally called a 100 micron axon. Its action potential varies from  $-45$  to  $+40$  mV.

For the Frog's skeletal muscle fiber, it is from  $-92$  to  $30$  mV. A contraction follows the wave.

Cardiac muscle of frog has a  $-55$  mV to  $+25$  mV change, and recovery is prolonged in any cardiac muscle. The top is flat almost.

Inside to outside, the concentration of  $\text{Na}^+$ ,  $\text{K}^+$  and  $\text{Cl}^-$  ions vary in a nerve cell.

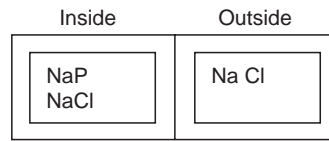


Fig. 1.7

The membrane is permeable to Na,Cl but not to Proteins. Therefore, the concentration of Na is greater than in the inside.

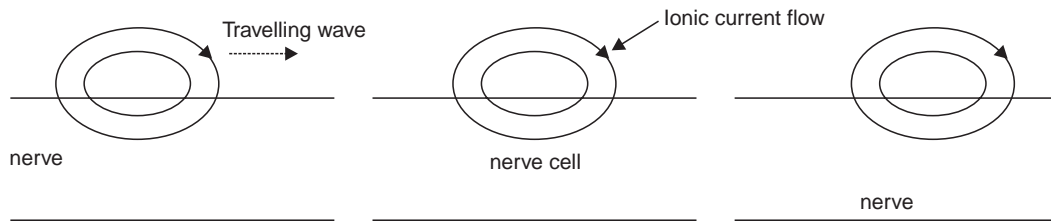


Fig. 1.8 Showing Electro-tonic conduction as a traveling wave down the nerve.

### Nernst Planck Equation

Consider the current flow (in A/s. cm) for diffusion, electrical conduction one by one.

$$J_{\text{diff}} = -DVC$$

$D$  = diffusion coefficient,

$\nabla C$  = concentration gradient

$$J_{\text{elec}} = -uzeC \nabla\phi$$

$u$  = elec. Field mobility of ion

$= v/\nabla\phi$  = velocity/elec. field

$z$  = valency of ion,

$\nabla\phi$  = field Electric.

The ionic current totally is

$$\text{So, } J_{\text{ion}} = -D\{\nabla C + (uzeC/D) \nabla\phi\}$$

Using Einstein relation

$$D = ukT \quad k \text{ being Boltzmann's constant,}$$

$$J_{\text{ion}} = -D \left\{ \nabla C + \frac{zeC}{kT} \nabla\phi \right\}$$

$$J_{\text{ion}} = -D \left\{ \nabla C + \frac{zFC}{RT} \nabla\phi \right\} \quad (\text{F is Faraday constant})$$

$$R = kL \quad \text{where L is Avogadro no.}$$

Faraday is defined as  $F = eL$ .

$e$  is electronic charge and  $F$  is in Coulombs.

The above equation is known Nernst Planck Equation. Using this only, the equation of the wave of action potential can be obtained.



**Donnan Equilibrium.** We get the steady state or Donnan Potential. When current  $J = 0$ .

$$J = 0 \text{ So, } \nabla\phi = -\frac{RT}{ZF} \nabla \log (C)$$

Integrating,  $E_{\text{Don}} = \phi_{\text{I}} - \phi_{\text{II}}$

where the I and II denote the inside and outside of the cell.

This is nothing but the potential difference across the cell membrane.

Thus, for Pottassium ions,

$$E_{\text{Don K}} = RT/F \log \{K_{\text{I}}/K_{\text{O}}\}$$

At rest state, this is equal to the chloride ion resting potential of  $RT/F \log (Cl_{\text{I}}/Cl_{\text{O}})$   
 $RT/F$  was what was stated earlier as 61.6 mV.

In amphibian muscle cells,

$$[K]_{\text{I}}/[K]_{\text{O}} = [Cl]_{\text{O}}/[Cl]_{\text{I}} \cong 50.$$

$E_{\text{rest}} - 99$  mV, while actual measurement gave 80 to 100 mV.,

But, if for Na+ ion,  $E_{\text{Don}}$  is calculated, it is not in agreement. So, the Sodium pump is a metabolic action of push out.

As per  $[Na_{\text{O}}]/[Na_{\text{I}}] = 10$ , we get

$$E_{\text{Don Na}} - 60 \log 10 = + 58 \text{ mV, which is not true.}$$

#### Permeabilities of ions

From measured values of V for varying outside concentrations, Hodgkin and Katz found

$$P_{\text{K}} : P_{\text{Na}} : P_{\text{Cl}} = 1 : 0.04 : 0.45$$

Keynes found  $P_{\text{K}} : P_{\text{Na}} = 1:0.013$  using influx and efflux measurements.

$$V = \{RT/F\} \log \frac{P_{\text{K}}C_{\text{Ko}} + P_{\text{Na}}C_{\text{NaO}}}{P_{\text{K}}C_{\text{Kin}} + P_{\text{Na}}N_{\text{Nain}}}$$

$$= -90 \text{ mV which agrees with the value of measurements.}$$

It is noted that in the above, Keynes [1951] assumes  $Cl^{-}$  is in equilibrium and does not enter calculations.

#### Electrotonus-Longitudinal Spread of Current in Nerve Fibres

The resting nerve cell membrane resistance is 1000 ohm/cm<sup>2</sup>, while the capacitance is around 1 μF/cm<sup>2</sup>.

If  $r_1$  and  $r_2$  are external and internal fluid resistances per unit length,

$$\begin{aligned} \frac{\partial V_1}{\partial x} &= -r_1 i_1 \\ \frac{\partial V_2}{\partial x} &= -r_2 i_2 \\ V_1 - V_2 &= -Z_m i_m \end{aligned}$$

If there is no current flow in this system,

$$i_1 + i_2 = 0$$

$$\partial i_1 / \partial x = - \partial i_2 / \partial x = i_m, \text{ the trans-membrane current.}$$

And

$$\partial^2 V / \partial x^2 = - (r_1 + r_2) i_m$$

Also

$$V = V_1 - V_2$$

$$i_3 = - C_m \partial V / \partial t$$

$$i_4 = (E - V) / r_4$$

$$i_3 + i_4 = i_m$$

$$= - C \partial V / \partial t + (E - V) / r_4$$

$$\partial^2 V / \partial x^2 = - \frac{(r_1 + r_2)}{r_4} \{E - V - r_4 C_m \partial V / \partial t\}$$

The characteristic length is defined by  $\lambda = \sqrt{r_4 / (r_1 + r_2)}$

And

$$\tau_{\text{memb}} = r_4 C_m \text{ which is a time constant.}$$

Therefore we get

$$\lambda^2 \partial^2 V / \partial x^2 - \tau_m \partial V / \partial t - V = - E$$

If the above is expressed in a moving co-ordinate system,  $y = x - vt$ , we get

$$\lambda^2 d^2 V / dy^2 + v \tau_m \partial V / \partial y - V = - E$$

$$E - V = e \text{ or } v = E - e$$

$e$  = voltage spread from the active area

$$\lambda^2 \partial^2 e / \partial y^2 - \tau_m \partial e / \partial y - e = 0$$

Except at  $y = 0$ ,  $\lambda$  is a constant.

So,

$$e = e_0 \exp(-y / \lambda_a)$$

Here,  $\lambda_a$  is a space constant and  $\tau$  is a time constant for the wave.

Current of conduction in the nerve falls off exponentially with distance from the edge of the (stimulated) active region.

For

$$\tau^2 v^2 / \lambda^2 \gg 4, \text{ (nerve and muscle fibres)}$$

$$e = e_0 \exp[-t / \lambda_a]$$

$$\lambda_a = \lambda^2 / \tau^2 v^2 = 1 / v^2 C_m (r_1 + r_2)$$

The critical period is the period of latent addition, which is maximum interval between successive sub-threshold stimuli to cause excitation.

## EXERCISE

1. Assuming that the net flow of ionic change in an action potential goes up only to charge the membrane capacitance ( $C = 1 \mu\text{F}/\text{cm}^2$ ) calculate the net micro moles transferred per unit action potential rising from  $-50$  mV to  $+65$  mV.

The change transferred	$Q = CV = 1 \times 10^{-6} \times (115 \times 10^{-3})$
	$= 115 \times 10^{-9} \text{ C/cm}^2$
The no. of. Coul. per mole	$= 9.65 \times 10^4$
Micromoles transferred	$= ((115 \times 10^{-9} \text{ C/cm}^2) / (9.65 \times 10^4 \text{ C/cm}^2))$
	$= 1.2 \text{ Moles}$

2. Calculate the change in concentration due to the entry of  $3\mu\text{M/cm}^2$  of Na into an axon 500 microns as a fraction of the initial concentration, which is  $50\mu\text{M/cc}$ .

$$\Delta C_{\text{Na}} = (3 \times 10^{-12} \times d) / (d^2/4)$$

$$= 12 \times 10^{-12} / d \quad (d \text{ is in cm}).$$

$$d = 500\mu = 500 \times 10^{-4} \text{ cm}.$$

therefore

$$\Delta C_{\text{Na}} = 1.4 \times 10^{-10} \text{ moles/cc}$$

$$\Delta C_{\text{Na}} / C_{\text{Na}} = 1.4 \times 10^{-10} / 50 \times 10^{-6} = 3 \times 10^{-5}$$

Note that is why a huge number of action potentials can be elicited.

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## *Chapter 2*

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### **Electrocardiography**

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#### **INTRODUCTION**

This chapter covers some of the more common measurement techniques used in the medical diagnostics. It is intended to give both Medical and Engineering oriented basis for developing measuring techniques in physiological field. But this covers more of the Engineering aspects that have been employed in most of the medical equipment. The Electrocardiogram and electrocardiograph will be dealt in this chapter.

Generation of electrical activity within the heart is discussed in this chapter. Electrocardiography (ECG) is the art of analyzing this electrical activity by measuring potentials at the surface of the body resulting from this electrical activity within the heart. This is achieved by applying electrodes to certain positions on the body and recording the potentials generated between various combinations of these electrodes with an amplifier and CRT display or strip chart recorder.

#### **ELECTROCARDIOGRAPHIC PLANES**

The heart can be regarded as an electrical generator enclosed in a volume conductor, the torso. As this electrical generator is completely enclosed by the torso, a direct measurement of the generator output is impossible without resorting to surgery. The electrocardiographer measures the potential existing between various points on the surface of the volume conductor and uses the information obtained to determine the clinical condition of the heart. The measurement can be carried out in three different planes as discussed below.

1. The Frontal plane
2. The transverse plane and
3. Sagittal plane

These various planes are shown in Fig. 2.1.

The projection of the cardiac potential is referred to as electrocardiogram (abbreviated as ECG). Various techniques are used to measure the projection of the cardiac potential along axes existing on each of the three planes.

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