When the passage of sodium ions is stopped, the ionic currents that lowered the barrier to sodium ions are no longer present and the membrane reverts back to the original (polarised) condition. By the action of sodium pump, the sodium ions are quickly transported to the outside of the cell and the cell is in its resting potential. Generally in nerve and muscle cells repolarisation occurs so rapidly following depolarisation that the action potential appears as a spike of as little as 1 millisecond total duration. But for heart muscle, the action potential is withstanding from 150 to 300 milliseconds and so it repolarizes much more slowly. Figure 1.2 shows the waveform of the action potential.

In a tissue the depolarisation disturbance of one cell is propagated to the next until the entire tissue depolarizes. In muscle, where cells are situated in an orderly manner, a time delay of 10 milliseconds between the action potential depolarisation and the subsequent muscle twitch as shown in figure 1.2 is observed.

Regardless of the method of excitation of cells or the intensity of the stimulus, which is assumed to be greater than the threshold of stimulus, the action potential is always the same for any given cell. This is known as the ***all-or-nothing law.*** A stimulus voltage generally does not affect a cell while it is changing its polarisation. Following the generation of an action potential, there is a brief period of time during which the cell cannot respond to any new stimulus. Thus the ***absolute refractory period*** is the time duration of cell nonresponse to further stimuli. It is about 1 millisecond in nerve cells. Following the absolute refractory period, there occurs a ***relative refractory period*** during which another action potential can be triggered but a higher stimulus is required to reinitiate an action potential and the subsequent contraction of muscle. In nerve cells, the relative refractory period is several milliseconds. The rate at which an action potential moves down a fiber of a nerve cell or is propagated from cell to cell is called the propagation rate or conduction velocity. The conduction velocity varies in nerves depending on the type and diameter of the nerve fiber and is from 20 to 140 m/s. But in heart muscle, it is very slower ranging from 0.2 to 0.4 m/s.

1.6 BIO-ELECTRIC POTENTIALS

As a consequence of the chemical activity in the nerves and muscles of the body, a variety of electrical signals are generated. For example, the heart and brain produce characteristic patterns of voltage variations. Bio-electric potentials are generated at a cellular level. That is, each cell is a minute voltage generator. Because positive and negative ions tend to concentrate unequally inside and outside the cell wall, a potential difference (resting potential) is established and the cell becomes a tiny biological battery.

In the normal resting state of the cell its interior is negative with respect to the outside. When the cell "fires" however, the outside of the cell becomes momentarily negative with respect to the interior. A short time later, the cell regains the normal state in which the inside is again negative with respect to outside. This "discharging" and "recharging" of the cell known as depolarisation and repolarisation respectively produces the voltage waveforms of interest to the clinician and biomedical engineer. Table 1.2 shows the various bioelectric signals, their frequency and voltage picked up by the respective electrodes.

1.5 RESTING AND ACTION POTENTIALS

The diffusion and drift processes give rise to membrane potential. The various ions seek a balance between the inside and outside of the cell by diffusion and drift. But the membrane of excitable cells, such as nerve and muscle cells, readily permits the entry of potassium and chloride ions while it effectively blocks the entry of sodium ions. For example the permeability of sodium ions is about 2×10^{-8} cm/s and for potassium and chloride ions, that are 2×10^{-6} cm/s and 4×10^{-6} cm/s respectively. Due to difference in the permeability of different ions, the concentration of sodium ions inside the cell becomes much lower than the outside the cell. Since the sodium ions are positive, the outside of the cell is more positive than the inside.

Similarly the concentration of potassium and chloride ions is more inside than the outside. Thus the charge balance is not achieved. However an equilibrium is reached with a potential difference across the membrane such that negative on the inside and positive on the outside. This membrane potential caused by the different concentration of ions is called the ***Resting potential*** of the cell.

Characteristics of Resting Potential

1) The value of resting potential is maintained as a constant until some kind of disturbance upsets the equilibrium.
2) It is strongly depending on temperature.
3) Since the permeabilities of different cell types vary, the corresponding resting potentials vary as well. Thus it varies from – 60 to – 100 mV.
4) By Goldman's equation, the resting potential 'V_r' of a cell can be written as

$$V_r = -\frac{kT}{q} \ln \left[\frac{P_K\left[K^+\right]_i + P_{Na}\left[Na^+\right]_i + P_{Cl}\left[Cl^-\right]_o}{P_K\left[K^+\right]_o + P_{Na}\left[Na^+\right]_o + P_{Cl}\left[Cl^-\right]_i} \right]$$

where
- k = Boltzmann's constant = 1.38×10^{-23} J/K
- T = Absolute temperature of the cell in Kelvin
- q = Charge of electron = 1.602×10^{-19} C
- P_K = Permeability of potassium ion
- P_{Na} = Permeability of sodium ion
- P_{Cl} = Permeability of chlorine ion
- $[K^+]$, $[Na^+]$ and $[Cl^-]$ = Concentration of potassium, sodium and chlorine ions and the subscripts i and o indicate inside the cell and outside the cell respectively.

Referring the Table 1.1, the resting potential of a cell at 37°C(310 K) can be calculated as

$$V_r = \frac{1.38 \times 10^{-23} \times 310}{1.602 \times 10^{-19}} l_n \left[\frac{2 \times 10^{-6} \times 140 + 2 \times 10^{-8} \times 10 + 4 \times 10^{-6} \times 103}{2 \times 10^{-6} \times 4 + 2 \times 10^{-8} \times 142 + 4 \times 10^{-6} \times 4}\right]$$

$$= -86.8 \text{ mV}.$$

5) If $P_{Na} \approx 0$ and $P_{Cl} \approx 0$, then Goldman's equation is reduced into Nernst equation such that

$$V_r = -\frac{kT}{q} \ln\left[\frac{[K^+]_i}{[K^+]_o}\right] = -94.9 \text{ mV}$$

Table 1.1: Chemical compositions of extracellular and intracellular fluids

	Extracellular fluid	***Intracellular fluid***
Na^+	142 millimol/litre	10 millimol/litre
K^+	4 millimol/litre	140 millimol/litre
Ca^{++}	1.2 millimol/litre	0.00005 millimol/litre
Mg^{++}	0.6 millimol/litre	29 millimol/litre
Cl^-	103 millimol/litre	4 millimol/litre
HCO_3^-	28 millimol/litre	10 millimol/litre
Phosphates	1.3 millimol/litre	25 millimol/litre
SO_4^-	0.5 millimol/litre	1 millimol/litre
Glucose	90 mg/dl	0–20 mg/dl
Aminoacids	30 mg/dl	200 mg/dl
Cholesterol	0.5 g/dl	2 to 95 g/dl
Phospholipids	0.5 g/dl	2 to 95 g/dl
Neutral fat	0.5 g/dl	2 to 95 g/dl
PO_2	35 mm Hg	20 mm Hg
PCO_2	46 mm Hg	50 mm Hg
pH	7.4	7
Proteins	2 g/dl	16 g/dl

In the case of blood serum (plasma), if the concentration of sodium ion is at the elevated condition then it indicates the renal damage and dehydration; when it is decreased, then it indicates the renal failure and adrenocortical hypofunction.

When concentration of potassium ion is increased, it creates shock and acidosis. When the concentration of bicarbonates is increased, metabolic alkalosis is produced and it is decreased, metabolic ***Acidosis*** is produced.

Further an increase of chloride ions produces respiratory alkalosis and hyperparathyroidism and decrease of chloride ions produces diabetic acidosis, lactic acid acidosis and persistent vomiting.

In acidosis, the patient has a reduced consciousness, tachycardia develops. the blood pressure falls and signs of cyanosis develop. ***Alkalosis*** can also be a threat to life since it can create cancer. When the cell is in the resting state. it is said to ***polarised*** such that inside of the cell is negative with respect to outside of the cell.

When a section of the cell membrane is excited by the flow of ionic current or by some form of externally applied energy, the permeability of the membrane changes so that the sodium ions are allowed to enter inside the cell. This movement of sodium ions into the cell constitutes an ionic current which further reduces the barrier of the membrane to sodium ions. The net result is an avalanche effect such that sodium ions rush into the cell and try to balance with the ions outside. Meanwhile potassium ions are leaving the cell but are unable to move as rapidly as the sodium ions. Therefore the cell has a slightly positive potential on the inside due to the imbalance of potassium ions. This positive potential of the cell membrane during excitation is called ***action potential*** and is about 20 mV. As long as the action potential exists, the cell is said to be ***depolarised***.

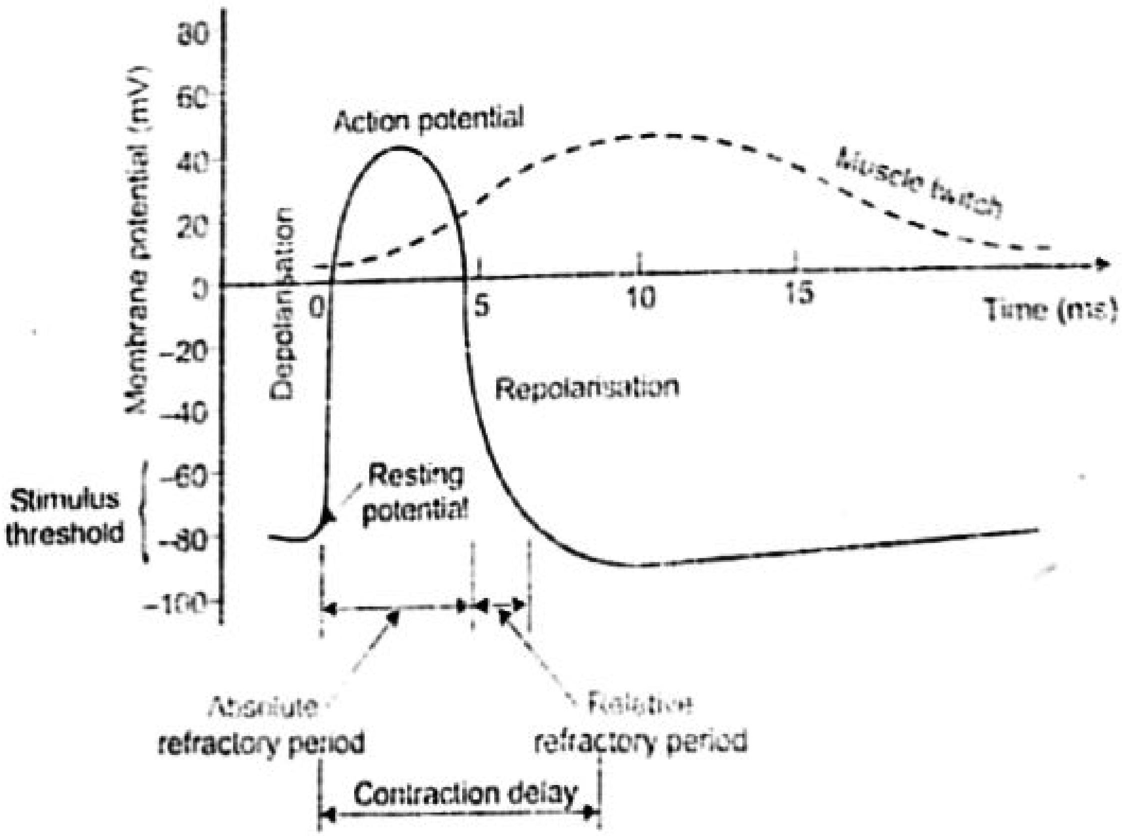

Figure 1.2: The relationship between the action potential and muscle contraction