1

water is a polar liquid with a static relative per-  
mittivity of about 80 (20°C), falling to 73 at 37°C (Fig. 4.1).  
The addition of electrolytes such as NaCl or KCl lowers the permittivity pro-  
portionally to concentration (e.g. with a dielectric decrement /span>/span>r of about 4 for  
250 mmol/L concentration of KCl (cf. Section 3.3)).  
The high permittivity is one reason for the dissociative power of water. Ionic  
bonds are split up so that ions exist in aqueous solutions in a free, but hydrated  
form. Because of the strong dipolar electric fi eld, water molecules are attracted to  
ions and local charges, forming a hydrated layer (sheet) which tends to neutralize  
the charge and increase the effective dimensions of the charged particle.

2

he living cell must contain and be surrounded by aqueous electrolytes. In human  
blood the most important cations are: H /span>, Na /span>, K /span>, Ca /span>/span>, Mg /span>/span>; and anions:  
HCO3  
/span>, Cl/span>, protein/span>, HPO4  
/span>, SO4  
/span>. Note that protein in the blood is considered  
as a negative (macro)-ion.

3

This common group is shown in ionized form as would occur at pH 7, the amino  
group has acquired a proton (NH 3  
/span>), and the carboxyl group has lost one (COO /span>).  
The charges are separated and represent a permanent dipole with zero net char and such substances are polar. At pH 7 all amino acids are more or less polar . Even  
so, the common group is also paradoxically called a “dipolar ion” or a zwitterion,  
because at other pH values it attains a net charge: at low pH values, the NH 3  
/span> group  
dominates and the acid is a cation with a net positive charge. At high pH values,  
the COO /span> group dominates and the “acid” is an anion with a net negative charge.  
Clearly, the term amino acid may be misleading, because in water solution they actu-  
ally can be an acid (proton donor) or a base (proton acceptor). Even if these condi-  
tions mostly are non-physiological, the acid–base behavior in vitro is valuable for the  
examination and mapping of amino acids The R symbolizes a side chain that determines the properties of each amino acid.  
The electrical properties of the protein are also strongly dependent on this R-group,  
but only if it is polar or charged. The amino acids are classified according to their  
R-groups, but the properties of an R-group and therefore the amino acid are very  
dependent on pH and molecule confi guration, so the classification differs in the lit-  
erature. The following classification for the 20 amino acids may be used at a physi-  
ological pH around 7.4:  
Eight of the amino acids are hydrophobic and therefore the R-groups are  
grouped as non-polar: they are without net electric charge and have a negligible  
dipole moment. The net dipole moment of all eight amino acids is equal to that  
of the common group.  
Seven are hydrophilic and the R-groups are therefore grouped as polar. These polar  
R-groups have an expected large infl uence on dielectric permittivity. Some of them  
tend to dissociate H/span> ions so that the amino acid also becomes charged and ionic.  
Two are with negatively charged R-groups and therefore have a net negative  
charge.  
Three are with positively charged R-groups and therefore have a net positive  
charge.

4

A protein may have a very regular form like an /span>-helix, or a chaotic morphol-  
ogy by denaturation at high temperatures or extreme pH values. The denaturation  
of a protein reduces the solubility in water, and heat coagulation of tissue is there-  
fore accompanied by water liberation. The denatured protein nearly always looses  
its characteristic biological activities, and the electric properties are often completely  
changed. This shows the importance of the higher orders of the geometrical (second-  
ary) structure of a protein.

s the forms become more complex, very different forms of charge distributions  
and bonds are possible. The rigidity of the bonds will be important for the electrical  
relaxation phenomena. In comparison with the displacement of electrons and nuclei  
during atomic polarization (10 /span>15 m), the distance between the charges in a macro-  
molecule can be very large (10 /span>8 m). Therefore the dipole moment of proteins could  
be very large. But the symmetry of the electric charges in protein molecules is also  
surprisingly high.

A protein with a large number of ionized groups is a polyelectrolyte if it has a  
net electric charge. If it is free, it will migrate in an electric fi eld. Usually it is not  
free, and may therefore only undergo local polarization. Because a polyelectrolyte  
has distributed charges all over the molecule, each charge is suffi ciently isolated to  
attract ions of an opposite charge.

6

The cell membrane is an absolute condition for life, because by it the cell can  
control its interior by controlling the membrane permeability. If the membrane is  
destroyed the cell dies. The membrane is a layer that separates two solutions, and  
forms two sharp boundaries toward them. The cell membrane consists of phosphol-  
ipids that form a bilayer lipid membrane (BLM) about 7 nm thick ( Fig. 4.6). Each  
monolayer has its hydrophobic surface oriented inward and its hydrophilic surface  
outward toward either the intra- or extracellular fl uids. The inside of such a bilayer  
is hydrophobic and lipophilic. A BLM is a very low electric conductivity membrane  
and is accordingly in itself closed for ions. It let lipids pass, but not water. However,  
water molecules can pass specialized membrane channels (cf. Chapter 5). The intrinsic

conductance is of the order of 10 /span>6 S/m, and a possible lipophilic ionic conductivity  
contribution can not be excluded.  
Even if the conductivity of the BLM itself is very low, the membrane is so thin  
that the capacitance is very high and the breakdown potential low. The electric field  
strength with 70 mV potential difference and thickness 7 nm is 10 kV/mm. This rep-  
resents a large dielectric strength, but not larger than, for example, Teflon. And as  
we shall see this is not the potential across the bilayer itself, but the potential of the  
bilayer /span> the potential difference of the two electric double layers formed on each  
surface of the membrane.  
A complex coating of special carbohydrates covers the external cell membrane  
surface, the glycocalyx, strongly modifying surface properties. Many of the glyco-  
calyx carbohydrates are normally negatively charged, so that living cells repel each  
other. During fever the blood sedimentation (mm/h) is increased because the elec-  
tric charge of the erythrocytes is diminished so that they lump together. According  
to Stokes law (eq. 2.6) fl ow friction is proportional to sphere radius a, while the  
weight is proportional to a3: the larger the sphere, the higher the sedimentation  
velocity (cf. also the electrokinetic effects described in Section 2.4.6)

7

Tissue is a very heterogeneous material, and interfacial processes are very important.  
The cells are of uneven size and with very different functions. There is a large dif-  
ference between the tissue conductivity: from the liquid tissue fl owing through the  
blood vessels to the myelin sheaths as insulators surrounding the axons of the nerve  
cells, from connective tissue specialized to endure mechanical stress to bones and  
teeth, muscle masses, the dead parts of the skin, gas in lung tissue and so on. From  
an electrical point of view, it is impossible to regard tissue as a homogenous material.  
Let us consider a simple case with a volume of many cells in interstitial fl uids  
(Fig. 4.7).  
The cell membranes are considered to have a high capacitance and a low but  
complicated pattern of conductivity. At DC and low frequencies current passes  
around the cells. Lateral conductance in the double layers is also possible. Cell inte-  
rior does to a smaller degree contribute to current fl ow. At higher frequencies the  
membrane capacitance let AC current pass. The membrane effect disappears, and  
the current flows everywhere according to local ionic conductivity.  
All interfaces give rise to Maxwell–Wagner and counterion polarization effects  
as described in Section 3.5.  
In general tissue is an anisotropic medium because of the orientation of cells,  
macromembranes and organs ( Figs 4.30–4.32 ). Such an anisotropy is a low fre-  
quency phenomenon if it is due to membranes, but not if it is due to, for example,  
air.

8

The *α* dispersion occurs in a low-frequency range, i.e., 10 Hz to 10 kHz, while the relaxation time (*τ*) is 6 ms. This mode is categorized by a very high permittivity increment and very high dielectric decrement values (Δ*εα* ≈ 106). This dispersion occurs near the cell membrane where the movements of charged particles are limited. The cell membrane is a complex structure consisting of phospholipids, cholesterol, proteins, and carbohydrates. There is a potential difference (approximately 60–70 mV) between the intracellular and extracellular media due to the ions which are distributed around the membrane (about 10 kV/mm).​

he *β*-dispersion arises within the frequency of 10 kHz–10 MHz with a relaxation time approximately 300 ns. The cellular membranes and other intracellular bodies become charged (capacitive), leading to this dispersion type. The cell membranes are electrically shorted, while the current can penetrate through the cytoplasm. This penetration decreases the impedance and leads to the *β*-dispersion or interfacial polarization or the Maxwell–Wagner relation. This effect occurs at the interface of membrane-electrolyte structures, which have two different dielectrics, leading to the formation of charges. The polarization magnitude depends on the conductivity, permittivity, and structure of the distinct intracellular components.​

​

9

Some protein solutions exhibit *δ*-dispersion, which lies between the *β-* and *γ*-dispersions. If present, the effect falls within the frequency of 0.1 to 5 GHz, and comparatively, its magnitude is small. *δ*-dispersion was first categorized in a study by Pethig [87] and was credited to the dipolar moments of proteins and other large molecules such as biopolymers, cellular organelles [88], and protein-bound water [89]. Mechanisms such as the relaxation of BW (dipolar) or molecules side chains and counterion diffusion in minor charged regions are possible origins of *δ*-dispersion.

In 1989, Foster and Schwan discovered *γ*-dispersion [90], which occurs due to the presence of water content in the cells and tissues. The dielectric properties of cells and tissues at frequencies above 0.1 GHz depend on the intracellular electrolytes and water (dipole polarization). At frequencies above a few hundred megahertz, the complex permittivity can be decoupled into terms of Cole-Cole and conductivity which are related to the dispersion of water (dipolar) and the electrolytic behavior,

10

Whole blood consists of erythrocytes (containing the hemoglobin) and other cells  
in plasma. Blood may be studied as whole blood in vivo, erythrocytes in suspen-  
sion, lysed erythrocytes in suspension, as plasma, etc. The erythrocytes are formed  
as doughnuts with an outer diameter of about 10 /span>m. Plasma is the liquid part with  
electrolytes and large organic electrically charged molecules. Lysed erythrocytes are  
destroyed cells with their intracellular material (hemoglobin) emptied into the liq-  
uid. The electrical properties of whole blood and lysed blood are of course very  
different, Figs. 4.13 and 4.14. From Maxwell–Wagner theory it is possible to fi nd  
an expression for the conductivity of a suspension of membrane-covered spheres  
(Section 3.5.1).  
Whole blood exhibits /span>-, - and /span>-dispersion, but curiously enough no  
/span>-dispersion, Foster and Schwan (1989). The /span>-dispersion has a dielectric increment  
of about 2000 centered around 3 MHz (hematocrit 40%). Erythrocytes in suspen-  
sion have a frequency independent membrane capacitance with very low losses  
(Schwan, 1957).

11

Epithelia are cells organized as layers, skin is an example. Cells in epithelia form  
gap junctions . Particularly in tight membranes these junctions are special tight  
junctions. The transmembrane admittance is dependent both on the type of cell  
junctions and to what extent the epithelium is shunted by channels or specialized  
organs (e.g. sweat ducts in the skin).  
The impedance of the skin is dominated by the stratum corneum at low frequen-  
cies. It has generally been stated that skin impedance is determined mainly by the  
stratum corneum at frequencies below 10 kHz and by the viable skin at higher fre-  
quencies (Ackmann and Seitz, 1984). This will of course be dependent on factors  
like skin hydration, electrode size and geometry, etc. but may nevertheless serve as  
a rough guideline. A finite element simulation on a concentric two-electrode system  
used by Yamamoto et al. (1986) showed that the stratum corneum accounted for  
about 50% of the measured skin impedance at 10 kHz, but only about 10% at  
100 kHz (Martinsen et al., 1999).

tratum corneum is not soluble in water, but the surface  
will be charged and a double layer will be formed in the water side of the interphase.  
Stratum corneum can absorb large amounts of water (e.g. doubling its weight).  
Stratum corneum may be considered as a solid state electrolyte, perhaps with few  
ions free to move and contribute to DC conductance. The stratum corneum con-  
tains such organic substances as proteins and lipids, which may be highly charged  
but bound, and therefore contributing only to AC admittance.