THE ELECTRIC CAPACITY OF SUSPENSIONS OF RED CORPUSCLES OF A DOG

HUGO FRICKE

ABSTRACT

Measurements were made with a bridge, using a substitution method whereby the suspension is indirectly compared with a diluted serum which has the same specific resistance as the suspension. The bridge may be used with frequencies ranging from 800 to 4,500,000 cycles and its sensitivity is such that a capacity in parallel to 100 ohms can be measured with an accuracy of a few $\mu\mu$f at the lowest frequency. Measurements with a frequency of 87,000 cycles per sec. were made of suspensions of red corpuscles of a dog with volume concentrations between 10 and 88 percent, confirming the formula $C(\rho) = C_{100}(1 - r_1/r)$ previously derived.[1] By these measurements and the previous formula $C_0 = C_{100}/aq$ the capacity per cm² of surface of a red corpuscle is calculated to be .81μf. This capacity is independent of frequencies between 3600 and 4,500,000 cycles and is also independent of the suspending liquid. It is probably the static capacity of the membrane which surrounds the corpuscle. According to this assumption and using 3 for the dielectric constant, the thickness of the membrane is 3.3×10^{-7} cm (monomolecular).

THE following experiments illustrate the application of the theory which was presented in the preceding paper[1] and confirm it.

The capacity, which for a one centimeter cube of normal blood is of the order of a few hundred micromicrofarads in parallel with a resistance of a few hundred ohms, was measured with a specially designed bridge over a range of frequencies from 800 to 4,500,000 cycles. The sensitivity of the bridge is such that such a capacity can be measured with an accuracy of a few $\mu\mu$f at the lowest frequency. Two arms of the bridge contain a Kohlrausch slidewire which is always used near its middle point; the third arm contains a decade resistance box R_1 (General Radio Company) with a decade condenser in parallel, and the fourth arm the electrolytic cell with a variable condenser C_r (General Radio standard condenser) in parallel. By means of a switch the electrolytic cell can be replaced by a decade resistance box R_r similar to R_1. The coils in the resistance boxes are wound by the Ayrton-Perry method and their effective inductances are rather low.

The current to the bridge is delivered by an audion oscillator and the heterodyne method of detection is employed, using three stage amplification. The bridge is connected to generating and heterodyne oscillation

[1] H. Fricke, preceding paper in this issue.

and to the detector tube by very loose inductive couplings. The electrolytic cell has the form of an hour-glass with large platinized platinum electrodes sealed into the glass at the ends; it is designed to have the lowest possible amount of polarization at the electrodes. The electrode area is between 10 and 20 cm^2; the distance between the electrodes between 5 and 10 cm. The cell constant is about 1. Effective stirring, which is essential, is accomplished by gently blowing through two glass tubes which are sealed to the top of the cell.

The abstract of the protocol, given in Table I, will explain the experimental procedure. The cell filled with the suspension is compared with the resistance box R_r; the difference between the settings of the condenser

TABLE I

Partial abstract of protocol for blood (11.1%)

	Units	Exp. IV$_1$		Exp. IV$_3$		Diluted serum	
R_1' (cell in)	ohms	93.3		93.2		93.1	
C_r'	arb.	6.47		6.61		8.08	
Setting of slide wire		+1		+7		−1	
R_r'' (R_r instead of cell)	ohms	93.9	93.8	93.7	93.6	93.7	93.8
C_r''	arb.	10.05	10.43	10.26	10.68	10.72	10.40
Setting of slide wire		−14.5	+7	+2.5	+24.5	0	−17.5
Temperature		23.30°	.....	23.20°	.....	22.40°	.....
$C_r''-C_r'$	$\mu\mu$f	217	240	222	247	160	141
Total inductance L	10^{-10}h	11790	11650	11480	11300	11480	11650
Equivalent capacity $(L/R_r''^2).10^2$	$\mu\mu$f	134	132	130	129	130	132
Capacity corrected for inductance	"	83	108	92	118	30	9
Corrected for difference in slide-wire setting	"	101		97		29	
Corrected for static capacity of electrolytic cell	"	95		91		21	
Capacity for cell filled with serum	"	21		21			
Capacity of blood	"	74		70			

C_r, $(C_r''-C_r')$, gives an uncorrected value for the capacity of the suspension. This value is first corrected for the inductance of the coils used in the resistance box R_r and for the difference between the inductances of the leads which connect the cell and R_r respectively to the bridge; this correction for our case is (L/R_r^2) farad, when this total inductance L is in henries. A small correction is thereafter introduced for the static capacity of the electrolytic cell, which, when filled with a homogeneous liquid of dielectric constant K, is $K/4\pi c'$ cm in which c' is the cell constant equal to the ratio of resistance to specific resistance. For the case of a suspension with a non-conducting disperse phase, like blood, K is the dielectric constant of the suspending liquid (for blood therefore about 81) and c' is the constant of the electrolytic cell c times r/r_1, r

and r_1 being the specific resistances of the suspension and the intracellular liquid. Consequently, the static capacity is $81/(4\pi c r/r_1) \times (10/9)\mu\mu f = 7.2/(cr/r_1)\ \mu\mu f$.

The value for the capacity thus obtained is still faulty, due to the difference in static coupling between the electrolytic cell and the other parts of the bridge on one side and on the other side between the resistance box R_r and the other parts of the bridge. The corresponding correction is obtained by making once for all a series of measurements with the cell filled with various dilutions of serum covering the total range of resistances used; the measured capacities are corrected as above and the values which vary very slowly with the resistance, are plotted against the resistance. From this curve a "zero value" for the capacity of the cell is found at the resistance observed in the case of blood which comprises the said difference in static coupling. This "zero value" is subtracted from the value for the capacity as obtained above.

The procedure described above would not have given a correct elimination of a polarization at the electrodes of the electrolytic cell if such an effect had been present to any appreciable amount within the experimental range of frequencies. The frequency at which the polarization becomes appreciable is easily determined by measuring the serum at decreasing frequencies; the setting of the standard condenser remains practically constant until the critical frequency is reached, when an abrupt change takes place.

A confirmation of the accuracy of this method was obtained by making measurements on cream, in which case the resulting capacity is zero. The fact that the value of the capacity of a corpuscle suspension is found to be independent of the form of the electrolytic cell and of the frequency serves as a further confirmation. (The capacity is found to be independent of the frequency between 3600 and 87,000 cycles per sec.; for higher frequencies the capacity decreases due to the fact that the impedance of the static capacity of the corpuscle membrane becomes comparable with the resistance of the corpuscle interior.)[2]

Tables II and III present the results of two series of measurements, typical of several, on the blood of a dog. They include corpuscle concentrations between 10 and 84 percent. The stated volume concentrations were derived from the resistances by an earlier formula[3] ($a/b = 1/4$). The capacity (C_{100}) for 100 percent volume concentration is calculated by formula (21) of the preceding paper.[1] The values are constant for

[2] H. Fricke and S. Morse, The electric resistance and capacity of blood for frequencies between 800 and 4,500,000 cycles, Jour. Gen. Physiol. (1925).

TABLE II

Capacity of suspensions of red corpuscles of a dog in own serum.

Defibrinated blood of dog No. 1 was concentrated by centrifugation, and the concentrated suspension was diluted with serum. Resistance r_1 of serum: 84.25 ohms; temperature: 18.95°C; constant of electrolytic cell: $c = .98$.

Frequency: 87000 cycles per sec. Date: March 22. 1925.

Experiment	Volume concentration	Resistance r	Capacity C	C_{100} (calc.)	
	(percent)	(ohms)	($\mu\mu$f)	($\mu\mu$f)	
I	83.9	931.0	374	411	Concentrated by centrifugation from original blood.
II	21.0	126.9	129	385	From 83.9 percent suspension by dilution.
III	72.0	498.	343	411	From 83.9 percent and 21 percent suspensions.
IV	47.5	230.2	237	374	From 72.0 percent suspension by dilution.
V	60.2	329.	286	385	From 83.9 percent and 47.5 percent suspensions.

TABLE III

Capacity of suspensions of red corpuscles of a dog in own serum.

Defibrinated blood of dog No. 1 was diluted with own serum. Resistance r of serum: 75.8 ohms; temperature: 23.10°C; constant of electrolytic cell: .98.

Frequency: 87000 cycles per sec. Date: March 23, 1925.

Experiment	Volume concentration	Resistance (r)	Capacity (C)	C_{100} (calc.)	
	(percent)	(ohms)	($\mu\mu$f)	($\mu\mu$f)	
I	43.9	188.7	232	388	Original blood
II	30.8	140.1	172	374	From original blood by dilution.
III	20.6	113.7	126	378	From 30.8 percent suspension by dilution.
IV	11.1	94.0	72	371	From 20.6 percent suspension by dilution.
V	10.6	93.4	74	391	From original blood by dilution.
VI	42.8	185.3	221	374	Original blood.

Average: 380$\mu\mu$f $\pm$ 2 percent

concentrations up to about 60 percent; for still higher concentrations, which approach the stage of total packing for which the theoretical foundation for the formula may be doubtful, there may be a slight tendency to an increase. Using the lower concentrations alone, we obtain $380\mu\mu$f as the average value of C_{100}. Since the constant of the electrolytic cell is .98 (=resistance/spec. resistance), the specific value of C_{100} (corresponding to a one centimeter cube) is $380\times.98=372\ \mu\mu$f.

Using $a/b=1/4$ as in our earlier paper[3] and taking 7.2 $(10)^{-4}$ cm for the diameter $2q$ of the corpuscle, by formula (22) we obtain for the capacity per cm^2 of the membrane

$$C_0=C_{100}/aq=372\times10^{-6}/(1.28\times3.6\times10^{-4})=0.81\mu f.$$

It has been shown elsewhere[2] that the capacity of blood is independent of the frequency between 3600 and 87,000 cycles per sec. For higher frequencies the capacity decreases; this decrease, however, for the experimental range of frequencies (up to 4,500,000 cycles), is satisfactorily explained as due to the impedance of the inter- and intra-cellular liquids, with which the capacity of the corpuscle membrane is in series, C_0 itself being independent of the frequency over the above range. We find also that the capacity is not changed when the corpuscles from defibrinated blood are suspended in Ringer's solution or in an isotonic solution of dextrose.

On the ground of our present, although rather incomplete, knowledge of polarization, such a constancy of the capacity would seem hardly possible if it were due to a polarization at the surface of the red corpuscle. Furthermore,[4] there is much evidence that the resistance of the membrane which surrounds the corpuscle is high as compared with the impedance of the capacity C_0 over our whole experimental range of frequencies; therefore, even with a constant polarization capacity at the surface of the corpuscle, the observed capacity should have decreased as the frequency increased. (The resistance of the membrane may, for instance, be estimated from known data for the diffusion of electrolytes from the serium into the corpuscle.) At present, therefore, it seems probable that the observed capacity is due to the static capacity of the corpuscle membrane. The order of magnitude of the thickness of this membrane, which may be derived on this assumption, is suggestive. By using a value of 3 as the dielectric constant of the membrane (a value which of course is

[3] H. Fricke, Jour. Gen. Physiol. **6**, 741-746 (1924); Phys. Rev. **24**, 575-587 (1924), Eq. (13).

[4] H. Fricke, The electric capacity of suspensions with special reference to blood, Jour. Gen. Physiol. (1925).

rather uncertain, the more so, since the membrane appears to be monomolecular), we obtain a thickness of 3.3×10^{-7} cm. This value corresponds to a chain of from 20 to 30 carbon atoms. Thus, we evidently arrive at the conclusion that the membrane of the corpuscle is monomolecular.[4]

DEPARTMENT OF BIOPHYSICS,
CLEVELAND CLINIC FOUNDATION,
CLEVELAND, OHIO.
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