ELECTRICAL FLUCTUATIONS IN LIPID BILAYER MEMBRANES

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The motion of ions in a membrane permeation process consists of a series of individual transport steps occurring at random. As a consequence, the current flowing through the membrane fluctuates. From an analysis of such current or voltage fluctuations information about the underlying molecular transport mechanism may be obtained (1). Most noise studies with biological membranes have been devoted to the analysis of opening-closing processes of ion channels in excitable membranes (2). But a well known difficulty in the analysis of electrical noise from biological membranes lies in the fact that usually different ion transport mechanisms, like the active and passive transport, contribute to the total noise signal. Besides this, the physical basis for the interpretation of electrical noise in terms of molecular ion pathways is still poorly developed. For this reason, studies with simple and well-defined transport systems are valuable for a better understanding of noise phenomena in membranes.

The noise analysis of equilibrium systems is based on the principle that any reacting system exhibits statistical fluctuations around its equilibrium state. As the time decay of a spontaneous fluctuation follows on the average the same time law as the relaxation from a sudden macroscopic perturbation of the system, both methods, the relaxation technique and noise analysis yield essentially the same kinetically information about the reacting system. The noise analysis has the advantage that the measurement is carried out while the system is in an equilibrium or stationary state. Moreover, the relaxation technique fails in cases where no sufficient perturbation of the system can be achieved. The common experimental tool of a noise analysis consists in the determination of either the spectral intensity or the corresponding autocorrelation function. Both functions are related by the Wiener-Khintchine theorem and therefore contain, in principle, the same information about the electrical noise sources. Despite this mathematical equivalence the application of one of this functions can be the more useful experimental approach depending on the type of ion transport mechanism.

Pore-mediated ion transport

It is well known that peptides like gramicidin, alamethicin or monazomycin form pore-like structures in artificial lipid bilayer membranes which offer to ions a hydrophobic pathway through the hydrophobic interior of a membrane. The opening-closing process of these ion-pores corresponds to transitions between different conductance states. Under non-equilibrium steady state conditions this type of noise is characterized by a so called Lorentzian spectrum which is frequency-independent and in excess of thermal noise at low frequencies and declines toward high frequencies (3) whereas the autocorrelation function shows an exponential behaviour. In general two pieces of information about the underlying molecular transport mechanism may be obtained from the experimentally observed spectrum. These are the mean life time of a conducting pore and the single pore conductance even for a multi-pore system. But it has to be pointed out that in any case the interpretation of the spectral intensity depends on the specific model used for the theoretical description of the ion transport process.

At equilibrium one obtains from the noise originating from ion movements in pores a spectral intensity which is frequency-independent ("white") as long as an adsorption of ions to the pore can be neglected.

Carrier-mediated ion transport

Although attempts have been made to study noise of biological membranes originating from active ion transport systems (4), unequivocal evidence for noise associated with carrier-mediated ion transport has not been obtained so far. But on lipid bilayer membranes this type of noise could be analyzed using cation-carrier like valinomycin or tetranactin. Valinomycin is a neutral hydrophobic depsipeptide which is known to form complexes with alkali ions such as K^+ or Rb^+. The charged complex which is formed at one membrane solution interface is able to jump by thermal activation across the membrane dielectric to the opposite interface where the ion can be released to the aqueous solution (5). Noise current of such transport mechanism arises mainly from random fluctuations in the number of charged ion-carrier complexes crossing the membrane from right to left and from left to right. This noise current can be analyzed under equilibrium and nonequilibrium conditions (6). In both cases the observed spectral intensity is frequency-independent both at low and at high frequencies as predicted by the theoretical model of carrier-mediated ion transport. The spectral intensity at high frequency represents the shot-noise intensity generated by the pulses originating from the translocation of the charged ion-carrier complex which declines at non-equilibrium compared to the equilibrium case. The transition-region between these limiting values is characterized by an increase of the spectral intensity with increasing frequency which is correlated to the time constants governing the voltage-jump relaxation behaviour of the system.
Under equilibrium conditions the theoretical analysis can be based on Nyquist's theorem which relates the measured spectral intensity to the admittance of the membrane. But at non-equilibrium the Nyquist theorem fails.
The corresponding autocorrelation function shows a delta-function at short correlation times and a characteristic exponential increase of negative amplitude for larger correlation times.

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