Molecular electric and magnetic field reception-Analytical access to cellular field effects

Eberhard Neumann*, Sergej Kakorin, Katja Tönsing, Andreas Kukol, Iana Tsoneva and Peter Siemens

*Physical and Biophysical Chemistry, Faculty of Chemistry, University of Bielefeld, P.O. Box 100 131, D-33501 Bielefeld, Germany, eberhard.neumann@uni-bielefeld.de

“Life is bioelectrochemistry. I believe that the ultimate goal of biological study is to translate the phenomena of life into meaningful physical concepts.” – Aharon Katchalsky (1913 - 1972)

Ongoing public concern on potential hazards and risks of even very low-intensity electromagnetic fields (EMFs) necessitates to reassure the solid scientific basis of molecular field reception [1]. Clearly, the physical targets of EMFs are electric and magnetic (transition) moments or susceptibilities of the field-receptive molecules. Reactive cellular expressions of the primary molecular EMF effects are modulations of ion flows and field-induced structural/conformational changes, such as a transition of the type $C \rightarrow P$, eventually coupled to bimolecular ligand binding processes [2].

Due to the necessity to amplify locally small EMF-effects, cooperativity and membrane structures provide the essential structural conditions for relevant field effects, i.e., those emerging out of local structural fluctuations due to thermal motion (kT). If the reaction moments $\Delta m = m(P) - m(C)$ or the reaction susceptibilities $\Delta \chi = \chi(P) - \chi(C)$ of field-sensitive processes are finite, then no matter how small they are, there are always field effects. The decisive question is, however, whether the product $\Delta m \cdot F$ or $\Delta \chi \cdot F^2 / 2$ is in the order of kT to be globally relevant or locally relevant for macroscopic amplification or even for hysteretic accumulative gain in particular structures [1, 2].

It is known that the so-called small-field approximation of chemical electrothermodynamics and kinetics are expressed as small relative shifts $\Delta K / K_0 = \int \Delta m dF / kT$ and $\Delta k / k_0 = \int m^* dF / kT$ of the measurable distribution constant $K$ and the rate coefficient $k$ with $m^*$ denoting the kinetic activation enthalpy of isothermal isobaric processes. This physical chemical formalism has been successfully applied to elucidate the field reception mechanisms of a variety of bioelectrochemical membrane processes.

Instructive examples for amplification by cooperativity are the well ordered (postsynaptic) clusters of the acetylcholine receptors. The lipid membrane-reconstituted receptor clusters, surprisingly for a protein traditionally qualified as a ligand-gated channel protein, become field-gated when chronically hyperphosphorylated, i.e., the channel is active even in the absence of the neurotransmitter [3]. Another example for cooperative electroclustering is the initially Ca-mediated surface association of human annexin V as field-induced transmembrane clusters of larger field-sensitive channels. The isolated single molecule
surface channels have lower conductance but exhibit the phenomenon of channel flickering with extremely non-linear conductance/voltage characteristics deceiving a threshold voltage [4].

Finally, membrane electroporation (MEP) shows a highly non-linear dependence on the electric membrane field, reflecting lipid-cooperativity in electropore formations. Here, too, the apparent field thresholds depend on the accuracy of monitoring the field reception [5, 6]. The electrothermodynamical analysis of kinetic relaxation spectrometric data primarily yields the polarization volume from which a mean radius of the electropores, inclusively the dimensions of the interactively diffusive, occluded pore passages, are derived, as in the case of DNA and oligonucleotide transport across lipid membranes [7].

In each case, the aim of studying field reception is to derive the characteristic reaction moments or susceptibilities from the respective field dependencies. The ultimate goal is to identify the molecules and molecular groups and the amplification mechanisms in order to quantify the physiological relevance of electromagnetic field reception data in physical chemical terms.

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[1] Neumann, E., Digression on chemical electromagnetic field effects in membrane signal transduction - the experimental paradigm of the acetylcholine receptor, Bioelectrochemistry, 52, 43 - 49 (2000)