On the Thermal Noise Limit of Cellular Membranes

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Comparison of thermal noise limits and the effects of low frequency electromagnetic fields (LFEMF) on the cellular membrane have important implications for the study of bioelectro-magnetism in this regime. Over a decade ago, Weaver and Astumian developed a model to show that thermal noise can limit the efficacy of LFEMF. A recent report by Kaune [Kaune (2004) Bioelectromagnetics 23:622–628], however, contradicted their findings. Kaune assumes that the conductance noise current of cell membrane can be decomposed into two components, where one of them is identical regarding all segments (coherent), while the other is different (incoherent). Besides, this decomposition is not unequivocal and contradicts to the statistical independence of the segment noise currents, and therefore to the second law of thermodynamics as well. We suggest the procedure based on the method of symmetrical components, by the means of which we can re-interpret the result of Kaune in a correct way. Bioelectromagnetics 26:28–35, 2005.

Key words: ELF; EMF; symmetrical components; Twiss’s theorem; Weaver–Astumian model

INTRODUCTION

The biological effects of low frequency electromagnetic fields (LFEMF) have raised significant interest and debate in the past. Numerous reviews [e.g., Bernardi and D’Inzeo, 1989; Ho et al., 1994] and articles report response of biological matter to LFEMF [Benett, 1994; Markov, 1994; Harland and Liburdy, 1997; Portier and Wolfe, 1998; Ahlbom et al., 2000; Greenland et al., 2000; Blackman et al., 2001; Bauerus Koch et al., 2003]. However, these observations proved controversial [Takebe et al., 2001] and the explanations describing these observations were often found inconsistent.

In the past, theoretical approximations compared thermal noise fluctuations of the cell membrane field strengths to the field strengths induced by LFEMF at the membrane [Weaver and Astumian, 1990]. The final conclusion of these comparisons was that LFEMF induced changes were several orders of magnitude lower than thermal noise-induced fluctuations. Therefore, the authors concluded that thermal noise limits the electromagnetic influences and no biological impact can be expected from LFEMF.

Recently, Kaune [2002] revised the W–A model and assumed that the field strength characteristic of thermal noise is not this, but the resultant of field

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strengths resulting from the thermal electromotive forces. Kaune showed that the field strengths typical of thermal noise converges to zero at low frequencies; therefore, the W–A model does not describe this region appropriately. He concluded that there are no thermal limits at low frequencies and that LFEMF can elicit biological effects. Nevertheless, the deduction of Kaune raises some criticisms:

Kaune introduces in (Eq. 7) of his article the arbitrary decomposition of

\[ I_\mu = \frac{1}{NR_m} \left( \varepsilon_{\mu} - \frac{1}{N} \sum_{i=1}^{N} \xi_i \right) \]

\[ + \frac{1}{NR_m} \frac{j \omega_m}{(1 + j \omega_m)} \sum_{i=1}^{N} \xi_i, \quad (\mu = 1, 2, \ldots, N). \]

As the second member of the membrane’s segment current is independent of the index \( \mu \) of segment, therefore, it is a coherent noise component current existent in every membrane segment. Herewith, the originally and statistically independent segment currents become statistically coherent, which contradicts to the second law of thermodynamics. Therefore, such decomposition of currents is physically impossible. It follows from this that the deduction by means of which Kaune gets this result shall be corrected at several points. In this article we are going to revise the theory of Kaune by the application of the widely used symmetrical component transformation [White and Woodson 1959], and eliminate the above mentioned problem.

MATHEMATICAL PRELIMINARIES

The physical derivation for this problem uses cyclic matrices; therefore, we will describe their most important properties within this section. We use the following notation: \( \overline{\mathbf{L}} \) is the cyclic matrix, \( \lambda_{Li} \) are its eigenvalues of \( \overline{\mathbf{L}} \), \( \mathbf{s}_i \) are the eigenvectors of the \( \overline{\mathbf{L}} \) generated from the powers of the \( g_i = \exp(j 2\pi i/n) \) root of unity (\( g_i \) are complex numbers).

\[ \mathbf{s}_i = \begin{bmatrix} s_{i1} \\ s_{i2} \\ \vdots \\ s_{in} \end{bmatrix} = \frac{1}{\sqrt{n}} \begin{bmatrix} 1 \\ g_i \\ \vdots \\ g_i^{n-1} \end{bmatrix} \]  

(1)

where

\[ g_i^n = 1, \quad g_i^{n+k} = g_i^k, \]

\[ 1 + g_i + \cdots + g_i^{k} + \cdots + g_i^{n-1} = 0, \quad \text{if} \quad i \neq 0 \]

\[ 1 + g_i + \cdots + g_i^{k} + \cdots + g_i^{n-1} = n, \quad \text{if} \quad i = 0. \]  

Using the asterisk to denote the conjugate of the complex numbers \( (g_i^* = g_{n-i}, \quad g_i^*g_i = 1) \), the eigenvalues of the cyclic matrix are

\[ \lambda_{Li} = l_0 + l_1g_i + \cdots + l_kg_i^{k} + \cdots + l_{n-1}g_i^{n-1}; \]

\[ (i = 0, 1, \ldots, n-1) \]  

(3)

and so, the cyclic matrix, can be expressed in the following dyadic form:

\[ \overline{\mathbf{L}} = \sum_{i=0}^{n-1} \lambda_i \mathbf{s}_i \mathbf{s}^*_i \]  

(4)

where \( T \) denotes the transpose. We may decompose any \( \mathbf{u} \) vector into eigenvector components:

\[ \mathbf{u} = \overline{\mathbf{T}} \mathbf{u} = \sum_{i=0}^{n-1} \mathbf{s}_i (\mathbf{s}^*_i \mathbf{u}). \]  

(5)

Where \( \overline{\mathbf{T}} \) is the unit matrix and where

\[ u_i^* = (\mathbf{s}^*_i, \mathbf{u}) = \frac{1}{\sqrt{n}} \sum_{k=0}^{n-1} u_k g_i^k \quad (i = 0, 1, \ldots, n-1) \]  

(6)

coordinates are referred to as the symmetrical components or modes of the \( \mathbf{u} \) vector.

If the coordinates of the \( \mathbf{u} \) vector are the same, we may see that in pursuance of (Eq. 2), only the symmetrical component (modal value) of zero index differs from zero. If the sum of the coordinates of \( \mathbf{u} \) vector equals to zero then the symmetrical component of zero index equals to zero.

From the symmetrical components we can generate the following column vector:

\[ \mathbf{u}^* = \begin{bmatrix} u_0^* \\ u_1^* \\ \vdots \\ u_{n-1}^* \end{bmatrix} = \begin{bmatrix} \mathbf{s}_0^* \mathbf{u} \\ \mathbf{s}_1^* \mathbf{u} \\ \vdots \\ \mathbf{s}_{n-1}^* \mathbf{u} \end{bmatrix} \]  

(7)

Let us create a matrix from the row vectors:

\[ \overline{\mathbf{S}} = \begin{bmatrix} \mathbf{s}_0^* \\ \mathbf{s}_1^* \\ \vdots \\ \mathbf{s}_{n-1}^* \end{bmatrix} \]  

\[ = \frac{1}{\sqrt{n}} \begin{bmatrix} 1 & 1 & \cdots & 1 \\ 1 & g_1^* & g_1^{*n-1} \\ \vdots & \vdots & \ddots & \vdots \\ 1 & g_{n-1}^* & g_{n-1}^{*n-1} \end{bmatrix}. \]  

(8)
This matrix is called symmetrical component transformation matrix. By using this matrix we may express Equation 7 in the following form:

\[ \tilde{u} = \bar{T} \tilde{u}. \]  (9)

On the basis of this relationship we can demonstrate that the symmetrical component transformation is unitary:

\[ \tilde{u}^T \tilde{u} = (\bar{T}^T \tilde{u})^T \bar{T}^T \tilde{u} = \tilde{v}^T \bar{T}^T \tilde{u} = \tilde{v}^T \bar{T} \tilde{u} = \tilde{v}^T u. \]  (10)

In our case, that leads us to conclude that the spectral electric power remains invariant in the case of symmetrical component transformation.

Let the \( \bar{T} \) cyclic matrix establish the connection among the vectors of \( \tilde{I} \) and \( \tilde{\xi} \) then among the symmetrical transformed vectors of (Eq. 9). The connection is established by the \( \bar{D}_L \) diagonal matrix, which consists of the eigenvalues of (Eq. 3):

\[ \bar{F} = \bar{F}_s \bar{I} = \bar{F}_s \bar{L} \tilde{\xi} = \bar{F}_s \bar{L} \bar{T}^{-1} \tilde{\xi} = \bar{D}_L \tilde{\xi}, \]

\[ \bar{D}_L = \begin{bmatrix} \lambda_{l0} & 0 & 0 & 0 \\ 0 & \lambda_{l1} & 0 & 0 \\ \cdots & \cdots & \cdots & \cdots \\ 0 & 0 & 0 & \lambda_{l_{n-1}} \end{bmatrix}. \]  (11)

Therefore the relations among the symmetrical components are:

\[ I_i^s = \lambda_{l_i} \tilde{\xi}_i, \quad (i = 0, 1, \ldots, n - 1). \]  (12)

For further details, please refer to White and Woodson [1959].

**PHYSICAL PRELIMINARIES**

It is well known that every linear electric network with internal thermal noise sources can be replaced by an equivalent network shown in Figure 1, where \( \bar{Z} \) is the impedance matrix of the network, which establishes the \( \bar{\xi} = \bar{Z} \tilde{I} \) connection between \( \tilde{\xi} \) noise potential vector and the \( \tilde{I} \) noise current vector, created from the \( I_i, (i = 1, 2, \ldots, n) \) current noise Fourier amplitudes and the \( \xi_i, (i = 1, 2, \ldots, n) \) noise potential (thermal electromotive forces) Fourier amplitudes. Note that these noise potentials can be different, as no parallel connection has to be made for the generators. It is also important that the construction generates a cyclic impedance matrix, which we will use in our description, since the cross-effects are identical.

The relationship between the Fourier amplitudes of noise potentials and the impedance matrix can be established using Twiss’ generalization of Nyquist’s theorem, Twiss [1955] [Haus et al., 1959]:

\[ \bar{\xi} \bar{\xi}^T = 2kT(\bar{Z} + \bar{Z}^T) \]  (13)

where \( T \) is the temperature and \( k \) is Boltzmann’s constant.

Here \( \bar{\xi} \) is a column matrix generated from the Fourier amplitudes of thermal noise potentials, while \( \bar{\xi} \bar{\xi}^T \) is the so called Hermitian power spectral matrix. \( \bar{\xi} \bar{\xi}^T df \) gives the portion of the mean-square value of the stochastical noise potentials belonging to the \( (f, f + df) \) frequency interval, that is \( d\bar{\xi} \bar{\xi}^T df = 2kT(\bar{Z} + \bar{Z}^T)df \). On the basis of this theorem we are able to determine the power spectral matrix of the symmetrical components. Therefore, its principal axis can be transformed by the transformation matrix (Eq. 9). This gives us a relationship among the eigenvalues of the power spectral matrix and impedance matrix, resulting in the generalized relationship known as Nyquist’s theorem:

\[ d|\xi|^2 = \xi \xi^T df = 2kT(\lambda_{Z_1} + \lambda_{Z_2})df \]  (14)

where \( \lambda_{Z_j} \) is the \( j \)th eigenvalue of impedance matrix, \( df \) is the frequency bandwidth of interest, and \( d|\xi|^2 \) is the time average of the square of the magnitude of \( \xi \) within this frequency bandwidth.

**PHYSICAL BACKGROUND OF THE KAUNE MODEL**

Both the W–A and Kaune’s model assume that the cell membrane can be replaced by the equivalent circuit shown in Figure 2 test electric noise. The membrane capacitance (\( C_m \)) is a common load on the individual noise generators. In the W–A model, the noise is generated by the charge distribution of the membrane capacitance, while in Kaune’s model the noise is generated by current flow through the membrane resistors.

![Fig. 1. Equivalent representation of a linear network with internal noise sources.](image-url)
Let us accept after Kaune that the effective field strength is the field strength which is established by the conductive current density—equivalent to the displacement current density—on the specific resistance of membrane. The field strength, as we may see later, is the resultant of the zero sequence component of the field strength of entirely electrical origin of the W–A model and the non-electrical origin field strengths belonging to the thermal electromotive forces.

Let us require, similarly to Kaune, that the conductivity of ion layer to be found on both sides of the membrane (armature) is very high. Then, at least at low frequencies, the displacement current density is uniform. In every membrane segment there are two stochastically changing current densities: the displacement and the conductive, where the first one is the same in each segment.

In accordance of the principle of the conservation of electric charge the displacement (capacitive) current of membrane is equal to the sum of conductive currents of segments.

\[ I_m = \sum_{i=1}^{N} I_{\mu i} \quad (15) \]

Because of the statistical independence the root-mean-square value of displacement current depends on

\[ \bar{I}_m^2 = \sum_{i=1}^{N} \bar{I}_{\mu i}^2 \quad (16) \]

namely, on the root-mean-square value of the segment currents. As we have not any preferential one among the segments, therefore they are equal, that is:

\[ \bar{I}_m^2 = NI_0^2, \quad \bar{I}_{\mu i}^2 = \bar{I}_0^2, \quad (17) \]

The introduced notation is justifiable. If we compare the above result to the form resulting from (Eq. 6) of zero sequence component, we may see that \( I_0^2 \)

is the root-mean-square value of the zero sequence component of segment currents.

To make this specific, let us imagine the following speculative experiment. If we wait sufficient time, then we have a moment when in every membrane segment the displacement and conductive current density are identical just for a moment; in this case the resulting current equals zero on the sheath inside the segment membrane. At this moment let us isolate the segments from each other. If the segment is large enough in a thermodynamic sense, then the output spectrum of displacement current density remains unchanged; and the conductance and displacement current density of the segment are equal, so that the thermal potentials of each already isolated segment become statistically independent. It is evident that the equivalent circuit of Figure 3a belongs to every segment.

From this equivalent circuit we may specify by the method followed by Kaune [2002] the quadratic average of the zero sequence current components.

\[ \bar{d}_m = \frac{1}{N^2 R_m^2} \left( \omega^2 \tau_m^2 \right) \bar{d}_0^2 = \frac{4kT \omega^2 \tau_m^2}{NR_m \left(1 + \omega^2 \tau_m^2\right)} \quad \text{df} \quad (18) \]

where we used the \( \bar{d}_0^2 = 4kTNR_m \text{df} \) Nyquist theorem. From this we get for the effective field strength of Kaune model by the application of (Eq. 17) that

\[ \frac{\text{d}E_{\text{Kau}}}{\text{df}} = \frac{1}{A_m \sigma_m^2} \frac{\text{d}I_m^2}{\text{df}} = \frac{N}{A_m^2 \sigma_m^2} \frac{\text{d}I_0^2}{\text{df}} \]

\[ = \frac{4kT \omega^2 \tau_m^2}{A_m \sigma_m d_m \left(1 + \omega^2 \tau_m^2\right)} \quad \text{df} \quad (19) \]

which is identical with the result of Kaune. Here \( \sigma_m \) is the conductivity, \( \tau_m \) is electric time constant, \( A_m \) is the area, and \( d_m \) is the thickness of the given membrane. It is easy to observe that from the equivalent circuit of Figure 3b, which is also used by Kaune in his essay, we may get the result directly.

**COMPARISON OF THE W–A AND KAUNE MODELS**

We are going to make the comparison according to Figure 3b. This equivalent circuit can be seen also in Figure 4, where we indicate the effective field strengths of each model.

Here \( E_{WA} \) and \( E_{Kau} \) are the effective field strengths in terms of the thermal noise of the membrane in accordance with the Weaver–Astumian and Kaune’s model, respectively.

We can further show that on the basis of this equivalent circuit, according to the \( \text{d}E^2 = 4kTNR_m \text{df} \)
Nyquist–Twiss theorem, we can determine the spectral power densities using the W–A model:

$$d|E_{W-A}|^2 = d\frac{|V_m|^2}{d_m^2} = 4kT \frac{1}{\sigma_m A_m d_m (1 + \omega^2 \tau_m)} df.$$  \hfill (20)

However, using Kaune’s theory, the spectral power densities are found to be:

$$d|E_{Kau}|^2 = \frac{1}{A_m^2 \sigma_m^2} dT_m^2 = \frac{N}{A_m^2 \sigma_m^2} dI_0^2 = 4kT \frac{\omega^2 \tau_m^2}{A_m \sigma_m d_m (1 + \omega^2 \tau_m^2)} df.$$  \hfill (21)

A common feature of the two models is that they use the zero sequence equivalent circuit for the specification of the noise limit.

The difference between the two models is that the W–A model assumes that field strength fluctuations are caused by surface charge density fluctuations, while Kaune’s model attributes field strengths fluctuations to zero mode membrane currents. We may see from Figure 4 that the $E_{Kau}$ field strength is the resultant of the zero sequence component of the pure electrical origin field strength of W–A model and the non-electrical origin field strengths belonging to the thermal electromotive forces.

**A NEW INTERPRETATION OF THE THERMAL NOISE LIMIT PROBLEM**

In this section, we are going to redefine and interpret the results by applying the method of symmetrical components, White and Woodson [1959]. Similarly to the previous models, we will also assume that the cell membrane can be modelled by the equivalent circuit shown in Figure 2 for the noise test. According to Figure 2 and with the help of Kirchhoff’s laws, we may show easily that the following relationship is valid between the $I$ current generated from the currents of each segment and the Fourier amplitudes of the thermal electromotive forces and the $\xi$ potential column vector:

$$I = \begin{bmatrix} I_1 \\ \vdots \\ I_i \\ \vdots \\ I_N \end{bmatrix} = \bar{L} \begin{bmatrix} \xi_1 \\ \vdots \\ \xi_i \\ \vdots \\ \xi_N \end{bmatrix} = \bar{\Xi} \xi$$ \hfill (22)

where the admittance matrix (inverse impedance matrix) $\bar{L}$ is a cyclic matrix. This cyclic admittance matrix $\bar{L}$ can be characterized by its first row: $(l_0, l_1, \ldots, l_i, \ldots, l_{N-1})$, where

$$l_0 = \frac{1}{NR_m} - \frac{1}{N^2 R_m (1 + j\omega \tau_m)},$$

$$l_i = \frac{-1}{N^2 R_m (1 + j\omega \tau_m)}, (i = 1, 2, \ldots, N - 1),$$

$$\tau_m = R_mC_m$$ \hfill (23)
is the cyclic matrix of the element. The $\tau_m$ electric time constant of cell membrane is in the interval of $1-100$ ms where we suppose that the range of membrane conductivity equals to $\sigma_m = 10^{-7}-10^{-5}$ S/m.

The eigenvalues of $\mathbf{L}$ matrix accordant to (Eq. 3):

$$\lambda_{L0} = \frac{1}{NR_m} - \frac{1}{NR_m(1 + j\omega \tau_m)} = \frac{1}{NR_m(1 + j\omega \tau_m)},$$

$$\lambda_L = \frac{1}{NR_m}, \quad (i = 1, 2, \ldots, N - 1). \quad (24)$$

Then we get from Equation 12 that the relationship of component currents and potentials can be expressed as follows:

$$I_0^s = \lambda_{L0}i_0^s = \frac{1}{NR_m(1 + j\omega \tau_m)}i_0^s,$$

$$I_i^s = \lambda_Li_i^s = \frac{1}{NR_m}i_i^s, \quad (i = 1, 2, \ldots, N - 1). \quad (25)$$

The equivalent noise circuits belonging to the equations can be seen on Figure 5.

As in the case of stochastical signals the power density itself has a sense; therefore we have to change over to these quantities in the above equations. According to Equation we may easily see that the relationship of spectral power densities is

$$I_0^{s*}I_0^s = \frac{\omega^2 \tau_m^2}{N^2 R_m^2 (1 + \omega^2 \tau_m^2)} \zeta_0^s \zeta_0^s,$$

$$I_i^{s*}I_i^s = \frac{\omega^2 \tau_m^2}{N^2 R_m^2} \zeta_i^s \zeta_i^s, \quad (i = 1, 2, \ldots, N - 1) \quad (26)$$

As the symmetrical component transformation is unitarian, it therefore keeps the power ratios in accordance with Equation 10. In our case, it means that the $E_{Kau}^{s*}E_{Kau}^{s} \sigma_m A_m d_m$ power calculated from the field strength of Kaune model is equal to the $NR_m I_0^{s*}I_0^s$ power of the zero sequence current. From this we may get the spectral power density of the effective field strength of Kaune model.

$$E_{Kau}^{s*}E_{Kau}^s = \frac{NR_m}{\sigma_m A_m d_m} I_0^{s*}I_0^s = \frac{4kT}{\sigma_m A_m d_m (1 + \omega^2 \tau_m^2)} \quad (27)$$

We can specify in a similar way the spectral power density of the field strength generated by the other components of segment currents.

$$E_i^{s*}E_i^s = \frac{NR_m}{\sigma_m A_m d_m} I_i^{s*}I_i^s = \frac{4kT}{\sigma_m A_m d_m} \quad (i = 1, 2, \ldots, N - 1) \quad (28)$$

For the comparison of each noise model we can use the spectral field strengths defined by the following relationships:

$$E_{net}^{WA} = \sqrt{\frac{4kT}{\sigma_m A_m d_m} (1 + \omega^2 \tau_m^2)} \quad (29)$$

The normalized spectral field strengths are shown as a function of normalized frequency in Figure 6 for each model.

The overall conductance current of the membrane generated by the spectral field strength has the form of

$$E_{net} = \sqrt{E_{Kau}^{s*}E_{Kau}^s + \sum_{i=1}^{N-1} E_i^{s*}E_i^s}$$

which increases indefinitely by the $N$ membrane segment number. This is why Kaune [2002] postulates that the non-zero sequential field strengths shall not be taken into account at the calculation of field strength effective in terms of noise.
These field strengths can be characterized, as we may see from Figure 5, by the fact that they do not change the charge distribution on the two sides of membrane, and solely dissipate the energy fluctuations of each membrane segment.

We know from the fluctuation dissipation theorem that every dissipation process is accompanied by the fluctuation of at least one energy type. In the case of the zero sequence current, this is the electrical energy of the membrane capacity. There is not any magnetic field in the zero sequence equivalent circuit, as the displacement and conduction current are equal and have reversed sense in the cell membrane itself.

The other current components, however, generate magnetic field. This means that the non-zero sequence equivalent circuit of Figure 5 shall be complemented by the n-times of membrane inductivity. This has the effect that the spectral power density of the non-zero sequence field strength will decrease at high frequency, because of the low membrane inductivity.

If we assume Kaune’s point of view and ignore these field strengths at the specification of the field strength effective in terms of noise limit, then at the same time we prefer the electric field to the magnetic one from the point of view of biological effect.

**DISCUSSION**

We compared the Weaver and Astumian [1990] and the Kaune [2002] models for thermal noise limits of LFEMF and provided a generalized solution to the problem. Our generalized model can therefore be used to determine if a given LFEMF could overcome thermal noise to elicit a biological effect.

As an example, we can examine the potential effects of external LFEMF sources. External sources induce a distribution of field strengths along the cell membrane. If the division of the cell membrane is sufficiently fine, the field strength can be regarded as a constant along each part of the membrane. Let us create a column vector from the normal coordinates of the field strength vector:

\[
E_{\text{ext}} = \begin{bmatrix}
E_{\text{ext} 1}^n \\
E_{\text{ext} 2}^n \\
\vdots \\
E_{\text{ext} N}^n
\end{bmatrix}
\] (31)

Since the component with zeroth index does not have a thermal limit, it can be regarded as biologically effective in the case of LFEMF. Under our assumption, this can only be the zero mode component of the above field strength, that is, if

\[
E_{\text{ext}}^s = \frac{1}{\sqrt{N}} \sum_{i=1}^{N} E_{\text{ext} i}^n
\] (32)

then the field strength is not equal to zero. The following figure shows an example for this type of field.

It is difficult to induce a pure zero mode field, shown in Figure 7, on a single cell using external field generators, since most applied external fields have translational symmetry. However, there are self-induced and non-direct methods of constructing zero-mode external field components. An example for self-induced zero mode field would be a perfectly uniform action potential exhibiting spherical symmetry, or possibly a piezoelectric-like processes during cell growth.

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**Fig. 6.** Comparison of noise models on the basis of their spectral field strength. The axis denotes the normalized frequency, while the y-axis denotes the normalized thermal field-strength.

**Fig. 7.** Example for an electric field with components of zero mode only.
Artificially, we can produce pure zero mode field indirectly by changing the extracellular matrix (ECM) composition and thus inducing ionic currents, or by heating the ECM and thus producing thermo-diffusion. Both of these methods induce a centrally symmetric effect by the surrounding ionic or thermal gradient through the cellular membrane.

Heating of the ECM could be achieved by capacitively coupled electromagnetic field application within a certain frequency range Szasz et al. [2001, 2003]. Provided that the frequency is low enough, the fields do not readily penetrate the cell membrane and thus the bulk of the energy is deposited within the ECM. This leads to thermal gradients (currents) from the ECM towards the inside of the cell. This thermal current also carries ions through, leading to thermo-diffusion and thus creating a zero mode electric current, which in turn induces a zero mode electric field in the cell membrane. Therefore, even small fields with zero mode components could elicit biological effects.

Note that these calculations primarily considered situations in which the thermal energy noise was significantly higher than the external electromagnetic effect in the low energy range [Szasz et al., 2003]. Although these methods are true in general, there could also be frequency and noise mode spectra, where the signal to noise ratio is clearly dominant, resulting in an effective low energy external signal [Adey, 1983; McLeod et al., 1992; Adair, 2003].

We may raise the question whether we could always ignore the non-zero sequence quantities at the specification of noise limit. The answer is no in the case where each of the membrane segments has different electrical properties, for example because of an illness. In this case, the impedance matrix is not cyclic, and for this reason the different noise components are coupled. Thus, at the calculation of the field strength effective from the point of view of noise, all components shall be taken into account.

The above conclusions are valid also for the W–A model.

REFERENCES

Portier CJ, Wolfe MS. 1998. Assessment of health effects from exposure to power-line frequency electric and magnetic fields. NIH publication 98-3981, National Institute of Environmental Health Sciences, Research Triangle Park, NC.