

Report from a Workshop on:

17th - 19th December 2001, Dresden (Germany)

„Physical Effects of at Microscopic and

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Brief summary

This workshop concerned several questions that bear on improved understanding of interactions of radio signals used in wireless communications with living systems: Are there physical mechanisms for effects of radiofrequency (RF) exposure in the absence of significant heating of the body? Are there physical mechanisms that could allow responses to modulated RF energy? Are there credible biophysical mechanisms, for example, involving energy transfer over molecular dimensions, that could lead to such effects? Are there hot spots at microscopic and molecular dimensions, or are hot spots possible only at anatomical dimensions? In reply, workshop attendees recognized that any temperature elevation over a small region would be very short-lived. The characteristic time for thermal equilibration of a

spherical object, for example, is proportional to the square of its diameter, showing that the temperature increase of any object of microscopic and molecular dimensions would be exceedingly small for realistic RF exposure levels.

Speakers at the workshop described the remarkable range for dielectric constants at molecular and supramolecular dimensions, for example, comparing water, protein, and lipid regions in the cell membrane. The limited extent of knowledge about short-range, short-term molecular energy transfer and the absence of expertise in this area among those at the workshop showed the need for additional review to more fully understand molecular energy absorption processes that might explain physical and biochemical changes in the absence of an overall increase in temperature. To date, no accepted theory exists to support the proposition that fast energy transfer processes (i.e., interactions of the RF-field with a biological molecule that occur on the 1-100 nanosecond time scale typical of some structural transitions) could affect biological systems, as suggested by limited and controversial experimental data in the biological realm. An initial approach to a quantum mechanical model of molecular vibrational modes was attempted at the workshop and led to the realization that vibrational modes excited by RF energy are at frequencies far below

(„Hot spots“ are regions of stronger energy absorption that might be heated to a temperature above the surrounding region.)

Depending on hot spot size and the effectiveness of heat removal, there may be no measurable increase in local or whole system temperatures.)



Pulsed RF Fields

Molecular Dimensions (Microdosimetry)

those corresponding to biological processes of energy transfer, which occur above 100 GHz.

The various theoretical approaches discussed at this workshop were undertaken to sharpen understanding of the mechanisms of RF-field effects in support of existing exposure limits or to develop alternative limits through new research.

In general, the discussions at this meeting reiterated the widely accepted view that RF fields at intensities that do not result in a general temperature increase are not able to cause biological reactions.

I. Background and intentions of the workshop

Rapid technical change in wireless communications and ever-wider human exposure to its radiofrequency (RF) fields add urgency to resolving long-standing questions about the nature of biological effects of RF exposure. This workshop continued discussions begun at a workshop held in Bad Münstereifel (Germany) in December 2000. The report of that meeting contained the conclusion, „Research on microdosimetry that applies interactions were discussed. (Reports from these meetings appeared in FGF Newsletter 1/01, p. 1ff, and 2/01, p. 26ff; <http://www.fgf.de> Publications.)

Public interest mostly focuses on the question, „Are there physical mechanisms

for effects of RF exposure in the absence of significant heating of the body, including responses to modulated RF energy?“ Frequently, the question is asked in context of wireless devices used for mobile telephony that operate in the range 0.9 to 2.4 GHz.

Electromagnetic fields at these frequencies often are called microwaves. Effects that are not caused by heat and those which occur when heating changes temperature insignificantly often are called „non-thermal effects.“ In contrast, „thermal effects“ are those attributable to an increase in temperature, which is the only established mechanism for biological effects of interaction. Although there is no direct evidence that nonthermal RF exposures adversely affects human health, and studies designed to identify biological hazards have generally been negative, questions persist. In part, this is because it is not possible to exclude adverse health effects without exhaustive studies, and in part because of experimental data, largely from studies of cells and tissues, that suggest there may be nonthermal effects.

As an alternative to the conduct of exhaustive studies without guidance from physical theory, this workshop focused exclusively on theoretical concepts that might show the plausibility of nonthermal effects and did not attempt to evaluate the experimental data.

The workshop was conceived with the expectation that research stemming from physical concepts can be used to develop consensus on the mechanisms for non-thermal effects and whether these are plausibly connected with exposures to common RF energies.

Five topics were chosen for discussion:

- The dielectric structure and RF-relevant properties of cells and membranes
- Energy absorption in tissue
- Heating of microstructures
- Energy absorption and transfer in molecular systems
- RF-demodulation by non-linearities of biological systems

dielectric theory to cells and subcellular entities is needed to achieve a better understanding of the manner in which RF energy might influence biochemical processes at microscopic dimensions“. This recommendation led to a subsequent meeting at Washington, DC in May 2001, where biophysical models of RF-frequency Advances on the last three topics depend on the first two, that is, on knowledge of the energy distribution in the tissues, cells, and subcellular constituents of the exposed biological system. Dielectric inhomogeneities occur from the limit of anatomical resolution (~1 mm) down to microscopic (less than ~10⁻² mm) and molecular (~10⁻⁹ mm) dimensions. Determinations of the spatial distribution of RF energy absorp-



tion by molecules and supramolecular assemblies at small distances and over brief durations are referred to as „microdosimetry.“ The inhomogeneity of dielectric properties of diverse cellular constituents (membrane lipids and proteins, bound water, cytosol, and mobile ions) and the possibility of locally enhanced energy absorption stimulate the need for deeper insight into the molecular mechanisms of RF energy absorption. It has as yet not been possible to rule out all possibility that such absorption might lead to effects distinct from those described by an overall increase in temperature.

The proposition that RF exposure too weak to significantly increase temperature might be accompanied by micro-thermal effects has been around for many years. The term „micro-thermal effects“ is used to mean either a persistent localized increase in temperature of very small magnitude or transient increases at microscopic or molecular dimensions. Could such microheating exist and be a „non-thermal“ mechanism for RF interaction? The response obtained from calculations that could easily have been made prior to the workshop was that it is impossible to maintain temperature gradients at microscopic dimensions because thermal time constants at the cellular scale (tens of micrometers) are so short (less than one millisecond) that any steady state temperature difference would be negligibly small. Thermal time constants decrease with the square of the size of the region. For example, they are of the order of one nanosecond for a submicroscopic object about $3 \cdot 10^{-8}$ m (0.03 micrometer) in extent. As a result, over subcellular distances thermal time constants are in the range of microseconds to nanoseconds. Despite the inherent implausibility of the

occurrence of microscopic „hot spots“ at any significant level, further consideration of microheating was put on the workshop agenda to evaluate the conjecture that other modes of energy transport within macromolecules, which cannot be characterized in terms of macroscopic heat conduction, might be significant in producing biological effects from RF exposures. This decision was taken with recognition of the exceedingly tiny increases in temperature that can be produced by „microheating“ over molecular, macromolecular, or cellular distances at reasonable SAR levels. The purpose of the discussion was to explore the possibility that molecular events caused by RF energy might occur over times as brief as approximately one nanosecond, which is long enough for a conformational change in a protein, assuming the availability of sufficient energy.

Workshop participants discussed a potential mechanism for low intensity RF-field interactions with ionic motions at some length. Although simple calculations can rule out direct field effects on ion velocities and trajectories in aqueous solution by low intensity fields, discussants examined the possibility of other mechanisms that could influence transmembrane ion transport, for example, involving ballistic conduction in ion channels.

If substantiated, such mechanisms also suggest non-linear effects on ion channel conduction and might predict biological responses to modulated RF fields. Such effects would render credible alterations in the regulation of various cellular processes, many of which depend on transmembrane ion transport, thereby radically changing the picture from present-day beliefs concerning biological potency of low-intensity RF fields.

2. Program and course of the workshop

The workshop did not feature general lectures because it was intended that most of the meeting time be used for technical discussions that would better clarify points of agreement and disagreement among the participants. A number of short papers were presented to stimulate discussions through brief presentations of experimental facts, theoretical considerations, and personal statements. To maintain focus, Asher Shepard (USA) moderated the workshop discussions. The interconnected nature of the meeting topics resulted in a flow of discussion that did not follow the proposed format in a linear way and resulted in inadequate attention on some topics. Discussants raised additional ideas that will need quantification in the future.

3. Principal results of the workshop

The dielectric inhomogeneity of tissue and biological cells

The first research question, „How do the inhomogeneous and anisotropic dielectric properties of cells, cell membranes, and other cellular constituents affect the spatial patterns and time constants of energy absorption at cellular and subcellular dimensions?“ was addressed along lines provided in presentations by James Weaver (USA) and Jan Gimsa (Germany).

Weaver presented calculations based on a lattice model of the type used for electrical transport problems to estimate field distributions in tissue. The geometric form of the model treated a particular arrangement of cells in skin tissue that was intended to be representative of anatomical structures. Differences in the electrical conductivities of cells and intercellular space as well as the variability of the geometri-

cal cellular arrangement led to a frequency dependent inhomogeneous field distribution. In discussion, Weaver indicated that the ratio of peak to average energy absorption could range from about 2 or 3 to a not yet defined upper limit („several fold“). However, even for the maximum field strengths permitted by international exposure standards, the resulting temperature differences in regions of peak absorption are negligibly small.

Jan Gimsa presented a new approach to modeling the field distribution in RF-exposed cells. Cell fields depend on cell geometry, electric properties of cell membranes and fluid media, and frequency. The calculated field distributions have been verified by experimental data obtained from single cell dielectric spectroscopy, using techniques such as dielectrophoresis and electrorotation. Human red blood cells provide the simplest system for study, but nevertheless the cytoplasmic properties of these cells exhibit a complex frequency dependence that reflects relaxation of interactions with protein structural cores, side chains, and bound water. Initial approaches treat a complex membrane structure consisting of lipid and protein domains that are hydrated and associated with bound water layers.

Later in the meeting, Dean Astumian (USA) pointed out that dielectric spectroscopy measures a „non-thermal“ response, a point with which Kenneth R. Foster (USA) agreed, and which Foster noted is made possible because these techniques measure a macroscopic polarization in a large ensemble of polarizable elements. The electric fields applied in these techniques are generally far below levels at which significant thermal effects occur.

The molecular structure and dynamics of lipid membranes and for protein do-

mains in membranes have been extensively explored, both theoretically and experimentally, although much more work remains to be done. Membranes exhibit a complex anisotropic, frequency-dependent structure and proteins in both membranes and cytoplasm can have markedly greater dielectric permittivity and conductivity than those of the surrounding lipid.

Differences in energy absorption, „hot spots“, „microheating“, and temperature gradients

A major focus of the workshop was directed to quantifying the differences in RF-energy absorption at microscopic and/or molecular dimensions and determining if these differences or associated temperature gradients and energy transfer could influence biological functions. Foster reported that microthermal heating had been considered and determined to be negligible (Schäfer and Schwan, 1943). He and Christopher Davis (USA) pointed out that the characteristic time for heat transfer to or from a sphere is in the range of 1 microsecond for a 1 micrometer object and in the picosecond and sub-nanosecond range for molecular size structures with dimensions of nanometers.

Schäfer and Schwan (1943) calculated there could not be significant temperature differences for water droplets suspended in oil or oil droplets in water, even for droplets with diameters in the millimeter range. Foster also emphasized the dominant role of viscous damping in preventing the occurrence of resonances postulated by various researchers and on occasion reported in experiments that later proved flawed. Davis pointed out that RF and conventional heating were not entire-

workshop results

ly equivalent because RF heating can produce temperature gradients of macroscopic size, although smaller than the scale of anatomic structure. In liquids, such as the media of *in vitro* experiments, the temperature gradients generate diffusion and convection that cause mixing. Mixing could affect nutrient supply to cells of *in vitro* experiments with potential effects on cell proliferation. Davis stated that some research papers may have mistakenly reported changes in cell proliferation as effects of RF fields although they actually had this artifactual cause. In summary, the rapid thermalization of heat in small structures that might selectively absorb RF energy assures there cannot be significant thermal gradients within a cell or subcellular component

These theoretical considerations were supported by experiments with RF pulses with extremely high peak power levels. Andrei Pakhomov (USA) reported results from neurophysiological studies of rat hippocampal brain tissue exposed to 0.5 second pulse trains at a time averaged SAR of 0.4 kW/g (4·10⁵ W/kg). The individual pulses were on the microsecond time scale (0.5 – 2 microsecond) with peak SARs of 1 MW/g (10⁹ W/kg). By using these extremely high peak SAR levels, the experiment was designed to provide definitive answers concerning possible hot spots created during pulses of a microsecond and longer. Electrophysiological measurements were made within 10 ms of the end of the 0.5 s exposure period. Pakhomov found a transient suppression of population spikes that was dependent on tissue temperature, but for all temperatures below 47°C, the tissue responses recovered almost completely within 10 s. Tissue temperature increases were adjusted by changing pulse repetition rate and therefore also chang-

ing the total number of pulses and total energy input. Pakhomov concluded that exposures to more common RF fields with peak and time-averaged SAR orders of magnitude less than those he applied are extremely unlikely to cause bioeffects due to transient „hot spots“ or other kinds of local heating.

William F. Pickard (USA) presented some rough calculations to show that typical energy inputs in RF experiments with biological systems and in maximal exposures permitted by existing standards were far too small to affect transmembrane potential or to achieve an appreciable signal-to-noise ratio. For example, RF exposure at a SAR of 100 W/kg would, for a 10 nm thick membrane, produce a transmembrane voltage below 40 microvolts, less than typical membrane electrical noise and far too little to influence cellular behavior. Any effect on ion mobility in this case would be unrealistic. As a demonstration of how weak microwave energy is compared with the energy needed for chemical and physical reactions, Pickard calculated that the energy density of a microwave frequency field is so low that it would require one second for a cube 7.5 nm on a side to absorb energy equal to kT (0.027 eV at 37°C) when exposed at a SAR of 10 W/kg. The corresponding volume of 430 nm³ is sufficient to contain many small molecules. The quantity kT, a benchmark of thermal energy in any material, is already small compared to chemical bond energies and would have to be concentrated at some molecular site to be a factor in chemical reactions. The conclusion drawn from this calculation is that even for exaggerated values for SAR, absorption volume, and absorption time, the total microwave energy in tissue is far too weak

and diffuse to cause biochemical effects by direct action of the field in contrast to indirect effects caused by heating.

Molecular processes of energy absorption and transfer; dynamical systems

The above calculations of absorbed energy and equilibrium thermal properties are based on phenomenological equations of physics applicable to systems that are „large“ in the sense that they contain enough molecules to use statistical averaging, and are more or less homogeneous. As a result, parameters like „temperature“, „density“, and „heat conductivity“ can be used without considering molecular structure and heterogeneity. This approach is justified for describing bulk properties. The same perspective applies to the definition of SAR and to the recommendations on exposure standards from national and international agencies that use averaging over macroscopic volumes and for times that range from seconds to minutes. A thorough assessment of possible influences of RF-energy absorption on particular processes of biological systems, however, requires a biophysical examination of individual molecules, molecular subgroups, and molecular groupings.

Earl Prohofsky (USA) addressed this issue with respect to energy transfer in system consisting of DNA and associated enzymes, particularly the bonding of a DNA double helix and a repressor molecule. Quantum-mechanical calculations for these bonds are formulated in terms of molecular modes of vibration and translation and their interactions that set a scale for molecular interactions of this type. Biological macromolecules surrounded by water, other molecules, and ions can be described by one of these excitation modes:

- Type 1: Intramolecular modes—excita-

tions (usually vibrational modes) that are primarily localized to the macromolecule itself, that is, these modes are not caused by vibrations in the surrounding environment of water and other molecules („bulk material“).

- Type 2: Bulk modes—excitations that the macromolecule participates in, but are strongly coupled to the bulk material around the molecule.

The possible effects of RF fields on biomolecular systems fall into two categories:

- RF absorbing modes—usually vibrational modes of either above types 1 or 2 that can resonantly absorb RF energy.
- Biologically active modes—excitations that bring about the biological function of the molecule. When the mode has a large amplitude, the repressor molecule is dissociated from the helix, making possible production of messenger RNA, which could be either desirable or inappropriate. All known biologically active modes are intra-helical modes (Type 1), which, for DNA, are in the THz (10¹² Hz) frequency region.

For DNA and associated enzymes, the calculated relaxation time between the double helix and its associated water is about 50 ps, corresponding to 20 GHz. Consequently, all modes at GHz and lower frequencies that are excited by RF energy absorption must be bulk-type modes (type 2). These bulk modes interact more strongly with other bulk modes than with type 1 intra-helical modes. It is also important to recognize that the large number of bulk modes is associated with a large specific heat and the rapid thermalization of RF energy.

To evaluate the probability of athermal biological effects, two steps need to be

considered: first, energy flows to molecules heterogeneously absorbing RF energy, and second, energy transfers between the RF-frequency absorbing mode and the biologically active mode. A large group of strongly coupled bulk modes exists near the absorbing mode. To realize an athermal effect, a significant fraction of bulk mode energy would have to transfer to the biologically active mode. However, such coupling between modes that differ in frequency and have very different degrees of localization should be very small. Prohofsky suggested that something might be learned from a careful, detailed analysis of other biologically important molecular mechanisms, for example particular protein systems. Friedemann Kaiser (Germany) remarked that the foregoing picture, although „99% correct“, ignores intermolecular modes that can reduce the magnitude of the energy gap between RF-pumped modes and biologically active modes.

In this context, Kaiser observed that although there was no satisfactory nonthermal model for coupling of RF energy to biological systems, the organizational and functional characteristics of complex, self-organizing, thermodynamic systems operating far from equilibrium should give pause before dismissing all possibility of a response to an energetically weak signal. Such systems can feature emergent properties where the whole is greater than the sum of the parts. Regarding cellular biochemistry from the perspective of coherent dynamical molecular machines, a cell is very different from a chemical reactor. A relatively few molecules (numbering in the tens) located in a particular place and time of a cell can be functionally significant whereas chemical reactors typically have thousands or more interacting mole-

cules in a homogeneous mixture. Kaiser cited data from oscillatory reaction cycles that can have relatively long periods and synchronization between internal modes and modulating signals with amplitude sensitivities that vary by factors of hundreds or thousands depending on their relative frequencies. These behaviors are typical of dynamic systems with multiple cooperative components that are interacting. A related consideration comes from the example of stochastic resonance, where, in some well-known examples, the addition of noise can enhance system output even for low signal-to-noise ratios. Enhancements can range from modest factors (e.g., ~ 2) to factors of several hundred, but stochastic resonance is not capable of overcoming signal-to-noise ratios $\ll 1$.

Possible influence on mechanisms of ion transport

Astumian described an ion transport model with two parameters representing a barrier height and potential well depth. Postulating that RF energy perturbs both parameters of the potential in the channel, the ion flux would be bilinear in these perturbations and nonlinear with respect to the RF frequency. Astumian stated that the model, which assumed ballistic conduction within the channel, showed that noise was not a fundamental limitation. Astumian's model treats pore formation in a barrier about 100 times thicker than a cell membrane. Experimental support comes from the properties of electron transport at a low temperature (40 K). Although this particular system is not a model for biological membrane transport mechanisms, Astumian cited it as an example of a kind of transport system that could be influenced by very weak perturbations,

such as from a RF field. He left open the possibility that ion conduction in membrane-spanning ion channel proteins might be analogous. Jürgen Rabe (Germany) doubted the existence of ballistic conduction for ions in a channel and Roland Glaser (Germany) remarked that ion channels occur only in some specialized cells, such as neurons, whereas usually ions cross the membrane via specific transport systems, for example, antiporters and symporters. Christopher Davis (USA) stated that if the model were made quantitative and noise were included, it would, like soliton models, be found unrealistic. Astumian replied that although soliton lifetimes may be short because of collisional damping, they nonetheless exist for a brief time. Davis asked what useful role could be played by such a transient phenomenon.

Davis also challenged the realism of the analogy with low temperature electronic transport because a direct influence of RF-fields on ion movement is quite impossible. The mobility of an ion (which is much more massive than an electron) is far too small for any significant influence of fields at RF frequencies. He pointed out that the typical ion displacement during a half cycle of the field is less than the diameter of an atomic nucleus.

Although a dynamical effect on ions did not seem realistic, a RF field of sufficient strength might affect ion transport mechanisms by modification of transport proteins or other conditions inside or near the membrane. In this context, Günther Boehm (Germany) demonstrated reproducible experimental data of membrane single channel currents over a range of RF powers. The data indicated an immediate (within 10-50 ms) influence of a 900 MHz field on ion transport through artificial membranes (BLM) containing the ionophores

gramicidin or alamethicin. The geometry of the exposure system created a very strong RF field at the membrane. An observed linear dependence on power was consistent with a temperature effect on the ionophores, but a direct temperature measurement without a membrane in place showed an increase at the membrane site that nonetheless was too small by a factor of ~ 3 to fully explain the data. Discussion produced doubts that there were any effects besides those of heat.

Several discussants expressed the opinion that the mechanism underlying the effects of RF on channel conduction in these experiments is unsettled.

Dielectrophoretic forces

Frank Barnes (USA) pointed out that although dielectrophoresis is a well-known mechanism, its potential role in RF-field effects has not been explored fully. The dielectrophoretic force exerted on an induced dipole moment by an electric field with a spatial gradient may lead to drift currents of proteins and other large molecules.

Because the induced dipole moment reverses with the changing direction of the applied RF field, the force is similar to that would be exerted by a DC gradient field on a molecule with a permanent dipole. Foster noted that the quadratic dependence on the electric field makes demodulation a possibility. Gimsa observed that more generally one could consider dielectric effects causing deformation, orientation, and rotation. Barnes' initial calculations using Brownian dynamics in one dimension showed that the dielectrophoretic force leads to a net displacement of a particle for the condition of a very large gradient occurring over a distance of a few atoms. Barnes noted that a large

RF field gradient occurs as a result of the discontinuity in the dielectric constant between the extracellular fluid and a cell membrane, leading to a membrane electric field strength that is estimated to be between 30 and 40 times the average field in the tissue and large gradients over the double layer at the membrane surface. Further calculations are in progress to determine the potential biological significance of dielectrophoretically induced RF currents of proteins and other molecules using at least a two dimensional simulation of the interface at the nanometer scale.

Are there plausible mechanisms for demodulation of amplitude-modulated RF fields?

This question is important because demodulation of amplitude variations of a carrier wave could lead to effects unique to particular modulation frequencies or pulse rates. As mentioned above, this question was discussed at the Bad Münstereifel 2000 workshop with the conclusion that there were no defensible models for physical demodulation of amplitude-modulated RF. Pickard restated previous conclusions based on a model for demodulation that shows electrical rectification at the cell membrane can occur because of asymmetrical ionic mobility across the membrane. This mechanism does not apply above several megahertz because, as has been shown experimentally, ions cannot traverse the membrane fast enough to follow the changing field, indicating that if there is demodulation, it does not involve transmembrane electrical rectification. Astumian and Glaser recognized that demodulation is possible without affecting ion transport kinematically. For example, oscillatory temperature shifts of a charged structure such as the electrical double lay-

er or proteins with strong dipole moments could yield periodic charge displacements to generate low frequency fields in this way.

Although a low frequency electric field could result from those processes, it would be very weak and unlikely to produce effects. This hypothetical mechanism is not yet developed with sufficient detail to make a quantitative assessment of its significance. Astumian and Barnes also noted that RF heating, which is proportional to the square of the electric field strength, follows the time course of any pulse or amplitude modulation of the carrier, that is, the time course of heating follows the carrier envelope and serves to demodulate the signal. Strong, brief pulses, for example, could produce brief temperature pulses that, however, do not result in a sustained temperature increase measurable by typical thermometry.

4. Conclusions

This workshop emphasized several statements of the previous meetings and drew attention to a few open questions needing future investigation. Anatomy and differences in the dielectric properties of biological structures result in macroscopic inhomogeneities that can produce hot spots in the distribution of RF energy absorption and possibly regions with higher tissue temperature. Because the characteristic time for thermal equilibration is proportional to the square of the size of a region, the temperature of a microscopic object quickly reaches the temperature of surrounding materials. A cell, cell membrane, and structures of molecular size that may absorb more energy than surrounding matter nonetheless remain at essentially the same temperature as the surrounding matter. This statement was generally accepted by meeting participants



because the characteristic time for temperature equilibration of supramolecular structures lies in the range of nanoseconds.

Recent progress in single cell dielectric spectroscopy can reveal differences in dielectric constants, for example, between protein and lipid regions in the cell membrane. Knowledge of the ultrastructural dielectric properties over a range of frequencies allows calculation of RF energy absorption at this fine-grained scale. Future research in this area can be expected to yield data valuable for quantification of RF energy absorption within cellular structures.

Considering these ultrastructural dielectric heterogeneities, the question of microthermal

effects can be restated in terms of possible effects induced by energy flow between structures having different energy absorption. Theoretical investigations of molecular energy transfer will require new biophysical models using the concepts of quantum and statistical physics. Preliminary discussions at the workshop favored studies of the vibrational modes of molecular systems, particularly interactions between modes with different frequencies, although it seems that biologically important molecular interactions occur at much higher vibrational frequencies than could be generated by RF fields. Model systems may benefit from consideration of the properties of ligand-activated receptor proteins, an approach that may benefit from

the active theoretical and experimental work on receptor proteins in mainstream molecular biophysics.

Future workshops on biophysical interactions of RF energy would benefit from the input of specialists in molecular biophysics whose work can entail processes that occur on time scales similar to those defined by both RF carrier waves and their much slower modulations. Concerning effects that may occur in the absence of general heating, these questions outline the issues needing clarification in order to more fully understand

RF energy absorption on the molecular scale and at short times:

- What are the molecular modes underlying the biochemical processes of biological importance?
- Can biologically relevant modes be coupled to RF energy absorption, and if so, how?

Investigations on this problem also will benefit from the above-mentioned research in dielectric spectroscopy.

Although demodulation by membrane rectification can be excluded, other demodulation mechanisms that may apply to the double-layer or molecular dipoles should be given quantitative form in future investigations, despite expectations that they are likely to be very inefficient. In general, the discussions at this meeting did not encourage the prospects of discovering biophysical models for effects from modulated or unmodulated RF fields

at intensities which do not result in a general temperature increase. The workshop disclosed areas worthy of further quantitative exploration by theoretical methods and other areas for which the participants did not have sufficient knowledge or expertise to draw firm conclusions.

Sponsorship and attendance

The meeting was sponsored by FGF (Forschungsgemeinschaft Funk) in cooperation with „Berufsgenossenschaft der Feinmechanik und Elektrotechnik“ (BGFE; Workmen's Compensation Board for Precision Mechanics and Electrical Engineering), and the European action „Cooperation in Science and Technology“ (COST) 281. The 43 meeting participants included experts from Germany (25), Sweden (2), USA (10), UK (2), and one each from Denmark, Finland, Hungary, and Italy.

References

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