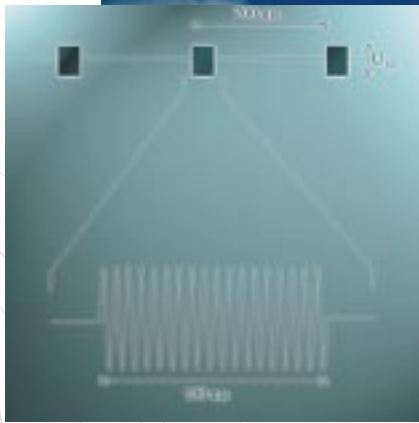


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Guidelines for Experiments to Investigate the Effect of Radio- Frequency Electromagnetic Fields on Biological Systems

- Radio-Frequency Aspects -

V. Hansen



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Editorial

Dear Readers,

with this English interpretation of the "Guidelines for experiments to investigate the effect of high-frequency electromagnetic fields on biological systems", originally published in German as volume 11 of the "Edition Wissenschaft" – September 1996 – of the Forschungsgemeinschaft Funk e.V., we try to meet numerous requests out of the scientific community.

In Germany, the Forschungsgemeinschaft Funk started in spring 1994 an initiative in order to enlarge the basis for experiments on the highly complex field of research with high-frequency aspects. A group of scientists from Germany started the work of compiling these "Guidelines" to give a sort of assistance for the planning, execution and evaluation of experiments which are usually carried out according to very different criteria. Consequently the comparison of the results of experiments with initially very similar objectives is often impossible.

Gerd Friedrich

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Guidelines for Experiments

to Investigate the Effect of Radio-Frequency Electromagnetic Fields on Biological Systems

- Radio-Frequency Aspects -

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1 Introduction

In recent years public interest concerning the effects of electromagnetic fields on biological systems has markedly increased. This interest is also reflected in a continually growing number of very different experiments in this area. Nevertheless, the increasing effort expended so far has not necessarily led to the public being better informed. Also the scientists who deal with this subject in depth can often only check the value of a new publication with great effort or frequently not at all. The reason for this is that, apart from the complexity of the research subject, the planning, execution and evaluation of experiments is usually carried out according to very different criteria. Consequently the comparison of the results of experiments with very similar initial objectives is often impossible.

In order to improve the basis for future experiments, a group of scientists from the Federal Republic of Germany started, initiated by the Forschungsgemeinschaft Funk e.V. in spring 1994, the work of compiling 'Guidelines for Experiments to Investigate the Effect of Radio-Frequency (RF-) Electromagnetic Fields on Biological Systems'. The editor is the author of this report, which summarize the considerations and discussions.

Experiments with low-frequency electric or magnetic fields are not the topic of the guidelines, though the lower frequency-limit is not defined too strictly. Up to higher frequencies the range of cm-waves shall still be included. This restriction is not made because effects can be excluded for even higher frequencies; rather, the recent emphasis on the application of RF-fields in industry, medicine and communication technology, covering a range of

some MHz up to some 10 GHz, creates an enormous demand for new knowledge.

Experiments on the effects of electromagnetic fields on biological systems require different kinds of approaches, methods and techniques from various disciplines like biology, physics, chemistry, medicine and electrical engineering, i.e. intensive interdisciplinary working. The main emphasis of these guidelines is put on the RF-aspects, but is also addressed to all disciplines involved. Hence one obvious difficulty in compiling the guidelines is that one can hardly presuppose the same language and the same state of knowledge in all of the mentioned groups. Moreover, the guidelines can neither replace textbooks on RF-technology (cf. [1], [2]) and field theory (cf. [3], [4], [5], [6], [7]) nor give an extensive description of each of the RF-aspects. They shall rather state some aspects which

should, according to the author, be considered in the concept, performance and evaluation of the experiments. This list of points is by no means complete. It is mainly based on the experiences made in the performance of previous experiments. The list should not be considered as finite, but shall be expanded with further knowledge.

The planning of an experiment is essentially determined by its proposed aim. Section 2 therefore describes and briefly discusses some possible aims. Section 3 deals with general requirements for experiments, which are in principle familiar to each scientist. Practice reveals, however, that due to the high expenditure connected with the experiments it is often not possible to respect them to a desirable degree. It is rather necessary to balance out completeness and economically justifiable expenditure. To make this easier, it seemed useful to list the general requirements here. Section 4 lists a catalogue with the criteria for the composition of the RF-measuring device. The chosen order had proved to be appropriate on the planning of various experiments. Section 5 gives a short characterisation of fields which are common in field theory to facilitate the choice of a suitable field. In section 6 some aspects of the forms of the signals are discussed.

The author is conscious of not having mentioned many important aspects. On the one hand he wanted to limit the content of the guidelines, on the other hand some aspects are only clarified in a concrete situation. Section 7 therefore reports experiences

gathered in three recent experiments initiated by the Forschungsgemeinschaft Funk. Only fundamental considerations are mentioned here. Further information is given in the reports published in the 'Edition Wissenschaft' by the Forschungsgemeinschaft Funk (see references). Section 7 is to be continued, once further projects with regard to the points of interests have been performed and analysed. The reader can find a detailed description of an exposure-device in [8].

A checklist for the planning and performance of measurements, taken from the series 'Umwelt', no. 164 of the BUWAL, Swiss 1992 is given in the appendix [9], as well as a brief description of the most important numerical methods for the analysis of field-problems.

The results of epidemiological studies cover a wide area of public discussion. In the course of these studies extensive RF-technical works often need to be carried out (e.g. measuring of field strengths). However, they are only concerned with observations and descriptions. Hence, epidemiological studies are not part of the experiments of interest here.

For the performance of experiments often certain preliminaries have to be obeyed. The author particularly emphasises DIN/VDE 0848 'Sicherheit bei elektromagnetischen Feldern' (Safety in electromagnetic fields). Part 1 contains 'Meß- und Berechnungsverfahren' (Methods for measurement and calculation) [10], part 2 deals with the 'Schutz von Personen im Frequenzbereich von 30 kHz bis 300 GHz' (Protection of

persons in the frequency range from 30 kHz to 300 GHz) [11]. Also of importance are here the reports of the Federal Office for Radiation Protection, Germany, volume 16: 'Nichtionisierende Strahlung' (Non-ionising radiation) [12] and volume 22: 'Schutz vor elektromagnetischer Strahlung bei Mobilfunk' (Protection against electromagnetic radiation of mobile communication systems) [13].

2 Aim of the Experiments

2.1 Detection of Possible Effects

The aim of most published studies is to detect the effect of electromagnetic fields on biological systems. The term 'effect' in its wider context describes a causal relation between an electromagnetic field, that exists nearby a biological system and a chemical and/or physical reaction of the system. The effect on higher living creatures also includes changes in the behavior, for instance. The problem of evaluating such effects can be put aside here (differentiation between thermal and nonthermal effects, occurrence of damage, consequences for health, therapeutic effects).

So far there are no secured hypotheses that are generally acceptable as a starting point for the design of experiments. As a consequence, the experimental details vary extremely with regard to both the RF-technical as well as the biological aspects. One aim of the guidelines should be to re-

duce this great variety for future experiments at least with regard to the technical parameters, and, if possible, to obtain a more standardised procedure.

2.2 'Proof' for the Exclusion of Effects

Public discussion frequently claims to carry out appropriate experiments to prove that effects can be excluded. This 'zero-proof' is in principle not practicable. It is nevertheless sensible to prove that with the methods of measurement and evaluation available today no effects can be observed within a certain experimental configuration. A frequent starting point for such reflections are concrete technical applications of RF-electromagnetic fields. These result in the conditions for the experimental parameters. Strong restrictions of the sets of parameters in real technical applications are necessary in order to work with a tenable expenditure. It must be emphasised, however, that the experimentally gained knowledge is primarily only valid for the actual experimental set-up, which is described by a number of technical and biological parameters. Further conclusions and generalizations are only of limited validity.

Generally, the same considerations apply for experiments to prove the exclusion of possible damage of biological material by electromagnetic fields. It is therefore first necessary to carefully distinguish the term 'damage' from the more general term 'effect' with the help of physicians and biologists.

2.3 Confirmation and Refutation of Theoretical Concepts and of Hypotheses

For the formulation of hypotheses about possible effects only initial steps have been made so far. Pre-set standards for experiments to confirm or disprove these steps cannot be formulated at the moment, as they need to be derived from the specific hypotheses. The same holds if single parameters of a theoretical model shall be determined experimentally.

2.4 Repetition of Experiments for the Confirmation or Refutation of Published Results

Experimental findings on complex problems can only be considered as valid if they have been confirmed by at least one other independent experiment. A great variety of experimentally gained statements has been published in this field which are partly very contradictory; therefore the verification at least of the most important statements must be particularly emphasized. The corresponding experiments first need to follow the experiments that are to be repeated as closely as possible. Only in a second step modifications of the experiment or of its evaluation can be made in order to verify the previous results (i.e. confirmation of the findings, verification of methodical mistakes of the initial experiment).

3 General Requirements for the Experiments

This section is only included in the guidelines for the sake of completeness, since the factors listed apply to any scientific experiment and hence are familiar to every scientist. Practice reveals, however, that they are often not respected to the desired degree.

The results of an experiment in the present field of interest should be considered as temporary until they have been confirmed by at least one other experiment carried out by a different group of scientists. Essential prerequisite is that each step of the experiment - from the fixing of the initial situation via its performance up to compiling the results - can be reproduced. This statement also holds for the biological aspects such as the selection of method, material, etc. However, as the guidelines only deal with the RF-technical aspects of the experiments, this shall not be dealt with in depth.

The first requirement for the RF-experimental set-up is to select a uniquely defined type of field (see chapter 5). Generally, one can also apply fields which can be described by a superposition of defined field-types (e.g. representation of a field by superposition of plane waves). It is, however, disadvantageous that a higher number of field-parameters is required to specify such fields than for the application of only one field-type. The exposure-device must be constructed such that only the wanted field-type is excited and/or able to propagate. For example,

waveguides operating with several modes (e.g. hollow cylindrical waveguides in which not only the fundamental mode is able to propagate) have to be strictly avoided, because small changes in the experimental set-up can then lead to strong variations of the field-distribution. The unambiguity of the field-type must be preserved after the insertion of the sample and must not be influenced by the necessary variation of its parameters during the experiment. One also must be able to determine the field-distribution within the sample unambiguously by experiment or by calculation. It should therefore be avoided to position the sample into areas in which the field has a strong local variation over areas of similar size as the sample. Regarding the form of the signal (see chapter 6) one needs to consider that complex signals (e.g. according to the GSM-standards [14]) are often not clearly defined. An error analysis has to confirm that the measured values are determined unambiguously by the requested parameters. In order to find out about the causal relations between the quantities describing the field-exposure and any biological effect observed, only few parameters should be changed during the run of an experiment. All other parameters should be constant.

It is obvious, that - depending on the interpretation of the experiment - the RF-technical requirements have to be completed by corresponding ones from the special field involved. It appears that often, the repeatability of the experiments can only be guaranteed with immense efforts and even then only with restrictions; already the clear descrip-

tion of the biological material, for example, with a finite number of unambiguously measurable parameters is in most cases impossible (e.g. cultures of bacteria, laboratory animals, test persons, etc.). The general requirement to determine, control and document all physical, chemical, physiological and sociological parameters of the experiment can therefore only be met with restrictions.

A fundamental part of the experiment deals with the processing of the directly measured physical data ('raw data'). To examine the effects of different evaluation methods, the raw data have to be saved carefully before any processing. The processing methods must be described precisely.

4 Criteria for the Selection of the RF-Exposure-Device

4.1 Field-Distribution before Insertion of the Sample

The selection of the field-distribution to which the sample shall be exposed, must primarily be discussed according to the experimental aims:

4.1.1 Detection of Possible Effects

In previously published investigations, different kinds of field-types, for example plane or standing waves, near-fields, field-types with predominant E- or H-field in certain areas, are applied. Up to now it is not clear whether a cer-

tain field-type is more likely to cause effects than another. Also the exposure given in practice - for example exposure of nerve cells in certain parts of the human brain when using a mobile phone - differs from the mentioned standard cases. The field-type can therefore be selected such that the unambiguity and repeatability of the field-distribution are ensured as well as possible.

4.1.2 'Proof' of the Exclusion of Effects

Experiments which prove the exclusion of presently measurable effects are usually motivated by technical uses of electromagnetic fields. The choice of the field-distribution must therefore correspond to these applications. As the exposure for those applications which are especially critically discussed in public, results from radiation fields, these also must be applied in the experiments. This implies extensive efforts in most cases (see section 5.2). In each single case it has to be carefully considered, whether field-types which are easier to generate can be used.

4.1.3 Confirmation or Refutation of Theoretical Concepts and of Hypotheses

The selection of the field-type is determined above all by the model on which the hypothesis is based.

4.1.4 Repetition of Experiments for the Confirmation or Refutation of Published Results

The selection of the field-type is primarily determined by the experiments, that are to be repeat-

ed. Modifications of the field-type have to be justified very carefully, for otherwise the aim of the experiment can be called in question.

4.2 Size of the Measuring Volume

The size of the sample including its attachments determines the size of the measuring volume. Such attachments (e.g. attachments for cell membranes or test-tubes with biological materials) are necessary in nearly all cases; often additional objects in close proximity of the biological substances are also indispensable. The RF-exposure-device must provide sufficient space.

4.3 Frequency, Bandwidth

To generate defined fields in the mentioned frequency range from some MHz up to some 10 GHz very different devices are necessary. The demanded bandwidth depends on the signals that are to be used (e.g. signal of the mobile communication systems according to the GSM-standard for 900 MHz and 1800 MHz).

4.4 Determination of the Field-Distribution in the Sample

To interpret the results one needs to know the field-distribution in or at the sample, depending on the problem. It is determined by the field-distribution before in-

serting the sample as well as by its geometric and material parameters. Additionally, the attachments or other indispensable objects in the proximity of the sample can strongly influence the field. The design of the exposure-device must be such that it allows a sufficiently precise determination of the field-distribution in the sample under consideration of all these influences. The field analysis also needs to clarify whether small changes in the experimental set-up can cause fundamental variations of the field-distribution in the sample, in which case the repeatability of the experiment would be invalidated. As for the biological substances and for the attachments or adjacent objects $\epsilon'_i \gg 1$, $\epsilon''_i \gg 1$ is mostly valid, the approximations for the field-distribution are often doubtful. Particularly it has to be considered, that - even when using simple field-types (see section 5) - no simple relation exists between the electric and the magnetic field components. DIN/VDE 0848 part 1 [10] gives references to experimental methods in section 3 and in the appendices A and B, and to numerical methods in section 4 and in the appendices C and D. Section B of these guidelines contains a short presentation and discussion of important numerical methods and a rough estimation of the computer capacity needed.

4.5 Shielding of Exterior Influences, Especially of Electromagnetic Interference

To ensure that an observed effect is caused only by the intended ex-

posure, other fields have to be largely shielded. Such interference fields are generated by sources outside the experimental room but also by the experimental set-up itself. Shielded devices should therefore be preferred, the measuring instruments of which are outside the device, if possible. Necessary power lines and cables have to be provided with appropriate filtering; pipes, for example for nutrient solutions or oxygen, have to be led through waveguide-beyond-cut-off feed throughs, in order not to deteriorate the shielding effect (waveguide-beyond-cut-off feed throughs can be regarded as short sections of waveguides, which are used below the so-called cut-off frequency of the fundamental mode. For formulas for specification see e.g. [2], p. K 23). One needs to consider that the shielding of low-frequency fields is often impossible due to the large effort required. Those fields have to be measured as carefully as possible and afterwards to be recorded.

4.6 Special Technical Requirements

are, for instance, the installation of special transmission lines and sensors, the observability of the sample during the experiment with the microscope, ...

4.7 Biological/Physiological Requirements

Constant temperature, supply with oxygen or nutrient solution, storage in nutrient substrate, free movement for laboratory animals, ...

5 Classification of Electromagnetic Fields

5.1 Preliminary Notes

RF-electromagnetic fields are described by the field quantities \vec{E} , \vec{D} , \vec{H} , \vec{B} . Their spatial and time-varying behaviour is determined by the kind of excitation and the distribution of material specified by the material parameters $\epsilon_0 \vec{\epsilon}_r(\vec{r})$, $\mu_0 \vec{\mu}_r(\vec{r})$ and $\vec{\kappa}(\vec{r})$ (\vec{r} local vector). In connection with biological experiments the material parameters can - except for special cases - be considered as scalar quantities; μ_r is assumed to be 1.

Mathematically, field-problems are described macroscopically completely and unambiguously by the Maxwell equations

$$\text{rot } \vec{H} = \vec{J} + \frac{\partial \vec{D}}{\partial t} \quad (5.1.1)$$

$$\text{rot } \vec{E} = - \frac{\partial \vec{B}}{\partial t} \quad (5.1.2)$$

$$\text{div } \vec{D} = \rho \quad (5.1.3)$$

$$\text{div } \vec{B} = 0 \quad (5.1.4)$$

and the respective material equations (see e.g. [3]). The field theory provides methods for the solution of the field-problems, i.e. for the Maxwell equations. However, only field-problems of very simple geometry can be solved analytically and with limited effort. Powerful computers are nowadays able to handle complex geometric. Electromagnetic fields can be experimentally investigated by field probes. It holds again that only those fields are easy to

measure which can be described unambiguously by few parameters in the essential part of the volume. Field areas with amplitudes and phases of the field components which vary quickly in space can only be partly analysed due to limited resolution.

To be able to discuss the suitability of electromagnetic fields for biological experiments it is useful to classify the fields. The following classification is based on the technically required devices for the generation of the fields. For each field-type the most important physical properties are shortly described; then the further criteria listed in section 4 are discussed. It is obvious that only a few important considerations can be listed; references to further literature [1]-[7], especially also to DIN/VDE 0848 part 1, section 2 (terms) [10] need to be emphasized here.

5.2 Radiation Fields

5.2.1 Far-Field of an Electromagnetic Source ([10], Section 2.5)

- Field-type: \vec{E} and \vec{H} are perpendicular to each other and perpendicular to the direction of propagation, and they are in phase with each other. The phase velocity is equal to the velocity of light. It is valid:

$$|\vec{E}| = Z_0 |\vec{H}| \quad (5.2.1.1)$$

$$|\vec{S}| = \frac{1}{2} \frac{|\vec{E}|^2}{Z_0} \quad (5.2.1.2)$$

Z_0 is the intrinsic impedance of free space; \vec{S} is the Poynting vector.

Locally the field is equal to that of a plane uniform wave. The polarization is determined by the excitation.

To generate far-fields, very expensive open area test sites (OATS) or anechoic chambers are needed. In typical laboratories only far-fields with rather poor quality may be produced. Thus, in order to guarantee repeatability, an extremely careful design of the set-up and its handling by an RF-experienced staff as well as measurements of the field-distribution are indispensable.

- Measuring volume: The maximum geometrical size of the sample d_{M0} is determined by the size of the source (antenna) d_A , the distance r and the wavelength λ

$$r \geq \frac{(d_A + d_{M0})^2}{\lambda} \quad (\text{far-field limit}). \quad (5.2.1.3)$$

One needs to consider that the induced currents in conductive objects in the proximity of antennas have to be regarded as a part of the source region.

- Frequency, bandwidth: are determined by the used signal source and antenna.

- Determination of the fields inside the sample: Although the far-field can be considered locally as a uniform plane wave, the numerical solution of such an unbounded field-problem for the determination of fields inside the sample is only possible with extensive efforts even for a simple set-up. Especially further measuring devices in the radiation field (not only those close to the sample under test) can lead to strong field variations which are

difficult to calculate. If the field-distribution is determined experimentally, the resolution is in many cases not sufficient even if very small field probes are used. Furthermore, the transmission line to the probe is necessarily located inside the radiation field. Respective interferences can be reduced by the use of fibre optics.

- **Shielding:**
On OATS, a shielding of interference fields does evidently not exist. Anechoic chambers are shielded in most cases; a shielding effect for low-frequency magnetic fields, however, often exists only partially.

- **Further remarks:**
As the sample is easily accessible, it is simple to install additional experimental devices. The sample can be easily observed until excessive field strengths (see DIN/VDE 0848, part 2) prohibit to enter the test site.

5.2.2 Near-Field Region of a Source Distribution ([10], Section 2.6)

The near-field region of a source distribution is defined as the space between the radiation source and its far-field region.

- **Field-type:**
For a common near-field region, general statements about the ratio of \vec{E} - and \vec{H} -field with regard to phase, amplitude and polarization cannot be made. Typically these values strongly depend on the location of the observation point. Only in special cases, for example in an undisturbed field of electric or magnetic elementary sources, areas with special properties, such as

$$|\vec{E}| \ll Z_0 |\vec{H}| \text{ oder } |\vec{E}| \gg Z_0 |\vec{H}|, \quad (5.2.2.1)$$

$$\arg(E_{\max}) \approx \arg(H_{\max}) \pm \frac{\pi}{2} \quad (5.2.2.2)$$

with E_{\max} , H_{\max} equal to the maximum field components in an observation point can be defined with the help of analytical terms.

Samples and other equipment located in the near-field region usually lead to strong field-variations. Even small changes of the measuring device can cause fundamental variations of the field-distribution. For objects in the close proximity of the antenna, effects on their properties also need to be taken into account, especially changes in the input impedance and therefore variations of the field-generating current. Overall, experiments with near-field regions require special care and expert knowledge.

The polarization is determined by the antenna, but it is typically strongly dependent on the position of the point of observation.

- **Measuring volume:**
The application of near-fields is only appropriate for special problems. The size of the measuring volume can therefore not be discussed in general.

- **Frequency, bandwidth:**
are determined by the signal source and antenna applied.
- **Determination of the field-distribution in the sample:**
The calculation or measurement of the near-field after insertion of the sample, of the attachment, etc., is, even with simple geometries, often limited, as well as the calculation of the field inside the sample.

Otherwise the same remarks are valid as with the far-field.

5.3 Waves on Open Transmission Lines

e.g. two-wire line, microstrip line, coplanar waveguide

The field-distribution is not only determined by the geometric shape of the cross-section of the line and the excitation, but also by the variation of the material in the vicinity. In distinct cases it is often extremely complicated to determine the field-distribution and to perform specific variations during the run of the experiment. Therefore waves on open transmission lines should only be used in special cases.

5.4 Propagating Waves on Shielded Uniform Transmission Lines

5.4.1 TEM-Waveguides (Shielded Two-Wire Lines, Coaxial Lines and their Modifications)

- **Field-type:**
 \vec{E} and \vec{H} are perpendicular to each other and perpendicular to the direction of propagation and are in phase with each other. The propagation velocity is equal to the velocity of light. It is valid:

$$|\vec{E}| = Z_0 |\vec{H}|, \quad (5.4.1.1)$$

$$|\vec{S}| = \frac{1}{2} \frac{|\vec{E}|^2}{Z_0} \quad (5.4.1.2)$$

By special design of the cross-section of the conductor it is possible to create areas in which the local

dependence of $|\vec{E}|$ und $|\vec{H}|$ is low, so that the field in these areas is roughly similar to that of a uniform plane wave (TEM-cells). TEM-waveguides can uniquely be operated within a range $0 < f < f_{c0}$ with f_{c0} equal to the cut-off frequency of the dominant waveguide mode with the lowest frequency.

- **Measuring volume:**
The cross-section of a TEM-transmission line and therewith the measuring volume depend on the condition $f < f_{c0}$. It has to be noted, that also a partly filling of the cross-section can diminish the cut-off frequency. One should not operate above f_{c0} , even if it is ensured that the field-distribution is not disturbed by waveguide modes before the insertion of the sample.

Example: For air-filled coaxial lines (diameter of the inner conductor d , of the outer conductor D) it is approximately valid:

$$f_{c0} = \frac{2c_0}{\pi(d + D)} \quad (5.4.1.3)$$

with equal to the velocity of light in air. One needs to consider that the cut-off frequency can be diminished even with only partial filling. As for the permittivity of the biological material is valid:

$$\epsilon_r = \epsilon_r' - j\epsilon_r''$$

with $\epsilon_r' \gg 1$, $\epsilon_r'' \gg 1$ (5.4.1.4)

a careful analysis might be necessary.

- **Frequency, bandwidth:**
The operating frequency and the bandwidth are limited by $f < f_{c0}$. In this range TEM-transmission lines are almost without dispersion, so that the form of the signal is not changed.

- **Determination of the field-distribution in the sample:**
As the shape of the cross-section of a TEM-transmission line is geometrically not very complicated, the field-distribution inside the sample can be calculated under certain restrictions.

- **Shielding:**
The TEM-transmission lines can be completely shielded with regard to RF-fields. The shielding for low-frequency electric fields is only partially possible. Low-frequency magnetic fields can only be shielded with extensive additional efforts.

- **Further requirements:**
Power lines, etc. can be brought in with careful performance. For the manufacturing of attachments, conducting materials need to be avoided if possible. If metals cannot be avoided the effects need to be carefully examined by measurements or calculations. The sample is not easy to observe.

5.4.2 Waveguides

- **Field-type:**
Generally, waves in hollow metallic waveguides are fields of six

components; only special modes have uncomplicated field-distributions, for example the TE_{10} -wave in a rectangular waveguide. One differentiates between TM-modes (no H-field component in the propagating direction) and TE-modes (no E-field component in the propagating direction). The phase-velocity v_{ph} of a mode in an empty waveguide lies between c_0 and infinite (see eq. 5.4.2.2); the ratio of the transversal field components of the E- and H-field, perpendicular to each other, is real and not a function of the point of observation:

$$\begin{aligned} (\vec{n} \times \vec{E}_{tr}) &= \frac{\omega\mu_0}{k_n} H_{tr} \quad \text{TE-mode} \\ (\vec{n} \times \vec{E}_{tr}) &= \frac{k_n}{\omega\epsilon_0} H_{tr} \quad \text{TM-mode} \end{aligned} \quad (5.4.2.1)$$

\vec{n} is a unit normal vector parallel to the propagating direction, and k_n is equal to the propagating constant ω/v_{ph} . In a waveguide only the modes above a cut-off frequency given by the geometry are able to propagate. For experiments a frequency range should be used in which only one mode - the dominant one - is able to propagate. One needs to consider that the cut-off frequency can be

Type of waveguide	interior dimension [mm × mm]	frequency range of the TE_{10} -mode $1.25f_{c10} \dots 1.9f_{c10}$ [MHz]
R 5	457.20 × 228.60	410... 620
R 6	381.00 × 190.50	490... 750
R 8	292.10 × 146.10	640... 980
R 9	247.65 × 123.80	760... 1150
R 12	195.58 × 97.79	960... 1460
R 14	165.10 × 82.55	1140... 1730
R 18	129.54 × 64.77	1450... 2200
R 22	109.22 × 54.61	1720... 2610
R 26	86.36 × 43.18	2170... 3300

Table 1

diminished even with an only partially filled cross-section.

Areas with linear, circular and elliptical polarisation can be generated. Waveguide modes can also exist in TEM-transmission lines (see section 5.4.1).

- The measuring volume: is determined by the sizes necessary for the dominant mode operation. The sizes of empty rectangular waveguides for frequencies between 450 MHz and 3 GHz are given as an example ($f_{c_{mn}}$ is equal to the cut-off frequency of the mn-th mode) (see table 1).

- Frequency, bandwidth: The possible operating frequencies are given by the data mentioned above. The waveguides are dispersive:

$$v_{ph} = \frac{c_0 \frac{f}{f_c}}{\sqrt{\left(\frac{f}{f_c}\right)^2 - 1}} \quad (5.4.2.2)$$

$$v_{gr} = \frac{c_0^2}{v_{ph}} \quad (5.4.2.3)$$

For measurements within a wide frequency range the waveguide is not suitable; it can, however, be used without restriction for narrow-band signals, for instance those used for mobile communication systems (see 6.2.2).

- Determination of the fields inside the sample: Rectangular waveguides and circular waveguides are the most simple geometrical devices for the generation of uniquely defined fields. Thus for the application of waveguides with propagating waves, a reliable numerical analysis of the field-distribution including attachments, supplies etc. can be achieved. With the help of

scattering coefficients measured at the input and output ports of the device and with the field-probing inside the waveguide, one can determine the field strength very accurately.

- Shielding: see 5.4.1
- Further requirements: see 5.4.1

5.5 Propagating Waves on Shielded Non-Uniform Transmission Lines

5.5.1 TEM-Transmission Lines (GTEM-Cell)

- Field-type: A GTEM-cell essentially consists of a finite section of a spherical waveguide with an inner conductor and an outer conductor. The excitation of the waveguide is carried out at the end with the smaller cross-section; the other end is matched with the help of absorbing material. The fundamental mode of such a spherical waveguide is a transversal electromagnetic (TEM-) spherical wave. For those is valid - as well as for the TEM-waves on uniform transmission lines - that \vec{E} and \vec{H} are perpendicular to each other and perpendicular to the direction of propagation, and that their propagating velocity is equal to the velocity of light. It is also valid:

$$|\vec{E}| = Z_0 |\vec{H}| \text{ and } |\vec{S}| = \frac{1}{2} \frac{|\vec{E}|^2}{Z_0} \quad (5.5.1.1)$$

By special design of the shape of the waveguide it is possible to create areas in which the local dependence of $|\vec{E}|$ and $|\vec{H}|$ is low,

so that the field in these areas is about equal to that of a plane uniform wave (GTEM-cells).

In a spherical waveguide with inner conductor also higher modes can be excited besides the fundamental mode. For these it is not possible to give the cut-off frequencies as for uniform transmission lines; but one can define cut-off radii r_c for which the appropriate mode in sections of the waveguide with $r \geq r_c$ is able to propagate, for $r \lesssim r_c$, is evanescent. The transition between the evanescent and the propagating section is gradual.

- Measuring volume: The measuring volume of a GTEM-cell is first of all limited by the maximum size of the cross-section. It has to be considered, however, that the field in close proximity of the absorber surface can locally be strongly non-uniform (e.g. due to scattering effects caused by pyramid-absorbers). This section is therefore not suitable as a measuring volume.

GTEM-cells are especially used if the properties of the sample shall be measured in the field of a uniform plane wave. It is prerequisite that the sample changes the undisturbed field only locally. To guarantee this, the manufacturers of GTEM-cells restrict the usable measuring volume to the section with about one-third of the maximum cross-section.

- Frequency, bandwidth: The spherical TEM-wave is not dispersive. A low-frequency limit for GTEM-cells can generally not be given, but it does exist for commercially available cells due to technological conditions (type

of absorbers, etc.). For high frequencies, modes have to be considered that are able to propagate above the cut-off radius. These can, like higher propagating modes in uniform waveguides, lead to strong interferences of the measurements, even if it is guaranteed, that the field-distribution is not influenced by these modes before insertion of the sample. The exact calculation of the cut-off radius of the dominant spherical wave needs substantial efforts. One can determine it approximately via the cut-off size of a uniform waveguide with the same shape of the cross-section and via of the aperture angles of the spherical waveguides.

- Determination of the field-distribution inside the sample: As the structure of a GTEM-wave is geometrically complicated, the calculation of the field-distribution inside the sample is only possible with great restrictions.

- Shielding: see 5.4.1

- Further requirements: see 5.4.1

5.5.2 Waveguides

e.g. cylindrical waveguides:

E-sector-waveguide, H-sector-waveguide;

spherical waveguides:

conical, pyramidal waveguide

In spherical waveguides without inner conductor modes can be excited which are evanescent in the range of $r \lesssim r_c$ (r_c : cut-off radius) and which are able to propagate in the range of $r \gtrsim r_c$. The field-distribution of the modes can be

given with some theoretical efforts. Non-uniform waveguides have not reached significant importance in combination with biological experiments so far. They are therefore not discussed any further.

5.6 Standing Waves on Shielded Uniform Transmission Lines

- Field-type:

If a section of a uniform line (TEM-transmission line or waveguide) is shorted or open-circuited at one end, a wave which is fed at the other end is completely reflected and superimposes with the incoming wave to form a standing wave (the transmitter be matched to the line). This standing wave has the property that, if short-circuited, the transversal electric field components are equal to zero in planes with a distance of $n \cdot \lambda_g/2$ (λ_g : wavelength of the line) to the short circuit; for transversal magnetic field components, this distance is $(2n - 1) \cdot \lambda_g/4$. For the open circuit one obtains the result by exchanging E and H. Hence it results for TEM-waves, that planes with $|\vec{E}| = 0$ and planes with $|\vec{H}| = 0$ can be produced. Thus, standing waves are suitable to examine the influence of the E-field or the H-field separately. The cross-sectional distribution of the standing wave is equal to that of the propagating wave.

- Measuring volume:

First of all the measuring volume is determined by the dimensions of the line. As the condition $|\vec{E}| = 0$ or $|\vec{H}| = 0$ is strictly only valid in distinct planes of the

cross-section, the size of the measuring volume in longitudinal direction depends on the deviation from the ideal case that can still be tolerated.

By the insertion of the sample into the line, the initially undisturbed standing wave is disturbed. The size of this disturbance can be easily found out by measuring the reflection coefficient at the input; it can be estimated depending on how far the condition $|\vec{E}| = 0$ or $|\vec{H}| = 0$ in the planes is still realized. It follows that typically the sample must be small compared to the diameter of the line and to the wavelength.

- Frequency, bandwidth:

The operating frequencies and bandwidths are the same as for lines with propagating waves.

- Calculation of the field-distribution inside the sample: The degree of difficulty does not differ from that one with the corresponding propagating waves.

- Shielding: see 5.4.1

- Further requirements:

The further requirements do not differ from those for lines with propagating waves.

5.7 Cavity Resonators

- Field-types:

Cavity resonators are composed of sections of uniform transmission lines (TEM-transmission lines or waveguides) of the length $n \cdot \lambda_g/2$ (λ_g equal to the wavelength of the guided wave), which are shorted-circuited at

both ends. Accordingly, the field-distribution of a resonance field is identical with that of a standing wave, i.e., there are planes with $|\vec{E}| = 0$ and with $|\vec{H}| = 0$. One can hence examine the effects of the E-field or the H-field separately, as in the field of a standing wave. In practice, the most important resonators are rectangular waveguide resonators, operating in the TE_{101} -resonance, and the circular waveguide resonator, operating in the TE_{011} - or TE_{111} -resonance. Resonators are marked by Q which is defined by

$$Q = \frac{\omega W}{P} \quad (5.7.1)$$

with W equal to the energy stored in the resonator and P equal to the time-averaged power loss. Q-values up to 10^4 can be obtained with TE_{111} -waveguide resonators, up to $5 \cdot 10^4$ with TE_{011} -resonators.

- Measuring volume: Resonators for measuring purposes are usually distinguished by a high Q-value, i.e. low power loss. Biological material is, however, strongly lossy; i.e., if the resonator is loaded with a sample even of small volume, Q can conspicuously decrease. Therefore not the volume of the sample is decisive but which change of Q can still be tolerated. This change can usually be easily estimated with perturbation theory.

- Frequency, bandwidth: The resonance frequency f_{res} of a resonator is determined by its cross-sectional shape (see section 5.4: uniform waveguides) and by the resonance length $n \cdot \lambda_g/2$. The 3 db bandwidth B is calculated from

$$B = \frac{f_{res}}{Q} \quad (5.7.2)$$

As a consequence, resonators with a high Q-value are very narrow-banded and therefore, for example, not suitable for GSM-signals.

- Determination of the field-distribution inside the sample: The distribution of the E-field and H-field of the unloaded resonator can be specified by means of simple formulas. Changes of Q by insertion of the sample can, however, lead to drastic variations of the field amplitudes, so that the calculation of absolute amplitude values from known input parameters can be strongly contaminated with errors. A numerical solution of the field-problem after insertion of the sample is, due to the simple geometry of the typical resonators, not very difficult. Yet even this solution does not give exact results for only weakly loaded resonators.

- Shielding: see 5.4.1

- Further requirements: see 5.4.1

6 Criteria for the Choice of Signal

6.1 Preliminary Remarks

The technically used RF-signals differ extremely depending on whether they are applied in communication systems, in medical technology or industrial production techniques. Even within one field of application,

for example the 900 MHz communication system defined by the GSM-standard, the currently occurring signals are determined by numerous parameters. Each experiment can, however, only be carried out with a restricted number of different signals. On the other hand, there is no established knowledge about causing mechanisms which might allow of an unambiguous choice for first experiments. For twenty years, however, there have been experimental reports on the effects of amplitude-modulated RF-fields with modulation frequencies between some Hz and about 100 Hz. Yet these reports are not secured sufficiently to permit a definite choice for experiments. In order to still obtain some initial basis, the following section attempts a determination of the signal based on the catalogue in section 2.

6.2 Choice of the Signal with Regard to the Experimental Aim

6.2.1 Detection of Possible Effects

The previous publications show - as already mentioned - that amplitude-modulated RF-carriers can cause biological effects, mostly changes of the cell membrane. It is not possible to conclude from the experiments for which modulation signal measurable effects are most likely. It is therefore proposed to choose signals which are as simple as possible, i.e., a carrier amplitude-modulated either with a low-frequency sinus- or rectangular function. The necessary

bandwidth can then be easily determined.

6.2.2 'Proof' of the Exclusion of Effects

Like in section 4.1.2 it can be stated that experiments for the proof of the exclusion of effects that are presently detectable are in most cases motivated by technical uses of electromagnetic fields. The choice of the signals must therefore correspond to these applications. The following cases shall be distinguished:

6.2.2.1 Technical Applications of Amplitude-Modulated Signals

For this category of signals, a test signal for frequencies below 150 kHz and a test signal for frequencies above 150 kHz (see appendix C) especially for the check of pacemakers are specified. (See DIN/VDE 0750 part 9A1 from November 1995: Safety of implantable cardiac pacemakers, protection against electromagnetic radiation, which contains the German version of the European standard EN 50061: 1988/A1:1995 [15]). By the choice of the parameters of these signals, the probability of the pacemaker confusing such a signal with that generated by the heart is particularly high.

For the present problems it is proposed to develop signals which are determined by frequencies, that are physiologically effective and known from low-frequency experiments from some Hz up to about 100 Hz, instead of using the heart frequency of 1.2 Hz.

The required bandwidths can be determined easily.

6.2.2.2 Mobile Communication Systems

The signals applied in these systems are very complex. Accordingly, any reduction to simple signals is very arbitrary. It is therefore proposed to work first with commercially available devices which can operate in a test mode 'transmit'. It must again be emphasized that these devices do not always generate an unambiguously defined signal. One can assume, however, that the characteristic and hence physically and physiologically determining features, for example of a signal according to the GSM-standard, are thus realized in the experiment [14].

Only the frequencies and the required bandwidths for the 900 MHz and 1800 MHz systems according to the GSM standard are given here:

900 MHz:

- downlink (base station (BS) to mobile station (MS)) 935 MHz - 960 MHz
- uplink (MS to BS) 890 MHz - 915 MHz
- 124 channels, carrier spacing 200 kHz
- modulation GMSK (Gaussian Minimum Shift Keying)

1800 MHz (European DCS 1800 system):

- downlink (BS to MS) 1805 MHz - 1880 MHz
- uplink (MS to BS) 1710 MHz - 1785 MHz
- 374 channels, carrier spacing 200 kHz
- modulation GMSK

Hence experiments that shall be carried out with these signals do *not* need special efforts with regard to the bandwidth!

6.2.2.3 Other Technical Applications

Due to the already mentioned variety of possible signals no specifications can be made. Like in the previous section, it is advised to comply with the signal actually occurring in technical applications as closely as possible or - like in section 6.2.2.2 - to derive a very simply structured signal from it.

6.2.3 Confirmation or Refutation of Theoretical Concepts and Hypotheses

The choice of the signal is primarily determined by the model concept underlying the hypothesis.

6.2.4 Repetition of Experiments for the Confirmation or Refutation of Published Results

The choice of the signal is first of all determined by the experiments, that are to be repeated. Modifications of the signal have to be justified very carefully, as otherwise the aim of the experiment can be called in question.

7 Examples

The following examples shall demonstrate the planning of three experiments with the help of the guidelines.

7.1 Examination of Cultures of Bacteria and Viruses [16], [17]

7.1.1 Introduction

A variety of published experiments deals with examinations of cultures of viruses and bacteria, as those are easy to handle; besides it is to be expected that fundamental effects can be most readily detected in these simple biological systems.

7.1.2 Aim of the Experiments

It is assumed, that the aim of the experiments is already formulated in the comments in sections 2.1 or 2.2, i.e., possible effects shall be detected or excluded.

7.1.3 General Requirements for the Experiments

The experiment has to be planned and carried out such that it can be repeated at any time and that the physical conditions are then adjustable as in the first experiment. An essential prerequisite therefore is the generation of a defined field which can be precisely controlled, into which the biological materials are inserted (section 7.1.4).

7.1.4 Choice of the RF-Measuring Device

7.1.4.1 Field-Distribution before Insertion of the Sample

For most experiments presently planned or carried out, there are no signs that for certain field-distributions effects are more probable than for others.

7.1.4.2 Size of the Measuring Volume

The size of the required measuring volume is given by the volume of the solution V_L with the bacteria or viruses and by the containers (e.g. test tubes, Petri disks). For the determination of V_L one needs to consider that both the absolute value of the field strength and the relative field-distribution in V_L are strongly dependent on size and shape of V_L , but also on the position of V_L with regard to the direction of propagation of the wave and with regard to the direction of the field vectors. As a result, necessary changes of containers during the experiment, for example the substitution of a test tube by a Petri disk or the substitution of a thin test tube by a less thin one, can lead to strong changes of the exposure conditions, even if V_L is not changed. Only in a few exceptional forms of V_L the field-distribution is roughly uniform, for example with very small ($\leq 0.1 \text{ cm}^3$), very thin cylindrical (e.g. very thin test tubes) or very flat disc-shaped (e.g. only slightly filled Petri disks) volumes. A non-uniform field-distribution leads, however, to different field-exposures of the freely movable viruses and bacteria in the solution depending on their location; this makes an unambiguous assignment of an observed/excluded effect to a single SAR-value impossible. To be still able to obtain a statement, the field-distribution inside each sample must be described accurately, for example by giving the maximal, minimal and averaged SAR-values, and by giving the probability of presence for the bacteria/viruses, if possible.

If the required volumes do not exceed some cm^3 , basically all field-

types listed in section 5 are suitable. Whether several samples can be examined simultaneously in the measuring device for a quicker performance of the experiments, needs to be clarified for each case. One needs to consider that with changing numbers of the samples the field-distribution in the whole exposure-device and hence in the remaining samples may change as well. So, if samples are removed during the experiment, they indispensably need to be replaced.

7.1.4.3 Frequency, Bandwidth

As the most urgent requirements for established knowledge are presently in the field of mobile communication technique, one has to work with the frequencies and signals given in section 6.2.2.2.

7.1.4.4 Determination of the Field-Distribution inside the Sample

To carry out a highly realistic modelling of the device with limited computer capacity, the geometries should be chosen as simple as possible. It is therefore advisable to use a rectangular waveguide with a propagating TE_{10} -mode, for which the cross-sectional dimensions for the mobile communication frequencies can be taken from section 5.4.2. The required length results from the number of samples which shall be put into the field simultaneously. For a first qualitative analysis of the field, the walls of the containers can be neglected. In the following, the Finite Difference Time Domain (FDTD)-method is used to estimate exemplarily the required calculation power. The bounded solution domain needs to be discretized according to

Examples

$$\Delta V = (\Delta_i)^3, \quad i = x, y, z \quad (7.1.4.4.1)$$

$$\text{with } \Delta_{\text{sample}} \leq \frac{\lambda_{\text{sample}}}{10} \quad (7.1.4.4.2)$$

The following example is given for explanation:

- $f=900$ MHz (cf. 6.2.2.2):
→ $\lambda_0 = 333$ mm
- volume of a sample: 4000 mm^3 ,
 $\lambda_{\text{sample}} \approx 40$ mm
- discretization of the samples:
 $\Delta_{\text{sample}} = 0,5$ mm (due to geometry)
- hollow waveguide: R 9, $247.65 \times 123.80 \text{ mm}^2$
- length of the waveguide section: 800 mm
- discretization of the waveguide section: $\Delta_{\text{waveguide}} = 0.5$ cm

To discretize this waveguide section containing 15 samples on the middle axis about 700 000 grid points are necessary. For the discretization of the coaxial-to-waveguide transition 200 000 grid points are additionally required. Hence the problem can still be calculated on a workstation with 128 MB RAM.

This first qualitative calculation must yield that the relative field-distribution inside the waveguide is only changed locally after insertion of the samples and that, above all, no higher order modes can propagate.

One obtains a higher resolution with the help of Huygen's principle by analyzing only a limited volume which contains the samples. The field-distribution in the walls of the containers and inside the samples can thus be determined very exactly.

The numerical analysis must be completed and confirmed by mea-

surements. With a power meter the power produced by the signal generator is measured. The parameters of the coaxial-to-waveguide transition can be measured by exact scattering coefficient measurements with the help of network analyzers. Likewise the scattering coefficients of the unloaded ($|S_{11}|$ and $|S_{22}|$) should be significantly better than -20 dB) and of the waveguide exposure-device equipped with the samples are measured. For controlling the standing wave ratio inside the waveguide can be scanned through a slot in the middle. A satisfying experimental determination of the field-distribution in the samples of some cm^3 volume at maximum is not possible, due to the expected problems (insufficient spatial resolution, strong disturbances by the transmission lines of the probes, etc.).

7.1.4.5 Shielding

The waveguide exposure-device can be completely shielded with regard to RF-fields. A shielding for low-frequency electrical fields is only partially given. Low-frequency magnetic fields can only be shielded with extensive additional efforts.

7.1.4.6 Special Experimental Requirements

As the waveguide-section used for exposure has a very simple structure, and as a very exactly defined field is generated, no special experimental requirements are necessary with regard to RF-technical aspects. Particularly the labour-intensive and difficult detection of the field inside the waveguide by sensors etc. can be omitted (see section 7.1.4.4).

7.1.4.7 Biological/Physiological Requirements

Biological processes usually strongly depend on temperature. Therefore the temperature must be kept constant during the entire experiment. The tolerable deviation depends on the processes that are to be examined, with an upper limit of about $\pm 0.5^\circ\text{C}$. The regulation of the temperature must be efficient enough to compensate fluctuations of the temperature in the surroundings. It must also draw off the heat produced by the electric field inside the measuring equipment and especially inside the biological material. Two possible solutions previously realized are given here:

- a) In the first case [16] a climatic chamber of the size $1.5 \times 2 \times 3 \text{ m}^3$ was at disposal for the experiments. Due to careful previous temperature measurements after differing periods of exposure it could be proved that at the given SAR-values in the samples of 0.1 cm^3 size, the stability of temperature was significantly below the above mentioned limit.
- b) As in the second case [17] no climatic chamber was at disposal, the samples were put into a heat bath filled with low loss white oil ($\epsilon'_r = 2.2$, $\epsilon''_r = 0.033$ with $f = 1800$ MHz), and the entire device was brought into the field of the waveguide. The temperature of the heat bath was kept constant via a closed circuit by a thermostat outside the waveguide. With careful heat isolations of the supplies, the deviation from the required temperature inside the samples can be kept clearly below

$\pm 0.5^\circ\text{C}$. One needs to consider that the heat bath including the supplies significantly complicates the geometry of the device and hence the numerical analysis of the fields inside the samples.

7.1.4.8 Realized Measuring Devices

Several measuring devices with waveguide exposure-devices for examinations in the frequency range around 900 MHz and 1800 MHz have already been constructed. In the case of small volumes (for example 20 samples of 0.1 cm^3 with 1800 MHz), standard waveguide cross-sections (see section 5.4.2) were taken. For bigger sample volumes, the cross-section was taken just big enough, so that higher modes at the upper limit of the applied frequency range are not able to propagate, even in the waveguide equipped with samples. Thus the stability of the field exposure was guaranteed.

Figure 7.1.1 shows the entire experimental set-up. Commercially available mobile phones as well as laboratory signal generators with amplifiers were used as transmitters.

7.2 Examinations of Single Biological Cells [18]

7.2.1 Introduction

Electro-physiological processes on cellular level are influenced by low-frequency electromagnetic fields. This fact is often used in medical applications, for example for the stimulation of cardiac myocytes by pacemakers. It seems

obvious to examine, whether effects can also be observed in cells within RF-electromagnetic fields.

7.2.2 Aim of the Experiments

see 7.1.2

7.2.3 General Requirements for the Experiments

see 7.1.3

7.2.4 Choice of the RF-Measuring Device

7.2.4.1 Field-Distribution before Insertion of the Sample

see 7.1.4.1

7.2.4.2 Size of the Measuring Volume

Cells have dimensions between some μm and several mm; typical dimensions, for example for cardiac myocytes, are about $10\ \mu\text{m}$ in height, $20 - 30\ \mu\text{m}$ in width and $100 - 200\ \mu\text{m}$ in length. Thus the dimensions of cells used in experiments up to 3 GHz usually carried out today are much smaller than the wavelength. To keep up the function of the cells during the experiment, they are kept in a chamber filled with electrolyte, whose dielectric data are of the same order of magnitude as those of tissue. The chamber's volume is

essentially determined by further experimental requirements (see section 7.2.4.6). It is, however, typically smaller than 1 ml.

7.2.4.3 Frequency, Bandwidth

see 7.1.4.3

7.2.4.4 Determination of the Field-Distribution inside the Sample

In order to guarantee the unambiguity of the field-exposure and hence the repeatability of the experiment, the field-distribution must be determined at the location of the cell; its resolution must at least be in the range of the size of the cell itself. As explained in appendix B, the applicability of appropriate local calculation methods depends on the ratio of the biggest dimensions of the measuring volume to the wavelength, but also on the smallest dimensions that are to be resolved. The dimensions of exposure-devices always correspond to the wavelengths of the used signals. For frequencies up to about 3 GHz they are hence within a range of at least some cm up to several dm. It is thus obvious that a numerical analysis for the required resolution of some μm can not be carried out with the methods usually available. Hence it is, on the one hand, important to guarantee the unambiguity and stability of the field-exposure by

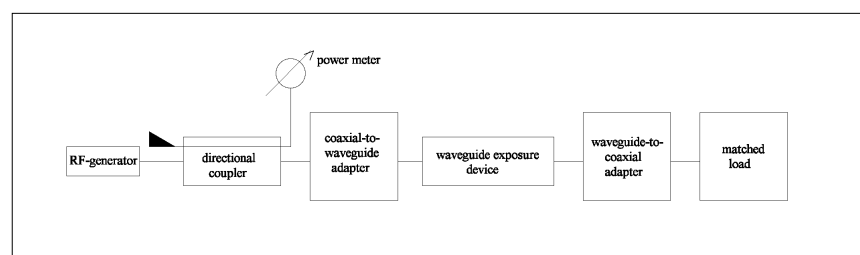


Figure: 7.1.1

the choice of the field-type and, on the other hand, to keep the measuring volume as small as possible. It is advisable to choose a rectangular waveguide with a propagating TE_{10} -mode, as in section 7.1. It is disadvantageous that the width of the waveguide cannot be diminished in comparison with the values mentioned in section 5.4.2, to ensure the propagation of the TE_{10} -mode. Yet the height of the waveguide can be significantly reduced (see section 7.2.4.8).

7.2.4.5 Shielding

The question of shielding is discussed in the following section 7.2.4.6 with regard to special experimental requirements.

7.2.4.6 Special Experimental Requirements

In order to evaluate the effect of the electromagnetic field on a single cell, one needs to be able to measure suitable parameters of the state of the cell before, after, and preferably in the course of the exposure. One example for this is the observation of the intracellular calcium concentration and of the calcium flow through the cell membrane by fluorescence microscopy and the Patch-Clamp-method [19]. For both methods, the cell inside the waveguide must be observable with a microscope from the outside. For this purpose the wall of the waveguide can be replaced in a small section of its broader side (10 mm diameter) by a very close-meshed metal grid. Special attention has to be paid to a sufficiently conductive connection between the grid and the wall of the waveguide. The metal grid causes in its close proximity a distortion of the electrical field

vectors, which were originally parallel and ended up vertically on the wall of the waveguide. Thus, the sample must not be located here. On the other hand, a large distance of the sample from the grid inhibits a clear observation of the sample. Careful calculations are necessary in order to determine the best suitable position of the cells which depends on the diameter of the wires of the net, on the size of the meshes and on the focus of the microscope. This calculation can be used as well in order to check the degree of shielding of the grid.

With the Patch-Clamp-method the current through the cell membrane is measured directly. One of the electrodes consists of a fine glass capillary (pipette) filled with electrolyte. The lumen of the electrode is in contact with the cytoplasm of the cell by a gap in the cell membrane (cf. fig. 7.2.1). The tip of the electrode must therefore be inserted into the interior of the waveguide; an adequate opening needs to be drilled into the waveguide wall opposite the grid. In order to suppress interaction with interference fields through the opening in very thin waveguide walls, a waveguide-beyond-cut-off feed through may be installed. Outside the waveguide the electrode is continued by a metal wire. Counter-electrode is the electrolyte inside the chamber, in which the cell is kept. A conductive connection between the electrolyte and the measuring device must be built to close the circuit. To keep the interference of the electromagnetic field nearby the cell as small as possible, an isolated metal wire is led along the bottom of the waveguide away from the chamber and then towards the outside.

7.2.4.7 Biological/Physiological Requirements

The temperature of the electrolyte containing the cell must be kept constant. For this purpose the container with the cell is put into another one filled with water. The temperature of the water is kept constant in a closed circuit by a thermostat outside the waveguide. The supplies and the drawing-offs are led parallel to the wire of the counter-electrode along the bottom of the waveguide away from the chamber and then towards the outside.

It is apparent that the distribution of material nearby the cell that is to be examined is made complex due to the devices described in this section and in section 7.2.4.6. It is hence not possible to carry out an analysis of this entire setup with the demanded resolution of some μm by means of the available numerical methods. However, by examination of carefully chosen subsections, the unambiguity and repeatability of the experiment can be ensured.

7.2.4.8 Realized Measuring Device

The RF-part of the measuring device corresponds to that of fig. 7.1.1. To meet the requirements mentioned in sections 7.2.4.6 and 7.2.4.7 a height of 30 mm proved to be sufficient for the waveguide. The measuring volume was thus significantly reduced compared with the experiments described in section 7.1, which considerably simplified the numerical analysis. A further advantage is that the glass capillary which is put through the opening of the waveguide wall into the cell,

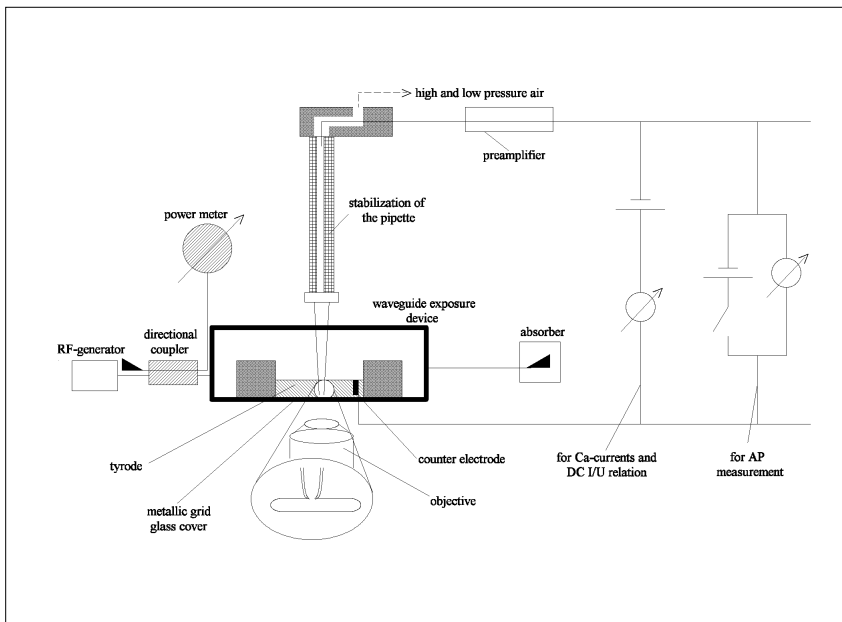


Figure: 7.2.1

could consequently be of short length. This fact improved the handling conspicuously.

7.3 Examinations of Possible Influences on the EEG of Test Subjects [20]

7.3.1 Introduction

The electroencephalogram (EEG) is a diagram of the temporal course of slow electrical phenomena, which accompany the brain activity. Recorded are the changes over time of potentials of electrodes, which are attached to the scalp, with regard to a point of reference.

7.3.2 Experimental Aim

The aim of the experiments is to examine whether any effects for a

proper use of the 900 MHz GSM mobile communication system (cf. 6.2.2.2) can be detected.

7.3.3 General Requirements for the Experiments

see 7.1.3

7.3.4 Choice of the RF-Measuring Device

7.3.4.1 Field-Distribution before Insertion of the Sample

Like in the experiments of the previous sections 7.1 and 7.2, there is no evidence that for certain field-distributions effects are more likely than for others. As in these guidelines, however, most emphasis is put on the technical use of mobile communication, it seems appropriate to apply a field-exposure similar to that in everyday use, if no objections derive from further essential viewpoints.

With a handheld or a portable unit the head of the user is in the near-field region of the antenna. As explained in section 5.2.2, the field-distribution in the near-field region is strongly dependent on the material distribution in the proximate vicinity of the antenna. When using a handheld unit which is kept closely to the head during the conversation, small, inevitable changes of the relative position between head and handheld unit would result in a significantly different exposure. Hence, a portable should preferably be used, as due to its larger distance to the head, small changes of the position hardly have any effect.

If the transmitter is activated in a normally equipped room, the field emitted from the antenna interferes with reflections from objects inside the room and from walls, floor and ceiling. The field-distribution in the room is thus strongly locally dependent and can change significantly even if the position of the objects is only slightly altered. Hence the field-exposure is not clearly reproducible. It is thus necessary to cover the walls, the ceiling and large parts of the floor with an absorbing material; the material reflection coefficient must be sufficiently small, especially for very small rooms. The adequacy of the room needs to be checked by measurements or calculations. Furthermore, metal objects must be avoided (wooden table, wooden chairs, etc.).

7.3.4.2 Size of the Measuring Volume

The room for EEG-experiments must be sufficiently big, so that

the test subject does not feel uncomfortable.

7.3.4.3 Frequency, Bandwidth

see 7.1.4.3

7.3.4.4 Determination of the Field-Distribution inside the Sample

For frequencies of mobile communication systems, the calculation of the field-distribution inside the sample - the test subject -, including the experimental room and the position of the antenna, is only possible by a very rough grid. This allows to check the adequate repeatability of the field-distribution close to the test subject, but one does not obtain detailed information about the field-distribution in the area around the head, for example. If the repeatability is guaranteed, the distribution can, however, be determined by appropriate subsectional analyses.

7.3.4.5 Shielding

Later shielding of rooms, for example in the clinical sector, is usually not possible with justifiable expense. One therefore needs to account considerable interference fields at frequencies of the entire technically used range, from some Hz up to several GHz. Hence, the consultation of the property management needs to ensure that the experimental room is not in close proximity of power lines, high-power appliances (for example nuclear magnetic resonance imaging-devices) and intercoms. One only obtains a reliable evaluation of the interference fields by a very

extensive measurement of the entire frequency range from some Hz up to several GHz. These measurements should also confirm, that the covering of the room with absorbers has led to a clear lowering of the standing wave ration.

7.3.4.6 Special Experimental Requirements

The potential differences that are to be measured, are in the range of up to some 10 μ V. The connections between the electrodes attached to the scalp and the input of the amplifier consist of unshielded metal conductors. Interferences from the exposure-field into the measurement instrument cannot be prevented. Hence one needs to examine the degree of the expected disturbances. A comparison of the results of the following measurements seems appropriate for that purpose:

1. Measurement with artificial head, mobile unit turned off, to register the interferences in the measuring room.
2. Measurement with artificial head, mobile unit turned on.
3. Measurement with test subject, mobile unit turned off.
4. Measurement with test subject, mobile unit turned on.

It should be guaranteed, that the degree of interference from the mobile unit (measurement 2) in the frequency range up to about 30 Hz are only of the same order as those from any other interference fields in the room (measurement 1). Both should be

significantly below the level of the signals that are to be analyzed (measurement 4).

7.3.4.7 Biological/Physiological Requirements

It must be guaranteed that the test person is not subject to any other influences during the stay in the room.

7.3.4.8 Realization of a Measuring Device [20]

For the performance of an experiment, a room of the size 2 x 5 x 2.6 m³ was provided in a clinic. It was covered with flat absorbers (reflection coefficient < -20 dB). Numerical field analysis confirmed that repeatable measurements of exposures in the near-field region could thus be carried out in the room. A commercial portable with the output power of 8 Watt was used as transmitter in the test. The transmitting antenna was fixed above the test subject. The distance was adjusted in such a way as not to exceed the limited value for the public exposure, defined in DIN VDE 0848, part 2. To control the perfect function of the transmitter, the field-distribution was measured with a $\lambda/4$ -dipole and a RF-detector and then recorded on a free channel of the EEG-appliance.

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Appendix

A Checklist for the Planning and Performance of Measurements (taken from 'Umwelt' no. 164 of the BUWAL, Swiss, 1992) [9]

The two following checklists shall be interpreted as a memory aid, so that in planning and performing measurements of non-ionizing electromagnetic radiation the most important information can be obtained early and completely recorded.

A.1 Checklist 1: Preparation

The following clarifications shall be carried out in the scope of the measurement planning. A preparatory measurement might already be necessary.

1. Source

- frequency range
- single or multiple frequencies
- higher harmonics
- modulation: none, pulsed, AM, FM, SSB, etc.
- polarisation: horizontal, vertical, circular
- radiation properties
- output power: nominal, real; variations over time
- operating parameters (e.g. transmission periods, direction of radiation)
- results of measurements from comparable sources
- other sources in the vicinity, that might influence the measurement
- strong static electric or magnetic fields (power supply)

- condition of the device: correct operation; damages; leaks

2. Area Under Test

- permission of admittance
- public admittance
- types of use
- typical period of stay of persons
- estimation of field strengths
- nonuniform fields: reflections, resonance, multipath propagation
- near-field/far-field regions
- essential limits and evaluation quantities
- interference objects in the area under test (secondary sources, absorbers)
- stable or alternating conditions in the area under test
- determination of measuring places and -periods
- determination of the measuring height
- safety for the measuring staff

3. Measuring Equipment

- probe/antenna: broadband or narrowband; isotropic or directional; E- or H-sensitive; circular or linear polarization
- connection between probe and measuring device
- measuring device: spectrum-analyzer, receiver, field-intensity meter, etc.
- attachment of the probe/antenna
- method of averaging
- suitable substituting source for operational test
- operational test, possibly preliminary measurement; suitability of the measuring device for the intended measurement
- calibration
- possible systematic or statistical errors of the measurement

A.2 Checklist 2: Record of the Measurement

The following information shall, as far as possible, be recorded during the measurements.

- description of the measuring device
- condition and operating parameters of the source
- sketch and description of the measuring place, closer vicinity and arrangement of the measuring device
- time and duration of the measurement
- height of probe/antenna above the floor
- distance of probe/antenna from conducting objects in close proximity
- polarisation and orientation of probe/antenna
- adjustment of the measuring instruments
- method of averaging and averaged time
- measured quantities
- observations of temporary deviations of the measured values
- weather conditions (temperature, humidity)
- composition and covering of the floor

B Numerical Methods for the Analysis of Field- Problems

B.1 Introduction

The field-problems, that are to be solved in the course of experiments, differ very much, depending, for example, on whether the biological material of interest is a cell membrane with a thickness of

about 10 nm or a test subject. General guidelines and statements for solution methods can therefore only be given under great restriction, as the advantages and disadvantages can have very different effects in each case. It can generally be noted, however, that analytical solution methods can be used only in a few special cases due to the complexity of the material distribution. They can nevertheless be very helpful if idealized models for the clarification of fundamental methods shall be discussed or if approximations or estimations shall be worked out and numerical methods be checked (e.g. examination of a cell described by a model of spherical shells). Exclusively numerical methods are usable for the 'determination of the field-distribution inside the sample' - as discussed in section 4.4 - if a theoretical solution is sought. It holds also for numerical methods, that only few general criteria can be formulated for an optimized proceeding for the solution of a boundary value problem. One essential reason for this is that, although numerous scientific reports have been published on each method, there is a lack of comparative analyses with sufficiently extensive tests of carefully defined standard cases. To give, nevertheless, an introductory guide particularly for the first phase of planning an experiment, the most important numerical methods are briefly described and classified in the following section B.2. Afterwards, the needed computer capacity is estimated exemplarily for one of the classes in section B.3. Detailed information on the methods is given in literature; here, only some summarizing descriptions are referred to, e.g. [4], [21], [22].

B.2 Characterization of Numerical Methods for the Solution of Boundary Value Problems

Within the field-problems, that are to be solved, boundary value problems for bounded and unbounded solution domains can be distinguished. The latter appear, if near- or far-fields (sections 5.2.1 and 5.2.2) or waves on open transmission lines (section 5.3) are used for the exposure. The field-types mentioned in sections 5.4 - 5.7 lead to bounded solution domains.

Starting point for the development of a numerical solution method is a suitable analytical formulation of the field-problem, which generally can be described by a linear operator equation

$$L\{\vec{F}\} = \vec{G} \quad (\text{B.2.1})$$

where \vec{F} is the field quantity sought (electrical and/or magnetic field, current density) and \vec{G} is the excitation function (antenna or a coaxial-to-waveguide transition). The operator L represents, for example, the system of Maxwell's equations (5.1.1) - (5.1.4) or an equivalent description derived therefrom. If the problem is unique, the solution can formally be written as

$$\vec{F} = L^{-1}\{\vec{G}\} \quad (\text{B.2.2})$$

The solution of the field-problem is equivalent with finding the inverse operator L^{-1} . With numerical methods, this is done with the help of approximations. Two proceedings may be mentioned: on the one hand, one can start with an approximation of the operator and apply it to an exact descrip-

tion of the field quantity; on the other hand, one can roughly approximate the field quantity and apply the exact operator. Besides, combinations of both methods can be developed. The most important examples for an approximation of the operator are the methods of **Finite Differences (FD)** [23] and of **Finite Integration Techniques (FIT)** [24]. The former starts with Maxwell's equations in differential form or from a differential equation derived from it, for example the wave equation; differential quotients are approximated by quotients of differences. In practice, the solution space is usually discretized by a uniform set of meshpoints. For the calculation of the quotients, the field values at the meshpoints are used. One obtains a system of equations of the field values at the meshpoints by approximating the operator in each meshpoint. The strong demand for applying uniform grids requires a high degree of discretization even in uniform sections of the solution space. This can have a negative effect on the numerical effort which essentially depends on the number of meshpoints. Non-uniform grids are possible to a certain degree (see section B.3). The required calculation- and memory capacity increases particularly for three-dimensional-problems with the size of the solution domain and the degree of the resolution. A complete discretization of the entire solution domain yields a high suitability for strongly non-uniform areas.

For the FIT the integrals are, starting from Maxwell's equations, approximated analogously. If the FIT-method is applied to a rectangular grid, a similar description as

with the FD-method is obtained. As in both methods every algebraic equation of the linear equation system combines field quantities in close proximity of a point of observation, they are part of the local methods.

Another local procedure is the method of **Finite Elements (FE)** [25], in which the solution domain is decomposed into finite parts (finite elements). In these parts simple approximating functions for the field quantity sought are estimated, which are set equal to zero outside these sections. In three-dimensional methods, mainly polyhedra (tetrahedra, hexahedra...) are employed. The procedure is highly versatile, as one is free to decide in the decomposition of the solution domain. Besides, one can adequately model complicated geometries and non-uniform areas with suitable elements. As approximating functions, polynomials of variable degree can be applied; lately, a wider spectrum of functions is discussed and tested as well. Especially tangential vector elements (edge-elements) must be mentioned here. These functions are particularly suitable for the modeling of the electric or magnetic field strength, as they always fulfill the conditions of continuity for field strengths as imposed by Maxwell's equations. For the transformation of the equations obtained by the FE-method into a system of linear equations, variational methods are usually used. Thus the field-problem can be formulated as a variational problem; its solution is equivalent to the solution of the differential equation assigned to the functional, as the functional is stationary, if the field is a solution of the

wave equation. Suitable functionals for the electric field strength E or the magnetic field strength H can be taken from literature. As the method of Finite Elements models the field quantity in the entire solution domain - as in the FD and the FIT - it is well suited for strongly non-uniform areas with complicated geometries. The numerical effort depends on the size of the solution domain and the resolution of the FE-grid. It may, particularly for three-dimensional problems, need considerable computer capacity. The choice in form and size of the finite elements is an advantage in comparison with the FIT and the FD, which allows to adapt the model well to the geometry and the included non-uniformities.

For the generalized **Multipole Technique** [26], also known as 'multiple multipole technique (MMP)', partial solutions of the wave equations for uniform areas (multipoles) are used for the starting description of the field quantities. The method can therefore be classified as a global method. Complicated geometries or non-uniform areas are thereby split up into uniform subsections. In each of the sections as well as in the room outside a local coordinate system is set-up, in which the multipoles can be determined. As the multipoles are solutions of Maxwell's equations for uniform areas, the field-problem is reduced by one dimension. This means, for example, that 3D-problems are turned into 2D-problems, for only the boundary conditions resulting from Maxwell's equations must be fulfilled at the boundaries of the single subsections. This is usually carried out by the Method of Least Squares or 'Pointmatching' for

discrete points at the interfaces. This is a very critical step of the procedure and must be executed with great care. The method is well suited for unbounded boundary value problems due to the representation of the field in the outer room around the actual solution domain. With regard to the handling of non-uniform areas and complicated geometries, the method has advantages for simple devices, as the numerical effort increases strongly with the number of the required subsections and their interfaces.

With some analytical effort, **integral equations** [27] of the electromagnetic field can be derived from Maxwell's equations with the aid of integral theorems and vector analytic transformations. An example for this is the so-called electric field integral equation (EFIE). In this equation, the field in a solution domain is described as the integral over the sources within the solution domain and as a closed surface integral over its surface. With the help of the concepts of the equivalent Huygens sources, the latter can also be formulated as an integral over sources. Numerical methods based on such formulations only need to approximate the sources of a field. This implies a high suitability for unbounded boundary value problems, as the field sources are usually located in finite distance; thus, only areas of finite volume need to be modeled. Yet such integral equations can only be given for certain geometries or non-uniform areas, respectively, which restricts their applicability significantly. Apart from uniform areas, especially plane, infinite, layered structures must be mentioned here, for

which it is possible to give closed sets of integral equations. After approximating the sources by suitable functions, the integral equations are usually transformed into a system of linear equations of the amplitudes of those functions; this is done with the aid of the **Method of Moments** [28], making use of the boundary conditions and the conditions of continuity of the electromagnetic fields. With the application of **surface integral equations** [29], usually non-uniform areas are decomposed into uniform subsections, so that the interfaces of the non-uniform areas are part of the surfaces of the single subsections. This results for strongly non-uniform objects in an enormous increase in the required computer capacity. This is particularly due to the fact that the systems of equations are strongly populated.

It seems sensible to try to connect the advantages of a local procedure with those of a global procedure in such a way that the respective disadvantages are levelled out, and that the strong points are preserved. Such a **Hybrid Method** [30] was developed from a combination of the method of Finite Elements and of surface integral equations. Thus, both a good handling of the non-uniformities and an exact inclusion of the non-uniform section into the uniform area were achieved. Non-uniform field areas are modelled with the help of finite elements; the field in the uniform section is described by a surface integral equation, with equivalent Huygens sources as sources on the closed surface around the uniform area. As in the case of pure integral equations, the set of surface integral equations is

transformed into a set of linear equations with the Method of Moments after an approximation of the sources by suitable functions. Both field-problems, in the non-uniform room and the outer room, are combined by enforcing the conditions of continuity for the field strengths. The advantage of this procedure is that only the non-uniform areas need to be covered with the local procedure. A disadvantage of the hybrid method is that the weak population of the set of FE-equations is partly lost due to the combination with the integral equations.

B.3 Estimation of the Required Computer Capacity for Local Methods (FD, FIT, FE)

For the estimation one assumes that a boundary value problem for a bounded domain is dealt with, or that one for an unbounded is already reduced to a bounded by suitable open boundary conditions. The numerical effort for the formulation of the open boundary condition strongly depends on the method chosen. It is therefore not discussed any further. To make the following considerations easy to comprehend, they are explained by the example of a waveguide exposure device with samples of biological material. The characteristic problem is that relatively small areas (the biological samples themselves) need to be highly resolved, but that for the remaining space up to the waveguide walls a significantly lower resolution is sufficient. The required resolution results on the one hand from the geometry to be modelled. On the other hand, the resolution in the examined material should by no means fall below ten subsections

Appendix

per wavelength. The waveguide exposure-device is of the size 25.0 cm x 12.0 cm x 50.0 cm, and it shall contain 30 samples in 3 longitudinal lines of a volume of 1 cm³, respectively. One assumes that the samples are cubic. The frequency is 900 MHz. The biological samples shall be modelled with a resolution of 1 mm. As for biological material with 900 MHz

$$\epsilon'_{r,bio} \approx 75 \quad (B.3.1)$$

is valid, the wavelength inside the material is

$$\lambda_{bio} \approx \frac{33.3 \text{ cm}}{\sqrt{75}} = 3.8 \text{ cm} \quad (B.3.2)$$

and a resolution of 1 mm is therefore sufficient. In the part of the waveguide filled with air, the resolution shall not fall below 1 cm, as it is usually recommended not to exceed a ratio of 10:1 from minimum to maximum resolution for local numerical methods. The most simple modelling is given by a Cartesian grid. If we assume that the calculation method is able to highly resolve the biological samples exclusively, then the minimum number of elementary cells results as

$$n_e = 30 * 1000 + 14970 = 44970. \quad (B.3.3)$$

Available numerical codes are usually restricted such that the resolution chosen in a certain part of the cross-section (for example in x-direction), must be kept for the respective transversal direction. This leads to a required number of elementary cells of

$$n_e = (22 + 30) * (11 + 10) * (40 + 100) = 152880. \quad (B.3.4)$$

It is advisable to have a gradual transitions between different

levels of resolution; a rule of thumb is that adjacent grids shall differ in their width of meshes by a factor 2 at maximum. Thus the number of elementary cells increases significantly. The calculation of the model with a finite difference time domain (FDTD)-method requires the storage of 6 real unknowns per elementary cell as well as the storage of the weakly occupied matrices for system- and material parameters. The resulting computer capacity needed strongly depends on the actual implementation of the FDTD-method into a numerical code; hence, general statements are not possible. Therefore, only storage need for the program package MAFIA [31] shall be exemplary given. For single precision, this results in a storage need of

$$b = (48 * n_e) \text{ byte} + 5 \text{ Mbytes} \quad (B.3.5)$$

as well as

$$b = (60 * n_e) \text{ byte} + 5 \text{ Mbytes} \quad (B.3.6)$$

For $n_e = 152880$ this results for lossy material in a storage need of about 14.2 Mbytes. For a finite difference method in the frequency range only three unknowns per elementary cell are necessary; these are, however, complex. The storage need is es-

entially determined by the weakly occupied, in the usual case (lossy material) complex system matrix. With double precision (in the frequency range often advisable), MAFIA needs about 400 byte storage per elementary cell. For $n_e = 152880$ this results in a storage need of about 60 Mbytes; this is only valid, if iterative procedures are used, for which the storage need does not increase during the process of solution. In concrete experiments, deviations of the samples from the cubic form and the modelling of further details, for example of the glass of a Petri disk, usually lead to a substantial increase in the number of elementary cells. As an example, the numbers of elementary cells and the storage need shall be given, which have been used for the examinations carried out in section 7.1 - 7.3 with the help of the numerical code MAFIA (see table 2).

FE-methods can, just like FD-methods, equally be applied to Cartesian grids in the time-domain as well as in the frequency-domain. Then, the finite elements are hexahedra. In such cases similar values apply also for the storage need. Typically, FE-methods are, however, used on the basis of the far more flexible tetrahedron models. For a typical tetrahedron

Section	frequency	elementary cells	RAM	CPU-time
7.1	1800 MHz	$1.6 \cdot 10^6$	120 MB	12.6 hours
	900 MHz	$2.3 \cdot 10^6$	165 MB	12.0 hours
7.2	1800 MHz	$3.7 \cdot 10^6$	250 MB	38.5 hours
	900 MHz	$2.6 \cdot 10^6$	180 MB	56.4 hours
7.3	900 MHz	$1.3 \cdot 10^6$	100 MB	1.0 hour

Table 2

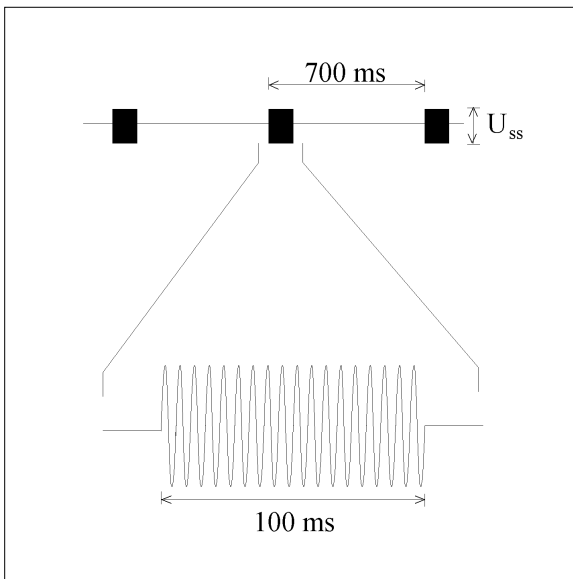


Figure C1: Test signal for frequencies below 150 kHz

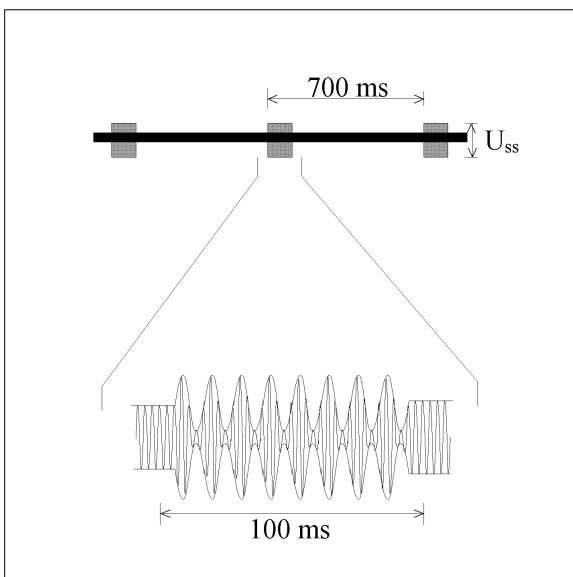


Figure C2: Test signal for frequencies above 150 kHz

method is essentially determined by the ratio of the smallest width of meshes to the wavelength, and therefore by the resolution in time. It also depends on the period of time the system needs to reach stationary response, i.e. on its physical characteristics. In frequency-domain analyses the choice of the solution method (iterative or direct) is decisive. In both cases, concrete statements are not feasible. In order to give at least an outline for the expected calculation time, the necessary values for the experiments described in sections 7.1 - 7.3 are given in the last column of table 2 (calculated on a workstation IBM RS 6000/58 H with 101.1 MFlops (according to LINPACK-DP) capacity).

C Test Signal from EN 50061/A1 from November 1995 [16]

C.1 Frequencies below 150 kHz

Fig. C1: Test signal for frequencies below 150 kHz. The oscillation packages start and end at the zeros of the carrier. Only complete carrier oscillations are allowed to be used.

C.2 Frequencies above 150 kHz

Fig. C2: Test signal for frequencies above 150 kHz. The oscillation packages of the modulation start and end at the zeros of the modulation. Therefore the envelope starts and ends at 100 %. The packages consists of 130 complete oscillations. The modulation depth is 95 %.

grid based on edge-elements, one can assume that about twice the number of unknowns is needed per Cartesian elementary cell than for a Cartesian grid. This might, as well as the level of occupation of the system matrices, strongly depend on the type of grid used. As a general rule, one can assume for FE-methods based of tetrahedra with edge-elements that the storage need in the time-domain as well as in the frequency-domain is at least twice as high as for a corresponding Cartesian

grid. However, one needs to consider that the degree of approximation of the field-distribution in the tetrahedron model is of higher order compared to the hexahedron model, although the geometric discretization does not fundamentally change.

The required calculation time for FD- and FE-methods for calculations in the time- and frequency-domain usually depends on the respective storage need. Hence, the calculation time for the FDTD-



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