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电磁场生物学效应实验中的辐射环境

作　者：赵建勋

专　业：无线电物理

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20 文

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答辩委员会对论文的评语

赵建勋同学的博士论文“电磁场生物学效应实验中的辐照环境”选题来自国家自然科学基金资助项目，与当前国际上生物电磁学实验研究密切相关。选题具有理论意义和重要的实用价值。

该论文的研究成果在以下几点上有所创新：

(1) 分析了大直径和小口径培皿内部毫米波功率流密度与各种可能的影响因素的关系，有助于相关实验中确定电磁辐照剂量；

(2) 分析了亥姆霍兹线圈对和三线圈装置内部磁场的均匀性和同向性与线圈大小尺寸的关系，可供设计实验时参考；

(3) 尝试了一种通过远场测量计算毫米波辐射器附近功率流密度的方法，设计编写了相关应用程序，并进行了实践检验，有新意。

总之，论文反映出作者具有扎实的基础理论及系统深入的专门知识，具有相当强的独立科研能力。论文立论正确，论据充分，条理清楚，在答辩过程中表述清楚，能正确回答问题。

答辩委员会表决结果

经答辩委员会表决，全票同意通过赵建勋同学的博士学位论文答辩，建议授予理学博士学位。

答辩委员会主席：安同一

2001 年 12 月 27 日

摘　要

辐照方式，辐照强度和剂量一直是电磁场的生物学效应实验中需要认真考虑的重要因素. 随着生物电磁学研究的深入发展，对这些实验要素提出的要求也变得更加严格. 因为生物电磁学实验研究的复杂性，实际上几乎每一类特定的实验都需要对这些要素加以分析确定.

在生物电磁学研究的前沿领域——电磁场对细胞信息转导和间隙连接的作用及其分子机制的实验研究中，存在不少涉及到辐照方式、辐照强度和剂量的问题，本论文给出了对其中三个主要问题的分析.

一类关于毫米波在细胞层次上的生物学效应的实验使用了内含细胞单层的培皿，并使毫米波从培皿的下方进行辐照. 透过细胞培皿底部后，只有部分入射的毫米波功率可以照射到细胞单层上，论文的第一部分针对大直径培皿分析了这部分功率在总入射功率中所占的比例，给出了理论模型，推导了相关的计算公式，通过计算和图示，给出了上述比例与培皿底层厚度、毫米波波长、培皿材料和培养液的电磁特性的详细关系. 论文的第一部分还分析了小口径培皿中细胞单层接收的毫米波功率流密度，使用了时域有限差分法计算了小口径培皿中的电磁场，并给出了细胞单层所在的小口径培皿底层上表面处的功率流密度分布. 从这些结果中可以获得小口径培皿的结构对入射毫米波功率流密度影响的定性认识.

亥姆霍兹线圈对常用来在研究磁场对生物材料的效应的实

验中产生符合需要的磁场. 为保证位于线圈对中心的生物材料在其所占空间的各处都能接受到同样的剂量，空间中磁场的均匀性是一个需要通过测量或计算加以确定的因素. 同样，对磁场的同向性也有一定的要求. 论文的第二部分利用了线电流段模型，通过计算分析了生物样品空间大小与其中磁场的均匀性和同向性的关系. 以图示的形式给出的结果可以用来评估亥姆霍兹线圈对内部一定大小的样品空间中磁场的同向性和均匀性. 结果中样品空间的大小是相对线圈对大小的相对值，这意味着结果也可以用来在给定样品空间的大小以及其中磁场的均匀性和同向性的要求时估算所需制作的亥姆霍兹线圈对的大小，或者在给定的亥姆霍兹线圈对中确定满足一定磁场均匀性和同向性要求的样品空间的大小. 除亥姆霍兹线圈对外，一种由三组线圈构成的装置已被证明可以有效地产生符合同样需要的磁场，设计这种三线圈装置需要解决的一个问题是确定中间组的线圈数，这对改善样品空间中磁场的均匀性和同向性起重要作用. 论文给出了这个问题的理论研究结果. 此外，文章还就样品空间中磁场的均匀性和同向性对三线圈装置和传统的亥姆霍兹线圈对进行了对比分析.

论文的第三部分也就是最后一部分进行的工作是设计一种方法来测量毫米波辐射器附近的功率流密度，这是生物电磁学实验中使用毫米波辐射器时经常提出的要求. 论文的这一部分详细地阐述了该测量方法的设计. 设计过程中使用了平面波展开技术，并推导了一种测量电场的简易方法. 在解决了诸如计算的离散化、采样定理和快速傅立叶变换的应用等细节问题后，编写提供了一个通用程序. 使用该测量方法时首先进行距离毫米波辐射器较远位置的两个方向的电场的测量，测得的数据交

由程序处理，将其变换成平面波谱，该平面波谱再经由另一个逆变换过程变换成毫米波辐射器附近位置的电磁场，进而计算出该位置的功率流密度. 测量方法和程序的有效性通过对一个毫米波辐射器附近的功率流密度的实验性测量得到了检验.

关键词　辐照，剂量，毫米波，细胞单层，功率流密度，时域有限差分法，磁场，均匀性，同向性，亥姆霍兹线圈对，三线圈装置，毫米波辐射器，电场，快速傅立叶变换

Abstract

Irradiation method, irradiation intensity and dosimetry have always been important factors to be considered seriously in conducting experiments concerning biological effects of electromagnetic fields (EMFs). The requirements for these factors are becoming far more rigorous with the further development in bioelectromagnetic studies. Due to the complexity of experimental studies in this area, these factors are to be determined individually for each specific sort of experiment.

The paper presents analysis of three major problems in relation to the irradiation method, irradiation intensity and dosimetry, which are among those obstacles encountered in experimental studies in the frontier of bioelectromagnetics where effects on gap-junctional intercellular communications of EMFs are being explored.

One sort of experiment concerning bioeffects of millimeter waves (MMWs) at the cellular level is performed using a culture dish containing a cell monolayer with MMW irradiated from the underneath. After going through the dish bottom, only part of the total incident MMW power density (PD) can penetrate into the cell monolayer and this proportion is to be analyzed for a large-diameter culture dish in the first part of the paper. A model describing the case is provided along with derivations of equations for involved calculation. With thorough calculations and

illustrations, detailed descriptions of the relationships between the PD proportion and the culture dish bottom thickness, MMW wavelength and the electromagnetic properties of the culture dish and culture solution are revealed. Another effort is also made in the first part of the paper for analyzing the MMW PD confronting the cell monolayer on the bottom of a culture dish featured by its small caliber. The finite-difference time-domain (FDTD) method is applied in computing EMF inside the small-caliber dish. The result is provided as the PD distribution on the upper face of the dish bottom where the cell monolayer is located. A qualitative understanding of the influence of the culture dish structure on the incident MMW PD can be reached from the result and so is the conclusion that a necessary rigorous analysis of the MMW PD should accompany each experiment of this sort.

Helmholtz coil pairs are often used to produce required magnetic fields (MFs) in experiments about MFs effects on biological materials. To make sure the biological sample located at the center of the coil pair can receive the same amount of dose everywhere within the space it occupies, the uniformity of MF in the space is an important factor to be decided either by direct measurement or by rigorous calculation. The unidirectivity of the MF is also seriously required. With involved calculation, the second part of the paper intends to use the current stick model to analyze the relationship between the biological sample space dimension and the uniformity and unidirectivity properties of the MF within it. Results are illustrated in charts so that they can be used to assess the uniformity and unidirectivity of the MF inside the sample space with a certain dimension in a Helmholtz coil pair. The provided dimension is a relative value against the size of the coil pair, so that the same results can also be useful to determine the size of the coil pair when we are required to design one to generate a MF with its uniformity and unidirectivity of a certain degree in a sample space of a specified dimension or to evaluate the size of the sample space when that of the coil pair is given. In addition to Helmholtz coil pairs, there has been the introduction of devices made up of three coils that have been proved effective in their performances. One problem related to the design of the three-coil device is to determine the number of turns of coil in the middle position, which plays a key role in improving the uniformity and unidirectivity of the MF. The paper finds a theoretical solution to the problem. In addition, comparisons between three-coil devices and the classical Helmholtz coil pairs are made in the aspects of the uniformity and unidirectivity of MF in the biological sample space.

The third and final part of the paper is assigned the job of working out a method to measure the EMF PD in the vicinity of MMW radiators, which is often required in experiments when MMW radiators are utilized. This section of the paper is detailed thoroughly. The technique of plane wave expansion is employed and a simplified way to measure electric field (EF) is derived in the designing process. A program purposed for universal usage is composed, compiled and provided after solving detailed related problems such as digitizing calculation, applying the sampling

theorem and the fast Fourier transform (FFT). During the procedure of the newly designed method, the EF components in two directions far from the MMW radiator are measured. The derived data are taken over by the program that processes them, transforming them into plane-wave spectrum. Then another inverse transform process in the program turns the spectrum into the EMF in the vicinity of the radiator. Then the EMW PD in this area is derived. The method and the program are tested to be valid when an experimental measurement of EMW PD in the vicinity of a MMW radiator is performed.

Key Words irradiation, dose, millimeter wave (MMW), cell monolayer; power density (PD), FDTD method, magnetic field (MF), uniformity, unidirectivity, helmholtz coil pair, three-coil device, MMW radiator, electromagnetic field (EF), fast-Fourier transform (FFT)

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Key Words: [illegible]

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