Contents

Preface xi

Introduction 1

1 Fundamentals of Electromagnetics 7

1.1 RF and Microwave Frequency Ranges 7
1.2 Fields 9
1.3 Electromagnetics 10
  1.3.1 Electric Field and Flux Density 10
  1.3.2 Magnetic Field and Flux Density 17
  1.3.3 Electromagnetic Field 22
  1.3.4 Electromagnetic Wave 25
  1.3.5 Antennas and Near Field 28
1.4 RF and Microwave Energy 30
  1.4.1 Power and Energy 30
  1.4.2 Influence of the Waveform 33
  1.4.3 Blackbody Radiation 33
    Planck’s Radiation Law 34
    Rayleigh–Jeans Radiation Law 35
    Stefan–Boltzmann Law 38
    Wien Displacement Law 38
    Wien Radiation Law 39
1.5 Penetration in Biological Tissues and Skin Effect 39
1.6 Relaxation, Resonance, and Display 44
  1.6.1 Relaxation in Dielectrics 44
  1.6.2 Resonance Absorption 45
  1.6.3 Cole–Cole Display 47
1.7 Dielectric Measurements 49
  1.7.1 RF Measurements 49
  1.7.2 Microwave Measurements 50
  1.7.3 Liquids 51
  1.7.4 Applicators 52
1.8 Exposure 53
References 54
Problems 55

2 RF/Microwave Interaction Mechanisms in Biological Materials 63
  2.1 Bioelectricity 63
    2.1.1 Fundamentals 63
    2.1.2 Cells and Nerves 65
    2.1.3 Bioelectric Phenomena 69
  2.2 Tissue Characterization 69
    2.2.1 Ionization and Nonionization 70
    2.2.2 Dielectric Characterization 70
      Dipolar Orientation 71
      Interfacial Relaxation 71
      Ionic Diffusion: Counterion Polarization Effects 72
    2.2.3 Dielectric Dispersion in Tissues 73
      Conductivity 74
      Permittivity 75
    2.2.4 Measurements 75
      Tissues 75
      Liquids 77
      Influence of Temperature 80
  2.3 Thermodynamics 82
  2.4 Energy 85
References 89
Problems 91

3 Biological Effects 93
  3.1 Absorption 93
    3.1.1 Fundamentals 93
    3.1.2 Dosimetry and SAR 94
    3.1.3 Thermal Considerations 96
  3.2 Nervous System 100
    3.2.1 General Description 101
    3.2.2 Effects on Brain and Spinal Cord 103
3.2.3 Blood–Brain Barrier 104
3.2.4 Influence of Parameters of Microwave Exposure 107
3.2.5 Nervous System Modeling and Simulation 110
3.3 Cells and Membranes 114
3.4 Molecular Level 116
3.5 Low-Level Exposure and ELF Components 117
  3.5.1 Microwave Syndrome 117
  3.5.2 Low-Level Pulsed Exposure 118
  3.5.3 ELF Components 119
3.6 Ear, Eye, and Heart 120
3.7 Influence of Drugs 123
3.8 Nonthermal, Microthermal, and Isothermal Effects 124
  3.8.1 Microwaves as a Trigger 125
  3.8.2 Entropy 128
3.9 Epidemiology Studies 131
3.10 Interferences 132
3.11 Radiation Hazards and Exposure Standards 134
  3.11.1 Standards and Recommendations 134
  3.11.2 Tissue Phantoms and SAR Measurements 136
  3.11.3 Computational Methods for SAR Evaluation 139
  3.11.4 Exposure of Body to Cell Phone and Base Station 140
References 142
Problems 150

4 Thermal Therapy 153

4.1 Introduction to Thermotherapy 153
4.2 Heating Principle 153
  4.2.1 Foundations of Dielectric Heating Principle 154
  4.2.2 RF Dielectric Heating Applicator 157
    Theory 157
    Actual Dielectric Heating Applicator Systems 159
  4.2.3 Microwave Dielectric Heating 163
  4.2.4 Foundation of Inductive Heating Principle 164
  4.2.5 Actual Inductive Heating Applicator 166
  4.2.6 Detailed Theory of RF Dielectric Heating 174
  4.2.7 Detailed Theory of Microwave Dielectric Heating 177
  4.2.8 Detailed Theory of Inductive Heating 179
4.3 Hyperthermia 182
  4.3.1 Biological Background of Hyperthermia 183
    Survival Rate and Hyperthermia Sensitivity of Cell 183
    Oxygen Partial Pressure, pH, and Hyperthermia Sensitivity of Cell 184
<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.4</td>
<td>Method of Thermometry</td>
<td>186</td>
</tr>
<tr>
<td>4.4.1</td>
<td>Invasive Thermometry</td>
<td>186</td>
</tr>
<tr>
<td>4.4.2</td>
<td>Noninvasive Thermometry</td>
<td>197</td>
</tr>
<tr>
<td>References</td>
<td></td>
<td>199</td>
</tr>
<tr>
<td>Problems</td>
<td></td>
<td>202</td>
</tr>
</tbody>
</table>

| 5       | EM Wave Absorbers Protecting Biological and Medical Environment       | 203  |
| 5.1     | Foundation of EM Wave Absorbers                                       | 203  |
| 5.2     | Classification of Wave Absorbers                                      | 204  |
| 5.2.1   | Classification by Constituent Material                               | 204  |
| 5.2.2   | Classification by Structural Shape                                   | 205  |
| 5.3     | Fundamental Principle                                                | 206  |
| 5.4     | Fundamental Theory of EM Wave Absorbers                               | 210  |
| 5.4.1   | Single-Layer-Type Wave Absorber                                       | 210  |
| 5.4.2   | Multilayer-Type Wave Absorber                                         | 213  |
| 5.5     | Application of EM Absorber                                            | 216  |
| 5.5.1   | Quarter-Wavelength-Type Wave Absorber                                 | 216  |
| 5.5.2   | Single-Layer-Type Wave Absorber                                       | 219  |
| 5.5.3   | Multilayer Wave Absorber                                              | 219  |
| 5.5.4   | Pyramidal Wave Absorber                                               | 221  |
| 5.6     | EM Wave Absorbers Based on Equivalent Transformation Method of Material Constant | 223  |
| 5.6.1   | Microwave Absorber with Multiholes                                    | 223  |
| 5.6.2   | Weakly Magnetized Ferrite Absorber                                    | 232  |
| 5.6.3   | Microwave Absorber with Surface-Printed Conductive Line Patterns      | 235  |
| 5.6.4   | Integrated–Circuit-Type Absorber                                      | 239  |
| 5.7     | Method for Improving RF Field Distribution in a Small Room            | 241  |
6 RF/Microwave Delivery Systems for Therapeutic Applications 250

6.1 Introduction 250

6.2 Transmission Lines and Waveguides for Medical Applications 251

6.2.1 Coaxial Cable 251

Cable Specifications 251
Design Consideration 252
Power Loss 252
Low-Loss Fully Coaxial Cable 255
Skin Effect 255
Coaxial Cable for Microwave Balloon Angioplasty 256

6.2.2 Circular Waveguide 258

Fundamentals 258
Power Capacity of a Circular Waveguide 261

6.3 Antennas 261

6.3.1 Fundamentals 261
6.3.2 Antenna Configurations 262

Electric Dipole 262

6.4 RF and Microwave Ablation 264

6.4.1 Fundamentals 264
6.4.2 RF Development 267
6.4.3 Cardiac Ablation 270

6.5 Perfusion Chamber 279

6.5.1 General Description 279
6.5.2 Dose–Response Curve 282
6.5.3 Depth and Rate of Heating 282
6.5.4 Effects of Flow on Surface Temperature 284
6.5.5 Lesion Volume 284
6.5.6 Limitations 285

6.6 RF Gastroesophageal Reflux Disease 286

6.7 Endometrial Ablation 287

6.7.1 Microwave Endometrial Ablation 287
6.7.2 RF Endometrial Ablation 287

6.8 Microwave Measurement Techniques: Examples 288

6.8.1 Introduction 288
6.8.2 Method of Measuring Blood Perfusion (Flow) in Heart Muscle by Use of Microwave Energy 289
6.8.3 Lumen Measurement of Arteries Utilizing Microwave Apparatus 290

6.9 Future Research 294