Contents

Preface iii

1. Executive Summary 1

2. Introduction 8
- **2.1** Background for Present Study 8
  - **2.1.1** Recommendations for Purposes of Radiation Protection 9
  - **2.1.2** Assumptions for Purposes of Cancer Risk Assessment 10
  - **2.1.3** Previous Reviews by NCRP 12
- **2.2** Importance of Present Evaluation 13
- **2.3** Term to Describe Modifying Factor to Represent Biological Effectiveness 15
- **2.4** Specification of Reference Radiation 17
- **2.5** Use of Effectiveness Ratio in Cancer Risk Assessments . . 19
- **2.6** Approach to Evaluation of Biological Effectiveness 21

3. Spectral Characteristics of Representative Low Linear-Energy Transfer Radiations 25
- **3.1** Production of Energetic Secondary Electrons by Photons 26
- **3.2** Representative Spectra of Incident Photons 29
- **3.3** Spectra of First-Collision Electrons and Tritium Beta Particles 32
- **3.4** Spectra of Lower-Energy Electrons Produced by First-Collision Electrons 36

4. Line of Evidence: Microdosimetry 39
- **4.1** Lineal-Energy Distributions Produced by Photons 43
- **4.2** Prediction of R_i Based on $f(y)$ 48
- **4.3** Evaluation of the PDF of R_i 59

5. Line of Evidence: Deoxyribonucleic Acid Damage 64
- **5.1** DNA Damage from Ionizing Radiation 64
- **5.2** Photon and Electron Damage to DNA 67
- **5.3** Experimental Data on Relative Biological Effectiveness for DNA Double-Strand Breaks 68
- **5.4** Relative Biological Effectiveness of DNA Double-Strand Breaks from Theoretical Simulations 79

5.5 Enhancement of Relative Biological Effectiveness for Slow-Rejoining Double-Strand Breaks 85
5.6 Enhancement of Relative Biological Effectiveness for Complex Double-Strand Breaks from Simulations 90
5.7 Role of DNA Base Damage 95
5.8 Estimation of Probability Density Functions for R_i of Double-Strand Breaks and also with Enhancement for Biological Severity 96
5.8.1 PDFs of R_i for 15 to 30 keV Photons 96
5.8.2 PDFs of R_i for 1.5 keV Photons 99
5.8.3 PDF of R_i for 40 to 60 keV Photons 100
5.8.4 PDF of R_i for >60 to 150 keV Photons 102
5.8.5 PDF of R_i for Tritium Beta Particles 103
5.8.6 Summary of Recommended PDFs 103
5.8.7 Relevance of R_i for Initial DSBs in DNA 104

6. Line of Evidence: Cellular Radiobiology and Animal Studies 106
6.1 Introduction 106
6.2 Structural Chromosome Aberrations 106
6.2.1 Studies Using Conventional Giemsa Staining . 107
6.2.2 Difficulties with Studies Using Giemsa Staining 112
6.2.3 Studies Using FISH and mFISH 116
6.3 Micronuclei 118
6.4 Cell Survival and Cell Killing 122
6.5 Cell Mutation 127
6.6 Cellular Transformation 129
6.7 Effects in Cells (*in vitro* and *in vivo*) from Low-Energy Radionuclide Emissions 131
6.8 Other Considerations of Cellular Effects 137
6.9 Studies of Cancer and Other Organ Endpoints in Whole Animals 138
6.9.1 Studies with External Radiation 138
6.9.2 Studies with Radionuclides Incorporated in Animal Tissues 139
6.10 Development of Probability Density Functions of R_i . . . 142
6.10.1 Photons of Energy 1.5 keV (Al_K) 142
6.10.2 Photons of Energy 15 to 30 keV 143
6.10.3 Photons of Energy 40 to 60 keV or >60 to 150 keV 143
6.10.4 Tritium Beta Particles 145
6.11 Summary 146

7. Line of Evidence: Human Epidemiology 149
7.1 Introduction 149

7.2 Discussion of Epidemiologic Methods 149
7.2.1 Representations of Excess Cancer Risks in Radiation Epidemiologic Studies 150
7.2.2 Transfer of Risks Between Populations of Different Nationalities 151
7.2.3 Comparisons of Risks from Different Types of Exposures 153
7.2.4 Other Complications in Comparing Estimated Risks in Different Populations 154
7.3 Limitations of Available Epidemiologic Studies 155
7.4 Comparisons of Results of Epidemiologic Studies 157
7.4.1 Studies of All Cancers 157
7.4.2 Studies of Leukemia Excluding Chronic Lymphocytic Leukemia 159
7.4.3 Studies of Lung Cancer 163
7.4.4 Studies of Breast Cancer 165
7.4.5 Studies of Thyroid Cancer 172
7.5 Summary and Conclusions 178
7.6 Proposed Subjective Probability Density Function of R_i for Lower-Energy Photons 182

8. Elicitation of Judgments and Processing of Probability Density Functions of the Effectiveness Ratio 184
8.1 Probability Elicitation Strategies 185
8.2 Holistic Assessment 187
8.3 Decomposition Modeling 187
8.4 An Alternative Formulation for Decomposition Modeling 191
8.5 Decomposition Probability Assessment 192
8.6 Computation 195
8.7 Sensitivity Analysis of Research Thread Contributions . 195
8.8 Discussion 198

9. Conclusions and Recommendations 201
9.1 Conclusions 201
9.2 Research Recommendations 205

Appendix A. Input Data from the Holistic and Decomposition Elicitations 206
A.1 Input Data for the Holistic Elicitation 206
A.2 Input Data for the Decomposition Elicitation 206

Abbreviations and Acronyms 225

Glossary 226

References 235

Scientific Committee 264

The NCRP 270

NCRP Publications 281