

## CONTENTS

NOTE TO THE READER.....	1
LIST OF PARTICIPANTS.....	3
PREAMBLE .....	9
Background.....	9
Objective and Scope .....	9
Selection of Topics for Monographs .....	10
Data for Monographs .....	11
The Working Group .....	11
Working Procedures .....	11
Exposure Data.....	12
Studies of Cancer in Humans .....	14
Studies of Cancer in Experimental Animals.....	17
Other Data Relevant to an Evaluation of Carcinogenicity and its Mechanisms .....	20
Summary of Data Reported .....	22
Evaluation .....	23
References.....	27
GENERAL INTRODUCTION .....	35
1.    Introduction .....	35
2.    Physical characteristics of electromagnetic fields .....	37
3.    Definitions, quantities and units .....	38
3.1    Electric fields .....	38
3.2    Current density .....	39
3.3    Magnetic fields .....	39
3.4    Magnitude .....	39
3.5    Frequency .....	40
3.6    Polarization .....	40
4.    Physical interactions with biological materials .....	40
4.1    Static fields .....	42
4.2    Extremely low-frequency (ELF) fields.....	42
5.    Studies of ELF electric and magnetic fields relevant to carcinogenicity .....	45
6.    References .....	46

STATIC AND EXTREMELY LOW-FREQUENCY (ELF) ELECTRIC AND MAGNETIC FIELDS .....	49
1. Sources, exposure and exposure assessment .....	51
1.1 Sources .....	51
1.1.1 Natural electric and magnetic fields .....	51
1.1.2 Man-made fields and exposure .....	52
(a) Residential exposure .....	53
(i) Background exposure .....	53
(ii) Fields from appliances .....	55
(iii) Power lines .....	57
(iv) Substations .....	61
(v) Exposure to ELF electric and magnetic fields in schools .....	61
(b) Occupational exposure .....	62
(i) The electric power industry .....	64
(ii) Arc and spot welding .....	64
(iii) Induction furnaces .....	65
(iv) Electrified transport .....	65
(v) Use of video display terminals .....	66
(vi) Use of sewing machines .....	66
(c) Transients .....	66
1.2 Instrumentation and computational methods of assessing electric and magnetic fields .....	67
1.2.1 Instruments .....	67
(a) Electric fields .....	71
(i) Survey meters .....	71
(ii) Personal exposure meters for measuring electric fields .....	71
(b) Magnetic fields .....	72
(i) Survey meters .....	72
(ii) Personal exposure meters for measuring magnetic fields .....	73
(iii) Frequency response .....	73
1.2.2 Computation methods .....	75
1.3 Exposure assessment .....	76
1.3.1 External dosimetry .....	76
(a) Definition and metrics .....	76
(b) Laboratory exposure systems .....	77
(i) In-vivo exposure systems .....	77
(ii) In-vitro exposure systems .....	79
1.3.2 Internal dosimetry modelling .....	80
(a) Definition for internal dosimetry .....	80
(b) Electric-field dosimetry .....	81
(c) Magnetic-field dosimetry .....	84
(d) Contact current dosimetry .....	86

(e) Biophysical relevance of induced fields.....	87
(f) Microscopic dosimetry .....	87
1.4 Biophysical mechanisms.....	89
1.4.1 Induced currents .....	89
1.4.2 Radical-pair mechanism .....	90
1.4.3 Effects related to the charge-to-mass ratio of ions .....	91
1.4.4 Biogenic magnetite .....	92
1.4.5 Other mechanisms.....	93
<b>2. Studies of cancer in humans.....</b>	<b>95</b>
2.1 Exposure assessment in epidemiological studies .....	95
2.1.1 Considerations in assessment of exposure to electric and magnetic fields relevant to epidemiology.....	95
2.1.2 Assessing residential exposure to magnetic fields .....	97
(a) Methods not involving measurement .....	97
(i) Distance .....	97
(ii) Wire code .....	97
(iii) Calculated historical fields .....	98
(b) Methods involving measurement .....	99
(i) Spot measurements in the home .....	100
(ii) Longer-term measurements in homes .....	100
(iii) Personal exposure monitoring .....	101
(c) Assessment of exposure to ELF electric and magnetic fields from appliances.....	101
2.1.3 Assessing occupational exposure to magnetic fields .....	101
2.1.4 Assessing exposure to electric fields .....	102
2.2 Cancer in children .....	103
2.2.1 Residential exposure .....	103
(a) Descriptive studies .....	103
(b) Cohort study .....	103
(c) Case-control studies .....	105
(d) Pooled analyses.....	132
2.2.2 Exposure to ELF electric and magnetic fields from electrical appliances .....	136
2.2.3 Parental exposure to ELF electric and magnetic fields .....	141
(a) Cohort study .....	141
(b) Case-control studies .....	142
2.3 Cancer in adults .....	143
2.3.1 Residential exposure to ELF electric and magnetic fields .....	143
(a) Leukaemia.....	147
(b) Brain cancer .....	154
(c) Breast cancer.....	159
(d) Other cancers .....	167

2.3.2	Occupational exposure to ELF electric and magnetic fields .....	168
(a)	Proportionate mortality or incidence studies .....	168
(b)	Cohort studies .....	170
(i)	Workers exposed to strong static magnetic fields .....	170
(ii)	Workers exposed to electric and magnetic fields (not strong static magnetic fields) .....	182
(c)	Case-control studies .....	194
(i)	Leukaemia .....	194
(ii)	Brain tumours .....	220
(iii)	Pooled analysis (leukaemia and brain tumours) .....	225
(iv)	Female breast cancer .....	225
(v)	Male breast cancer .....	226
(vi)	Other cancer sites .....	228
<b>3.</b>	<b>Studies of carcinogenicity in experimental animals.....</b>	<b>231</b>
3.1	Chronic exposure studies .....	231
3.1.1	Mouse .....	231
3.1.2	Rat .....	234
3.2	Exposures in association with known carcinogens.....	236
3.2.1	Multistage studies of mammary cancer .....	236
(a)	Multistage studies with <i>N</i> -methyl- <i>N</i> -nitrosourea .....	236
(b)	Multistage studies with 7,12-dimethylbenz[ <i>a</i> ]anthracene .....	237
3.2.2	Multistage studies of skin cancer .....	244
(a)	Mouse (conventional) .....	244
(b)	Mouse (genetically modified).....	248
3.2.3	Multistage studies of liver cancer .....	248
(a)	Mouse .....	248
(b)	Rat.....	249
3.2.4	Multistage studies of leukaemia or lymphoma.....	250
(a)	Mouse (conventional) .....	250
(b)	Mouse (genetically modified).....	252
(c)	Other studies .....	253
3.2.5	Multistage studies of neurogenic cancer.....	253
<b>4.</b>	<b>Other data relevant to the evaluation of carcinogenicity and its mechanisms .....</b>	<b>255</b>
4.1	Adverse effects other than cancer in humans .....	255
4.1.1	Reproductive and developmental effects .....	255
(a)	Exposure to ELF electric and magnetic fields during pregnancy ..	255
(b)	Paternal exposure to ELF electric and magnetic fields .....	256
(c)	Exposure to mixed ELF and higher-frequency electric and magnetic fields .....	256
4.1.2	Immunological effects.....	258
4.1.3	Haematological effects .....	259

4.1.4	Neuroendocrine effects .....	260
(a)	Exposure under laboratory conditions .....	260
(b)	Exposure in occupational and residential environments .....	262
4.1.5	Behavioural and physiological effects .....	265
(a)	Static fields .....	265
(i)	Perception of electric fields .....	265
(ii)	Perception of magnetic fields.....	265
(iii)	Cognition .....	265
(iv)	Cardiac effects .....	266
(b)	ELF electric and magnetic fields .....	266
(i)	Perception of electric fields .....	266
(ii)	Magnetic phosphene.....	266
(iii)	Electroencephalograms and event-related brain potentials ...	267
(iv)	Cognition .....	267
(v)	Mood .....	268
(vi)	Hypersensitivity .....	268
(vii)	Sleep electrophysiology .....	268
(viii)	Heart rate .....	268
(c)	Epidemiological studies .....	269
(i)	Neurodegenerative diseases .....	269
(ii)	Suicide and depression.....	269
(iii)	Cardiovascular disease .....	270
4.2	Adverse effects other than cancer in experimental systems .....	270
4.2.1	Reproductive and developmental effects .....	270
(a)	Static magnetic fields .....	270
(i)	Homogeneous fields.....	270
(ii)	Static fields with strong gradients .....	271
(b)	Strong static magnetic fields combined with weaker time-varying fields .....	271
(c)	ELF electric fields.....	272
(d)	ELF magnetic fields .....	273
(i)	Mammalian teratological studies .....	273
(ii)	Mammalian perinatal exposure and behavioural effects .....	275
(iii)	Mammalian multi-generation studies.....	278
(iv)	Effects of paternal exposure on mammalian reproduction ...	278
(v)	Chick and quail embryos exposed to magnetic fields <i>in vitro</i> .....	280
(vi)	Other non-mammalian embryos.....	282
(vii)	Interactions with known teratogens .....	282

4.2.2	Immunological effects.....	283
(a)	In-vivo studies.....	283
(i)	Static fields .....	283
(ii)	ELF electric and magnetic fields .....	283
(b)	In-vitro studies .....	287
(i)	Static fields .....	287
(ii)	ELF electric and magnetic fields .....	287
4.2.3	Haematological effects .....	289
(a)	Static fields .....	289
(b)	ELF electric and magnetic fields .....	289
4.2.4	Neuroendocrine effects .....	291
(a)	Electric fields .....	291
(b)	Magnetic fields .....	297
(i)	Studies in mice .....	297
(ii)	Studies in rats .....	297
(iii)	Studies in seasonal breeders.....	298
(iv)	Studies in non-human primates .....	299
(v)	Cellular effects .....	299
4.2.5	Behavioural effects .....	300
(a)	Static fields .....	300
(b)	ELF electric and magnetic fields .....	301
(i)	Behavioural effects related to perception of fields .....	301
(ii)	Activity, aversion responses.....	301
(iii)	Neurobehavioural teratology .....	302
(iv)	Learning, performance and memory .....	302
4.3	Effects of ELF electric and magnetic fields on bone healing .....	304
4.4	Genetic and related effects .....	307
4.4.1	Genotoxic effects .....	307
(a)	Studies in humans .....	307
(i)	Static magnetic fields .....	307
(ii)	ELF electric and magnetic fields .....	307
(b)	Studies in animals .....	309
(i)	Static magnetic fields .....	309
(ii)	ELF electric and magnetic fields .....	310
(c)	In-vitro studies .....	312
(i)	Static magnetic fields .....	312
(ii)	ELF electric and magnetic fields .....	313
4.4.2	Effects relevant to non-genotoxic carcinogenesis .....	316
(a)	In-vivo studies.....	316
(i)	ELF electric and magnetic fields .....	316

## CONTENTS

ix

(b) In-vitro studies .....	317
(i) Static magnetic fields .....	317
(ii) ELF electric and magnetic fields .....	319
4.5 Mechanistic considerations .....	328
<b>5. Summary of data reported and evaluation .....</b>	<b>331</b>
5.1 Exposure data .....	331
5.2 Human carcinogenicity data .....	332
5.3 Animal carcinogenicity data .....	334
5.4 Other relevant data .....	336
5.5 Evaluation .....	338
<b>6. References .....</b>	<b>339</b>
LIST OF ABBREVIATIONS .....	391
GLOSSARY .....	393
CUMULATIVE INDEX TO THE <i>MONOGRAPHS</i> SERIES.....	397

## **NOTE TO THE READER**

The term ‘carcinogenic risk’ in the *IARC Monographs* series is taken to mean the probability that exposure to an agent will lead to cancer in humans.

Inclusion of an agent in the *Monographs* does not imply that it is a carcinogen, only that the published data have been examined. Equally, the fact that an agent has not yet been evaluated in a monograph does not mean that it is not carcinogenic.

The evaluations of carcinogenic risk are made by international working groups of independent scientists and are qualitative in nature. No recommendation is given for regulation or legislation.

Anyone who is aware of published data that may alter the evaluation of the carcinogenic risk of an agent to humans is encouraged to make this information available to the Unit of Carcinogen Identification and Evaluation, International Agency for Research on Cancer, 150 cours Albert Thomas, 69372 Lyon Cedex 08, France, in order that the agent may be considered for re-evaluation by a future Working Group.

Although every effort is made to prepare the monographs as accurately as possible, mistakes may occur. Readers are requested to communicate any errors to the Unit of Carcinogen Identification and Evaluation, so that corrections can be reported in future volumes.