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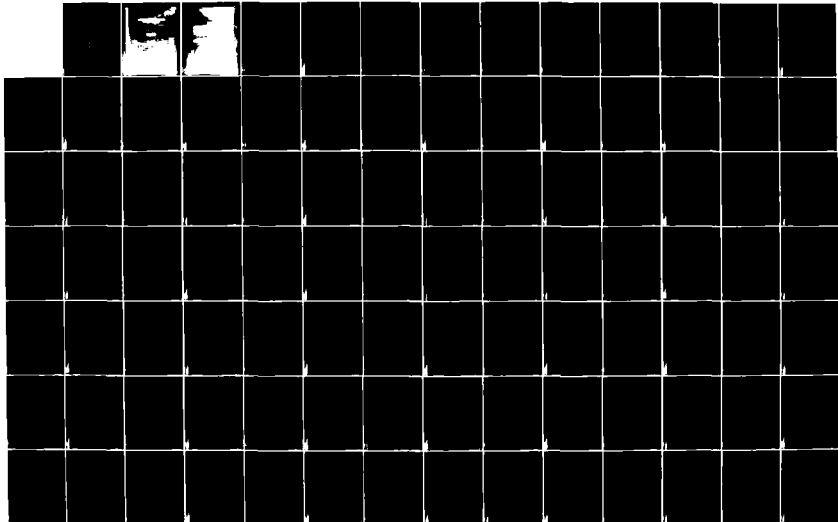
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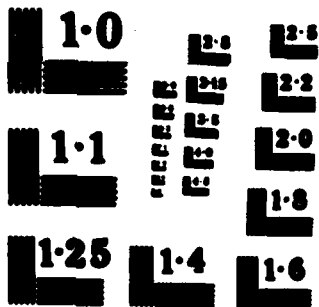
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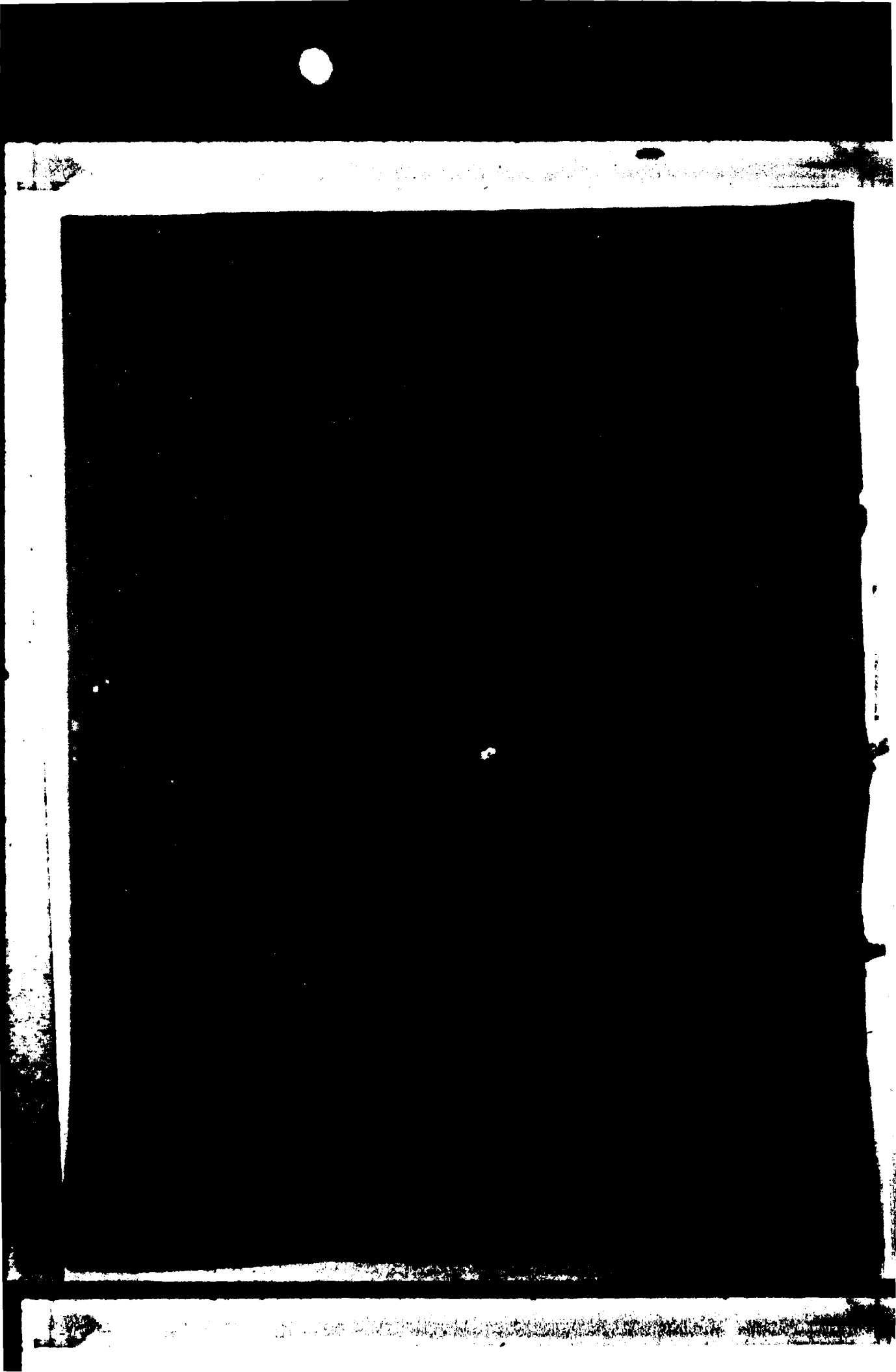
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20. Abstract (continued)

Section II reviews the contributions of various natural factors which influence the inherent radiosensitivity of biological systems. Included in the list of these factors are water, oxygen, thiols, vitamins and antioxidants. Brief attention is given to the model describing competition between oxygen and natural radioprotective substances (principally, thiols) in determining the net cellular radiosensitivity.

Several theories of the mechanism(s) of action of radioprotective drugs are described in Section III. These mechanisms include the production of hypoxia, detoxication of radiochemical reactive species, stabilization of the radiobiological target and the enhancement of damage repair processes. Section IV describes the current strategies for the treatment of radiation injury. Likely areas in which fruitful research might be performed are described in Section V.

Appendices are devoted to lists of currently-funded research projects involving chemical radiation protection and a brief compendium of compounds which have been tested for radioprotective activity.

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CHEMICAL PROTECTION AGAINST IONIZING RADIATION

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Preface

The field of radiation protection carries a certain amount of stigma from the public about the sources of radiation, its effects, and uses. Certainly, few would fail to acknowledge the beneficial effects of diagnostic radiology and radiation therapy. However, the public concern over low levels of radiation, coupled with concern over nuclear issues in general, is pressing and likely to continue. In this atmosphere of concern, the topic of chemical protection against ionizing radiation is viewed by many people as a means of skirting or minimizing the hazards of exposure to ionizing radiation, or as a way to make increased exposure more acceptable. However, radiation exposure is with us as a fact of life, and accidents with ionizing radiation sources do occur, as recently happened in Juarez, Mexico (Marshall, E., *Science* 1984 223, 1152-1154). The presence of nuclear power plants, and their finite lifetime, will result in occupational exposure to radiation as they are decommissioned early in the next century. As one looks at the types of radioprotectors and their effectiveness, the notion that radiation exposure will increase because of reliance on chemical means of preventing the damage of ionizing radiation becomes quite implausible. Certainly, no chemical means can prevent or even significantly reduce the horrors of strategic use of nuclear weaponry or the large scale accidental emission of radiation from power sources. However, benefits from effective radioprotectors can be realized. Some of the hazards of modest accidental exposure to radioactive materials (such as the recent Juarez incident) may be lessened by the application of radioprotectors or effective treatments for "radiation sickness." Individuals who are genetically highly susceptible to natural radiation sources may derive benefit from research on chemical radioprotection. The clinical use of radioprotective agents as prophylactic adjunct therapy in radiation oncology has been a continuing goal of radiation oncologists for many years. It is for these purposes that we have reviewed the literature on chemical protection against ionizing radiation and submit this report on our efforts.

Summary

The scientific literature on radiation-protective drugs is reviewed. Emphasis is placed on the mechanisms involved in determining the sensitivity of biological material to ionizing radiation and mechanisms of chemical radioprotection. In Section I, the types of radiation are described and the effects of ionizing radiation on biological systems are reviewed. The effects of ionizing radiation are briefly contrasted with the effects of non-ionizing radiation.

Section II reviews the contributions of various natural factors which influence the inherent radiosensitivity of biological systems. Included in the list of these factors are water, oxygen, thiols, vitamins and antioxidants. Brief attention is given to the model describing competition between oxygen and natural radioprotective substances (principally, thiols) in determining the net cellular radiosensitivity.

Several theories of the mechanism(s) of action of radioprotective drugs are described in Section III. These mechanisms include the production of hypoxia, detoxication of radiochemical reactive species, stabilization of the radiobiological target and the enhancement of damage repair processes. Section IV describes the current strategies for the treatment of radiation injury. Likely areas in which fruitful research might be performed are described in Section V.

Appendices are devoted to lists of currently-funded research projects involving chemical radiation protection and a brief compendium of compounds which have been tested for radioprotective activity.

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I. Effects of Radiation on Biological Systems.

A. Introduction.

In this section, some of the general terms and concepts dealing with radiation and with radiation injury to biological systems are introduced. In Section II, radioprotection and radioprotective agents are discussed in more detail. The related topics of radiosensitization and of non-ionizing radiation effects are considered only to the extent that such consideration is relevant to chemical protection against ionizing radiation. Among the reviews which have been published on the general subject of radiation biology are those of Dertinger and Jung [120] and Pizzarello and Witcofski [352], which were used as sources of much of the introductory material in this section.

B. Types of Radiation.

Table 1 lists forms of radiation that are pertinent to this review. Those forms which consist of energetic particles and certain of the electromagnetic spectrum rays (cosmic, gamma, and X-rays) are commonly designated as ionizing radiation. When these types of radiation penetrate biological tissue (or other forms of matter), some of the neutral atoms along the paths of penetration are converted to ions. At the other end of the electromagnetic spectrum are microwaves and radiowaves which are characterized as non-ionizing radiation. Ultraviolet wavelengths are intermediate, in both frequency and biological effects, between ionizing and non-ionizing radiation.

C. Effects of Ionizing Radiation at the Atomic and Molecular Levels.

The physical and chemical lesions produced when ionizing radiation penetrates biological tissue result from the transfer of radiation energy to the tissue. The first tissue/radiation interaction is at the physical level (energy transfer to some tissue component) with secondary and higher order effects at the physico-chemical, chemical, and biological levels. As approximate orders of magnitude the relative time required for these stages is: physical = 10^{-13} sec., physico-chemical = 10^{-10} sec., chemical = 10^{-6} sec., and biological = seconds to years.

Whether one considers direct effects (terminal absorption of the energy of an incoming particle or photon by DNA or another functional biomolecule, with resultant chemical change of that molecule) or indirect effects (damaging energy transfer to the biomolecule only after intermediate absorption

TABLE 1: SOME TYPES OF RADIATION		
TYPE OF RADIATION	SOURCES	I/NI*
Particulate:		
Electrons (β^- particles)	Radioactive decay	I
Positrons (β^+ particles)	Radioactive decay	I
Protons	Cyclotron; Van de Graff generator	I
Neutrons	Nuclear fission, Cyclotron	I
Helium nuclei (α particles)	Radioactive decay	I
Nuclei of heavier elements	Particle Accelerators	I
Electromagnetic (wavelength)		
Cosmic rays (5×10^{-9} nm)	Stars	I
Gamma rays (5×10^{-4} - 1.4×10^{-1} nm)	Radioactive decay	I
X-rays (1×10^{-2} - 10 nm)	X-ray machine	I
Ultraviolet (\approx 280-400 nm)	Sunlight, artificial sources	Int
Microwaves (\approx 0.3-300 cm)	Radio, television, other transmitters, other artificial EM fields	NI
Radiowaves ($>$ 0.3 cm)	Communications; cosmic sources	NI

* I, Ionizing; NI, Nonionizing; Int, Intermediate.

and transfers by diffusible ions and radicals), the basic cause of radiation damage is the same: disruptive absorption of the energy of photons and/or energized subatomic particles.

1. Modes of Energy Transfer.

For the most part, primary energy transfer occurs through ejection or excitation of orbital electrons in atoms along the radiation path, although some transfer occurs through direct collision with the nuclei of those atoms. The paths of low-mass particles, such as electrons, will be irregular since these particles are subject to scattering and deflection by collisions with electrons of the medium.

Ionization: In ionizing events, the passage of an energetic particle (or a photon) causes ejection of an electron from an atom with the resultant creation of a positive and negative ion pair. This is the principal means by which the energy of ionizing radiation (whether particulate or electromagnetic) is transferred to biological tissues. Water is most frequently the molecule from which the electron is expelled because of its preponderance in most biological tissues. The "water radicals" that result are the principal

agents which re-transfer the absorbed radiation energy to "target" biomolecules.

Excitation: In addition to ionization, a significant fraction of the energy of energetic particles or of electromagnetic radiation is dissipated by electron excitation. In this process, an outer electron of a target atom absorbs enough energy to move to a higher energy state but remains associated with the atom.

Collision: Whereas X-rays, γ -rays, ultraviolet radiation, and charged particles interact chiefly with intercepted atoms to eject or excite orbital electrons from these atoms, the energy of neutron radiation is absorbed chiefly by direct collision with nuclei, causing the ejection of disintegration fragments (such as neutrons, protons, or alpha particles) bearing the transferred kinetic energy of the colliding neutrons. In biological tissue with its preponderance of hydrogen atoms, the production of high-speed protons (hydrogen nuclei) is the most frequent consequence of these collisions. Nuclear disintegration can also be produced by high energy photons. Photons or electrons can interact with target nuclei to produce secondary X-ray emissions.

Indirect Energy Transfer: Whether the radiation energy is initially absorbed by ionization, excitation, or collision, a secondary production of free protons, electrons, ions, free radicals, or photons can occur as the energy is re-transferred to other atoms and molecules. The disintegration of target nuclei which have become unstable due to ejection or absorption of particles also contributes to the secondary production of ions by releasing a shower of energetic particles.

Among the products of the energy-absorption process, "free radicals" are of particular significance. A free radical is an atom with a single unpaired orbital electron, atomic hydrogen being the simplest example. A free radical is more long-lived than an ion pair and has a high probability of reacting with another atom either by pairing of its unpaired electron with an electron of that other atom, by releasing its unpaired electron to the other atom, or by capturing an electron from the other atom. Each of these interactions can in turn create additional ions or free radicals. Most of the radiation damage to organic molecules is associated with such chains of secondary free-radical interactions.

2. Significant Variables.

The nature of the effects which will occur when ionizing radiation penetrates tissue depends upon a multiplicity of variables. Some of the more significant ones are listed here.

Type of radiation: The results of the interaction between radiation and tissue will be influenced by whether the radiation is particulate or non-particulate and, if the former, by the size and charge of the energetic particle. For example, because neutrons are not slowed or deflected by the negative charge or the much smaller mass of encountered electrons, their energy is more likely to be absorbed by direct nuclear collisions. The energy of the smaller charged particles of β -rays, on the other hand, will be largely dissipated in ionization or excitation interactions with orbital electrons. Interactions of heavy ions from particle accelerators are influenced by both their charge and their mass. The more highly charged a particle is, the more frequent will be its interactions and the greater will be the density of ions produced along its track. The more massive it is, the slower it will be (at a given energy level) and the greater will be the density of ionization events. The energy of massless ultraviolet, X- and γ -rays is transferred in photon/electron collisions and biological damage produced by this radiation is due almost entirely to the action of the free radicals and ions produced.

Particle velocity: The density of ions produced along the track of an ionized particle is influenced by its velocity. The slower it is, the greater will be the number of ions produced per millimeter of track. For this reason, ionization density increases continually along a particle track as the particle is gradually slowed by incremental energy transfers. The most abundant ion production occurs just before the particle comes to rest.

Wavelength: For non-particulate radiation, the greater its energy (i.e., the shorter its wavelength), the greater is its potential to support damaging energy transfer events in tissue.

LET/RBE: Linear Energy Transfer, or LET, is a measure of the amount of energy released (by any mechanism) per micron of track of any ionizing radiation and is an indicator of the level of biological disruption to be expected. Biological damage is greater and postirradiation recovery is slower [324] for high-LET than for low-LET radiation. LET is determined in part by the variables already mentioned: it varies with the kinetic energy level

(velocity and size) and charge of radiation particles and with the wavelength (energy) of electromagnetic radiation. Since particle velocity decreases continuously along the particle path, LET also changes continuously, increasing as the particle slows until it falls abruptly to zero when the particle comes to rest. Because LET varies for different types of radiation, biological effect is sometimes expressed in terms of relative biological effectiveness (RBE), which is a ratio of the biological disruption from the radiation in question to that from some reference radiation (usually γ -rays).

Dose: Biological damage from ionizing radiation increases with the dose (i.e. the amount of radiation energy absorbed). Standard units of absorbed dose include:

- the rad (R) (deposition of 100 ergs per gram of tissue),
- the Gray (Gy) (100 rads, or 1 joule per kilogram of medium),
- the rem (the rad corrected for the radiation quality under consideration), and
- the Sievert (100 rem).

Dose rate: The extent of biological damage can also vary with the rate at which a given dose is administered (absorbed), especially for low-LET radiations. As will be discussed below, biological tissues possess some capability of repairing sub-lethal damage from ionizing radiation. For low-LET radiation (that tends to produce sub-lethal damage to cells) and low dose rates or divided doses, repair mechanisms may to some extent counteract radiation damage as it occurs whereas at low-LET/high dose-rates, the repair capacity can be overwhelmed. With high-LET radiation, where damage is more likely to be non-repairable, dose rate is less influential.

Tissue and field: Some tissues are more radiosensitive than others. Proliferating cells (e.g. hemopoietic stem cells) are more sensitive than non-proliferating cells, with the period of chromosome formation being most sensitive and the period of onset of DNA synthesis being relatively resistant. Some types of damage are produced at lower doses than are others, and the dose required for a given effect is influenced by the proportion of the tissue or organism (the "field") that is irradiated. There is also a genetic component to "radioresistance". For instance, some types of microorganisms show much greater radioresistance than others. Repair capability is one of many factors that contribute to variations in sensitivity among tissues or organisms.

Modifiers: Modifiers of the radiobiological response to ionizing radiation must be included in the list of variables governing the nature of radiation injury. Both sensitizers (e.g., oxygen) and protectors (e.g., glutathione, tocopherol) may be present and the net effect of the presence of modifiers will be determined by the type of modifier present, their concentration and relative potency. These topics are discussed more fully in §II.

3. Critical Radiation Targets.

Much effort in the field of radiobiology has been devoted to the identification of the critical radiation target whose inactivation leads to cell death. Whereas recent observations on this problem suggest that the critical factor may be the interrelationships between several targets [108], some evidence is presented below for the idea that individual targets can be identified as being of overriding importance for cell inactivation.

Nucleic Acids: A number of lines of evidence show that DNA is a critical target for radiation damage. Whereas other molecules and structures, such as enzymes and membranes, can be damaged by radiation, effects on DNA are more likely to have negative consequences for the organism. A radiation-induced defect in only one molecule of DNA can theoretically bring about the death of the cell, the death of the entire organism (if the defect is a carcinogenic one) or a severe abnormality in the progeny of the damaged cell or organism (if the defect is a mutagenic one). One would not expect the effects of a single lesion in a non-nucleic acid molecule or structure to have such significant effects.

Reasons for the identification of DNA as the critical target molecule for ionizing radiation are briefly summarized in Chapter 14 of the monograph by Dertinger and Jung [120]. Perhaps the most persuasive evidence is the correlation of radiation sensitivity (in viruses, bacteria, yeast, cultured cells, and plants) with DNA content, rather than with the size of the cell or some other variable.

Ionizing radiation brings about changes in both the physical/chemical and functional characteristics of DNA [216]. Radiation-induced free radicals and ions chemically disrupt the DNA molecule in a number of ways. Atomic hydrogen produced by water radiolysis attacks the double bonds of the purine and pyrimidine bases, and can thus produce altered DNA structures. Under aerobic conditions, the hydroxyl radical attacks the 5-6 purine double bonds

to produce unstable hydroxy peroxides. Radicals produced during water radiolysis (hydrogen and hydroxyl free radicals and the aqueous electron) also attack the deoxyribosyl component of DNA, producing chain breaks. Other chemical effects include breaking of hydrogen bonds which produce conformational changes, crosslinking of DNA with DNA or protein, and the removal of the bases.

Functional evidence of radiation-induced degradation of DNA is also seen, not only in the DNA-mediated production of mutations, birth defects, arrested cell division, and cancer (see below) but also with the loss of a number of other basic DNA functions as summarized by Dertinger and Jung [120]. These effects include radiation-induced decrease or cessation of DNA/RNA synthesis, loss of infectivity of irradiated bacteriophage, loss of bacterial transformation ability, dose dependent failure of irradiated DNA in its action as a primer for nucleic acid synthesis when incubated with DNA or RNA polymerase, diminished in-vitro hybridization between irradiated DNA and messenger RNA, loss of enzyme induction capacity in bacteria, and inactivation of viruses.

Ionizing radiation has also been shown to disrupt RNA functions in whole cells and cell-free preparations. The functions of messenger RNA, transfer RNA, and ribosomal RNA are inhibited, as was reviewed briefly by Dertinger and Jung [120]. However, RNA is more radioresistant than DNA, and transfer RNA is more resistant than messenger RNA, when measured by functional parameters. These sensitivity relationships may be explained by the relative sizes (target sizes) of the nucleic acid molecules. It is partly on the basis of these relative sensitivities that the critical event in radiation-induced cell death is considered by most workers to be interference with the function of DNA.

Membranes: A number of lines of evidence indicate that radiation also damages membranes and membrane function. Peroxidation of membrane lipids and lipids of model membranes has been reported by various groups [252,251,186, 371,369,370,491]. Irradiated yeast cells show increased amino acid influx and loss of membrane sulfhydryl groups without survival being affected [237]. The increased radiosensitivity of embryonic cells during the period of gastrulation is suggested by Dertinger and Jung [120] to be due to an effect on cell membranes. Jozwiak [229] reported increased osmotic fragility

of irradiated porcine erythrocytes. Schuurhuis [403] showed that X-irradiation of human erythrocytes or ghosts produced some cross-linking of membrane proteins and alteration of the cell shape.

The relationship between lipid peroxidation of model or cellular membranes and radiosensitivity of organisms is not well established. Attempts to define this relationship by altering the composition of membrane lipids have produced somewhat equivocal results [138,485]. Incorporation of polyunsaturated fatty acids (PUFA) into the membranes of mouse fibroblasts did not alter the radiosensitivity of these cells [485]; although lipid peroxidation was not measured in this study, a significant decrease in the membrane fluidity was observed when cells were supplemented with arachadonic acid. Similarly, cells of the prokaryote Acholeplasma laidlawii exhibit similar radiation survival characteristics when grown in the presence or absence of high concentrations of dilyncoylphosphatidylcholine and irradiated in air at 5 Gy/min at 37°C [138]. While these conditions are optimal for the development of lipid peroxidation in model membranes [139], the antioxidant defenses of these cells may be sufficient to prevent significant lipid peroxidation from occurring [139,485].

The localization of repair enzymes and nucleases on the cell membrane [163,417,445] means that free radical damage to membranes could interfere with repair and provides a rationale for regarding membranes as important radiation targets. Bacq and Alexander [38] proposed that a significant component of radiation effects is attributable to cell membrane damage. However, current evidence concerning radiogenic membrane damage does not indicate that such damage is of major significance except at exposure levels above those where DNA lesions are critical. At very high exposures, early effects on membrane permeability, i.e. allowing entry of macromolecules into vascular space, can be life-threatening.

Enzymes: A report of Zajac et al. [491] showed decreased enzymatic activities in irradiated microsomes. As reviewed by Singh and Singh [415], some enzymes are resistant to radiation, some are inhibited, and some are stimulated. There is no clear evidence to date to suggest that enzyme inactivation is a critical aspect of radiation damage, although several reports suggest that nucleic acid polymerases may be important targets leading to cell death [429,430].

D. Effects of Ionizing Radiation at the Functional and Systemic Levels.

1. Cell Survival Curves and Models of Cellular Inactivation.

At sufficient dosage, ionizing radiation kills cells or prevents their proliferation. Much of the current theory concerning the mechanism of irradiation damage to biological tissues is based on observations of radiation-induced cell inactivation in mammalian-cell tissue cultures. Use of such systems enables the researcher to determine the proportion of cells killed under a given set of experimental conditions. From the slope and form of curves relating the proportion of cells surviving (plotted with a logarithmic scale) to the dose (linear scale), various inferences and hypotheses concerning the mechanism of radiation damage may be drawn.

One of the characteristics of such curves which is often (but not always) observed is a so-called "shoulder" - a rather abrupt steepening in the slope of the curve above some critical dose range. This shoulder (indicating existence of a "threshold" dose, below which the cells are more resistant to the lethal effects of radiation) must be accommodated by any hypothetical model of radiation-induced cell inactivation. Only two of these models are mentioned here.

Target Theory: This model of cell inactivation assumes that each effect of ionizing radiation stems from a specific critical "hit" of a particular target molecule. This theory of radiation action has been dominant for many years. For a cell survival curve without a shoulder, the logarithm of the level of inactivation is directly proportional to the dose. A curve with a shoulder is interpreted as indicating a system in which accumulation of multiple hits (a specific number per cell) is required before the final hit can produce a lethal effect. When the dose is increased sufficiently that the energy absorption events per cell exceed this number, the low-dose threshold is exceeded and the slope of the survival curve steepens.

Repair Theory: This alternative to the multi-hit target theory, as an explanation of cell survival curve shoulders, rests on the fact that cells have a limited capability to repair radiation damage. According to this theory, even a single radiation absorption event may be potentially lethal but if the lesion is repaired in time (for instance, before cell division is attempted), cell death will be avoided. Because of such repair processes, cell death as a result of radiation damage is prevented or the degree of

lethality diminished at lower dose rates. At higher dose rates (those above the shoulder) the limited repair capacity (or "Q factor") is saturated and the slope of the cell survival curve is therefore steeper. Cell survival curves with no shoulder indicate that the cells have no repair capability for the damage being inflicted under the particular observation conditions.

Several types of observations support this theory, including those of increased cell survival if a given dose is administered as successive fractions (allowing between-dose repair by a system that would be overloaded if the same total dose were absorbed without interruption). Support for the repair theory is based upon the fact that certain chemicals (e.g. caffeine, actinomycin D) which are known to inhibit DNA repair also diminish or eliminate cell survival curve shoulders and the fact that curves without shoulders are seen for certain mutant microorganisms which have repair deficiencies.

Definitive experiments which will support one model of cell inactivation while being incompatible with others apparently have not been devised. However, support for the repair theory seems to be steadily increasing while the target theory no longer meets with the general acceptance that it enjoyed for many years. It seems likely that the ultimate model of cell inactivation will include elements of both theories.

2. Effects on Cell Division and Differentiation.

Chromosomal aberrations: The earliest microscopically apparent effects of radiation on cells are chromosomal alterations (such as breaks, deletions, and translocations). These alterations become detectable as the mitotic apparatus condenses for cell division. The visible chromosomal alterations are manifestations of earlier physical and chemical alterations of DNA molecules. If these alterations are sufficiently severe, the cell will fail to complete the transition through mitosis. At lower levels of DNA alteration, non-lethal damage may take the form of transmissible chromosomal abnormalities (mutations), abnormal differentiation in embryonic cells (terata), or neoplastic transformation.

Mutation: Mutations arise when a radiation-induced change in the DNA of reproductive cells is non-lethal to the cell and can be reproduced and transmitted during mitosis. The mutation is normally heterozygous (since it is extremely unlikely that the same damage would occur to the two separated members of a chromosome pair) and is usually recessive. Such a mutation may become apparent only after many generations when two individuals bearing the

mutation happen to mate. Although mutations occur spontaneously, ionizing radiation increases the mutation frequency. It has been estimated that the amount of radiation needed to double the spontaneous human mutation rate is 50-250 rads [321].

Teratogenesis: Teratogenesis is one of the well-recognized effects of ionizing radiation [449]. The fetus and embryo are particularly vulnerable because dividing cells are more sensitive to radiation than are resting cells. Among dividing cells, both undifferentiated embryonic cells and differentiated cells are less sensitive than are those which are undergoing differentiation. Therefore, radiosensitivity varies continuously during embryonic and fetal development. The nature of a radiation-induced teratogenic effect will depend in part upon the organ systems undergoing development at the time of irradiation. In the mouse, for example, abdominal hernia can be produced by irradiation on the 4th to the 16th day, cleft palate on day 8, 10, or 11, skeletal abnormalities on the 9th to 16th day, skull defects on day 12, etc.

Carcinogenesis: A significant effect of ionizing radiation in moderate doses is carcinogenesis [72,447,449]. The relationship has been conclusively shown in humans and other animals. The major types of cancer induced by human whole body external radiation are breast, thyroid, and lung cancer, and leukemia. For equal doses, high-LET radiations such as neutrons are more carcinogenic than low-LET radiations such as X-rays. It is widely believed that the essential carcinogenic event involves alteration of cellular DNA although this event may not be manifested as cancer for decades.

3. Acute Radiation Syndromes.

This term is used to refer to the effects of high-dose, whole-body radiation. These effects can be subcategorized under 3 major headings: bone marrow, gastrointestinal, and central nervous system syndromes [361].

Bone Marrow Syndrome: The bone marrow syndrome occurs at the lowest dosage of the three syndromes (about 100 R with a fatality threshold at 200 R). This syndrome is characterized by lethal damage to bone marrow and lymphatic stem cells, with consequent depletion of blood cells and the alteration of immune function. If exposure is sufficiently severe, death from the bone marrow syndrome occurs at approximately 3 weeks to 2 months after the incidence of radiation.

Gastrointestinal Syndrome: The gastrointestinal syndrome appears at a dose of approximately 500 R with lethality at 1000 R. It is characterized by gastrointestinal symptoms and failure of the intestinal mucosa which, if sufficiently severe, will result in death within about 2 weeks.

CNS Syndrome: The central nervous system syndrome, with encephalitis, meningitis, and CNS edema, is apparent at 2000 R. At about 5000 R, lethality from these causes occurs within 2 days - before the otherwise fatal gastrointestinal and bone marrow syndromes are expressed.

4. Summary of Effects of Ionizing Radiation on Biological Systems.

Because normal cell function is more vulnerable to disruption by alterations in DNA molecules than by alterations in molecules of other types, damage to DNA is believed to be the most critical effect in cells exposed to radiation. Depending on the number of cells which are damaged and the intensity of the damage, the effects of whole-body irradiation of animals can range from minimal and repairable DNA alterations with no life-threatening effects, through apparent recovery of the organism (but with residual life-threatening effects such as mutation, teratogenesis, and carcinogenesis), to massive cell lethality resulting in acute illness and death of the organism.

E. Effects of Ultraviolet Radiation on Biological Systems.

On the electromagnetic spectrum, ultraviolet radiation (approximately 280 to 400 nm in wavelength) falls between the ionizing X- and γ -rays (less than 10 nm) and the non-ionizing microwaves and radiowaves (greater than approximately 0.3 cm). Although ultraviolet radiation is not usually included within the concept of "ionizing radiation," its effects on interaction with biological tissues (particularly in the near ultraviolet wavelengths below 320 nm) have much in common with those of X- and γ -rays and will be discussed with them in the following sections.

Biochemical effects of ultraviolet radiation, including changes in DNA, RNA, enzymes (which may be either activated or inactivated), and synthesis of macromolecules are reviewed by Parrish *et al.* [340] and by Hall and Mount [190]. As do X- and γ -radiation, near-ultraviolet radiation generates superoxide radicals in cell culture growth media, an increase in chromosome damage, inactivation of enzymes, oxidation of polyunsaturated lipids, and membrane damage. In cell culture experiments, these effects can be prevented by exogenous superoxide dismutase [77,148].

Ultraviolet radiation can be absorbed by a variety of endogenous and exogenous biological compounds. As with other types of radiation, this absorption can result in generation of highly reactive, relatively short-lived intermediates (free radicals and ions) which through further energy transfers can chemically modify nucleic acids and other biomolecules or structures. As pointed out in the review by Parrish et al. [340], it has been concluded that the primary event in lethal ultraviolet irradiation of bacteria is alteration of DNA. Ultraviolet inactivation spectra for a wide variety of cells correspond relatively closely to the absorption spectrum of DNA, with a peak near 260 nm.

The mimicry of X- and γ -ray effects by ultraviolet radiation is emphasized by Peak and Peak [344]. Among these effects are changes in soluble and membrane-bound enzymes and in RNA, with these effects of near-ultraviolet (but not those of far-ultraviolet) being potentiated by oxygen (as are those of ionizing radiation). One of the most prominent effects is the induction in DNA of cyclobutane dimers at adjacent pyrimidine base sites. Peak and Peak reported that this induction was several orders of magnitude less efficient and the dimers were more efficiently repaired for near-ultraviolet (greater than 320 nm) than for far-ultraviolet (less than 320 nm) irradiation. Radioprotectants which were protective against X-rays also protected against near- but not against far-ultraviolet radiation. In these respects, the effects of near-ultraviolet light more closely resemble those of X-rays than they do those of far-ultraviolet radiation [344].

Carotenoids protect against the adverse effects of ultraviolet irradiation through their action in quenching radiation-induced singlet oxygen and oxy-radicals [254] (as reviewed by Urbach et al. [451]), while other chemicals may potentiate ultraviolet-induced carcinogenesis.

F. Effects of Non-ionizing Radiation on Biological Systems.

1. Types of Non-ionizing Radiation.

The term "non-ionizing radiation" refers to microwave and radiowave (MM and RF) frequencies on the electromagnetic spectrum. Although frequency demarcations between types of radiation on the spectrum are not precise nor standardized, "microwaves" can be considered to include those with frequencies of approximately 300 kHz to 300 MHz and "radiowaves" are a sector of the radiofrequency domain which includes all frequencies below 300 MHz [304].

Microwave and radiowave exposures to the general population are now pervasive as the result of the large numbers of radio, television, and radar transmitters in use and the numerous other electromagnetic fields that are generated in a technological society. Exposures are commonly measured as mW/sq cm of exposed surface.

2. Contrasts Between Effects of Ionizing and Non-ionizing Radiation.

The most biologically significant contrast between these two types of radiation is that identified by their characterizations, ionizing and nonionizing. Below the infrared frequencies, quantum energies are too low to induce electronic excitations but are sufficient for resonance absorption. Therefore, radiation in the MM/RF ranges does not transfer its energy to biological molecules by the formation of chemically reactive ion pairs and free radicals. Rather, most of the energy transfer is accomplished by simple thermal conversion. This difference in the mode of energy deposition in irradiated tissue results in profound qualitative differences in the types and significance of resultant injury to the tissue.

While it is clear that at the most common levels of exposure, the health effects of non-ionizing radiation are not comparable to those of ionizing radiation, in practical significance it is also true that they are less well understood. There is still a residuum of uncertainty concerning the fundamental question of whether there are any adverse health effects of microwave and radiofrequency radiation which are not due to simple heat injury resulting from the thermal conversion of the absorbed energy.

Biological effects of non-ionizing radiation have been reviewed [181]) under the auspices of the NATO Scientific Affairs Division. The collection reveals areas of agreement, disagreement, and uncertainty concerning interactions of microwave and radiofrequency radiation with tissue. There is general agreement that tissue absorption of non-ionizing radiant energy is predominantly mediated by water, with conversion of the absorbed radiant energy to heat. High intensity exposures lead to irreversible thermal injury.

There is less general agreement as to whether low-intensity MM/RF exposures can also lead to non-thermal reversible or irreversible effects. Kaiser [232] states that "... well documented biological effects exist which arise from an irradiation at very low intensities (e.g. below 10 mW/cm²)

where thermal effects can be excluded" and cites several studies. Reference is made to a theoretical concept which assumes the existence of metastable oscillating systems (e.g., in membranes) which are self-sustained by metabolic energy in special active states and can be triggered to a biological response by non-thermal absorption of low-intensity MW/RF radiation. The paper by Grundler [185] reaffirms previously published observations of changes in yeast growth rate caused by low intensity MW radiation with the effects being dependent on frequency and not correlated with power density in the range of 6 to 34 mW cm⁻².

Berteaud [59] suggests that thermal-gradient-mediated phase transitions in membrane lipids may be a primary site of MW/RF tissue alterations, even when no thermal gradients are apparent to the investigator. In contrast, Michaelson [305] reviews reported biological effects of RF/MW energy and finds no adequately documented evidence of non-thermal responses.

In any case, it is clear that except for the straightforward thermal injury of very high intensity MW/RF radiation, the biological effects of non-ionizing radiation are uncertain and are not comparable to those of ionizing radiation.

There has been no suggestion that chemical protection from non-ionizing radiation injury might be feasible. Work concerning protection has instead focussed on shielding and other dose-attenuation strategies. Therefore, MW and RF radiation will not be considered further in this review.

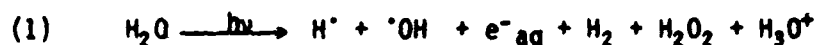
II. Endogenous Factors which Influence Radiosensitivity.

A number of characteristics of cellular biochemistry and physiology interact to determine natural or inherent radiosensitivity of both cells and the higher level structures which they comprise. Since some exogenous chemical radioprotectors may exert their effect by altering the normal balance between these endogenous factors, it is instructive to begin with a brief discussion of these factors and their relative effects. Some of these factors may be exploited for therapeutic gain to either increase or decrease natural radiosensitivity whereas others are not amenable to manipulation.

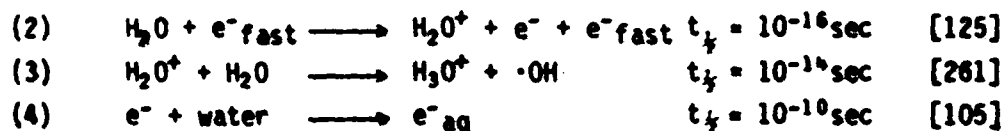
A. Water.

Energy deposition within a biological sample is dependent on a number of physical factors (as discussed in §I.C.2) whereas damage to critical targets (§I.C.3) is influenced by the interaction of energy with the molecules which

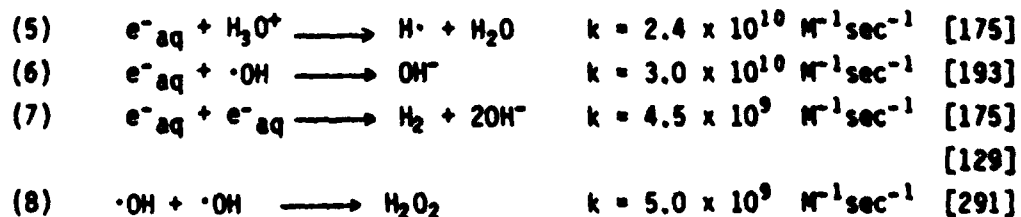
comprise the cell matrix. The deposition of energy in the target molecules themselves has been referred to as direct action whereas deposition of energy in the surrounding medium, with subsequent transfer to the critical targets, is referred to as indirect action. Since 55-70% of the cell mass is water [134], and since the absorption of energy in a mixture is in direct proportion to the mass ratio of its constituents [241], the products of water radiolysis as denoted in equation 1 have been thought to figure heavily in radiation damage to cells.



The formation of these highly reactive species has been extensively studied [92,130,415]. The deposition of energy is not uniform in radiolyzed water [284,405]. Approximately 10^{-14} sec after a pulse of high energy radiation, fast electrons interact with water molecules to produce the primary species of water radiolysis, according to equations 2-4.

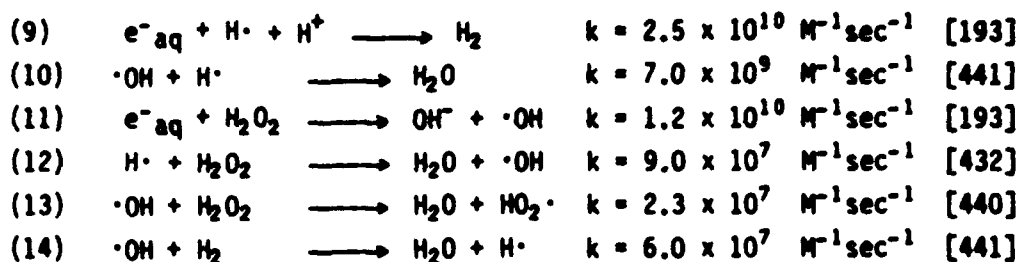


These primary products of water radiolysis are formed in small localized regions known as spurs, of approximately 2 nm radius. The e^-_{aq} is formed throughout the spur whereas the formation of H_3O^+ and $\cdot\text{OH}$ are located primarily in the core of the spur in a sphere of ≈ 0.75 nm radius. These primary species undergo radical reactions in the spurs between 10^{-14} to 10^{-12} seconds by reactions 5-8.

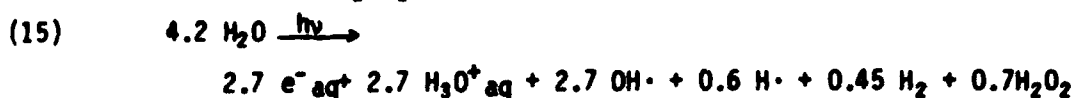


As the spur enlarges and the radical products begin to diffuse out into the surrounding medium, they undergo reactions with other radicals, forming

radical and neutral molecular products (equations 9-14).

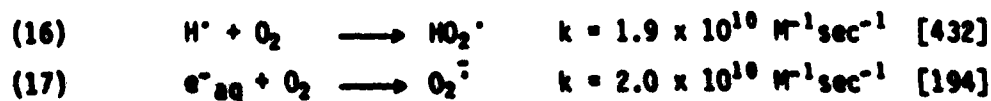


Within 10^{-3} sec of the receipt of the radiation pulse, the reactions of the primary free radicals are complete and a homogeneous solution of the products of water radiolysis as shown in reaction 1 has been formed. The yield of these species per 100 eV of absorbed energy (the G-value) is approximately as is shown in reaction 15 [93].



Within a spur at $< 10^{-12}$ sec after radiation incidence, the concentration of H^{\cdot} and e^{-}_{aq} may reach 10 and 100 mM respectively [415], while in the core of the spur, H^{\cdot} and OH^{\cdot} may be formed at concentrations which approach 0.5 and 2 M respectively [130,227,228,405]. As the dimensions of the spur increase over time and the products of water radiolysis undergo their reactions, the concentrations of the reactive species decrease so that by 10^{-3} sec a homogeneous solution is formed with concentrations of radicals which are orders of magnitude lower than what is initially formed ($< 10^{-12}$ sec) in the core of the spur on interaction of water radiolysis products with molecular oxygen.

The yield and nature of radical and molecular species formed on irradiation of water is influenced to a great degree by the presence of molecular oxygen (reviewed by [78]). Molecular oxygen has a high affinity for the reducing radicals H^{\cdot} and e^{-}_{aq} , forming perhydroxyl



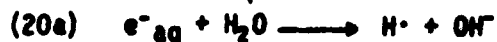
(equation 16) and superoxide anion radicals (equation 17), respectively. The

rates of these reactions are so high that in oxygen saturated water, few solutes can compete with oxygen. Thus by 10^{-8} sec after irradiation, the radiolysis products in oxygenated water include:



Oxygen interacts with the hydroxyl radical only under conditions of extremely high pH; under these conditions the ozonide ion $\text{O}_3^{\cdot-}$ is formed.

The reactions between organic compounds and the primary products of water radiolysis have been studied extensively. Under anoxic conditions, reactions of the hydrated electron and the hydrogen atom will be important. Reactions between the hydrated electron (e^-_{aq}) and organic compounds are, by definition, electron transfer processes. Since one-electron transfer reactions with most organic compounds do not produce stable species, the primary reaction products undergo secondary reactions to produce stable products. The hydrated electron undergoes addition reactions with many organic compounds, depending on their electron affinity and redox potentials [27,193]. The hydrogen atom ($\text{H}\cdot$) participates in addition reactions with sites of unsaturation in organic compounds, abstraction of hydrogen from organic compounds and charge transfer reactions with metal ions [26,28]. The hydroxyl radical similarly reacts by hydrogen abstraction, addition to sites of unsaturation and electron transfer [153]. The reactivities of the superoxide anion radical [399] and the perhydroxyl radical [64] have been reviewed. In each case, the reactions of transients formed from water (and oxygen, if present) involve a competition between reactions of the radical species with organic solutes (equation 19) and with water (equations 20a-c) and the ratio of these reactions will depend upon the strength of the carbon-hydrogen bond and the stability of the free radicals produced.



The relative importance of direct and indirect effects in the genesis of radiation damage has long been debated. Whereas these effects are conceptually distinct, the practical boundaries between them have become blurred as

more is learned about the radiation chemistry of water. The practical difference between direct interaction of a target molecule with photons or Compton electrons (e^-_{fast} in equation 2) and the presence of a target molecule very close to a water radiolysis spur having very high concentrations of e^-_{aq} and $\cdot OH$ is not clear [425]. Furthermore, the direct effects of radiation do not always result in damage at the site of energy absorption, as direct effects may also involve energy transfer processes [75,198]. Nevertheless, water does contribute to the expression of radiation effects in some simple model systems [34]. However, water content is not a variable which is amenable to manipulation during the exposure of mammalian cells to radiation, so while water radiolysis must be taken into account when describing the mechanisms by which radiation effects are produced, we are not able to alter this variable to change the radiosensitivity in higher cellular systems.

B. The Oxygen Effect.

1. Definition and Historical Notes.

Few substances have a more pronounced effect on cellular response to radiation than oxygen. As defined in radiobiology, the oxygen effect refers to the increase in the sensitivity of cells to ionizing radiation as the concentration of oxygen is increased from zero to a fixed value [244]. This effect was first noted by Holthusen in 1921 in experiments with Ascaris eggs [208]. At the time, this effect was incorrectly ascribed to the non-dividing nature of these cells under anaerobic conditions. Some years later, Anderson and Turkowitz defined the absence of oxygen during irradiation as the primary factor, showing that yeast cells dividing anaerobically were similarly protected during hypoxia relative to the aerobic state [29]. Studies in a variety of test systems noted the sensitivity to oxygen (reviewed by Patt [342]), but studies conducted by Mottram [318] and later by Gray and colleagues [14] quantified this relationship, noted its clinical relevance, and brought it to the attention of radiation therapists.

2. The Oxygen Enhancement Ratio.

Survival curves (plotting the logarithm of the surviving fraction of cells [ordinate] against radiation dose [abscissa]; see §I.D.1) for mammalian cells irradiated in the presence or absence of oxygen show the same shape. However, the dose of radiation required to achieve a given level of effect (to reduce cell survival to a given level) is greater in the absence of oxygen than in its presence. The ratio of the dose required to achieve a given

cell survival in the presence of oxygen to that dose required to achieve the same effect under anoxic conditions is referred to as the oxygen enhancement ratio (O.E.R.). Although there is some controversy about the magnitude of the oxygen effect at low radiation doses [276,381,382](cf[243,244]), the effects of oxygen are said to be "dose-multiplying", that is, independent of the dose of radiation and the survival level. The O.E.R. varies with the type of radiation (see §I.C.2) and decreases with increasing Linear Energy Transfer (§I.C.2)[46]. For sparsely ionizing radiations such as X- and γ-rays, the O.E.R. has a value of between 2.5 and 3. Dose multiplication by oxygen requires the replacement of the anaerobic dose term (D) in algebraic relationships describing the survival of cells by a multiple of D, without deviating from the fitted curve [14].

In studies of the effect of oxygen on the radiosensitivity of isolated macromolecules, a rather confusing picture emerges. The inactivation of enzymes such as ribonuclease [206], carboxypeptidases [112], trypsin [294], ferricytochrome c [47] and others (cited in [215]) shows a dependence on the presence of oxygen. Yet, oxygen has been reported to confer protection in such systems in certain cases [120]. For the inactivation of transforming DNA, similar discrepancies have been noted. Several authors report no effect of oxygen [114,215] while others report protection by oxygen [68,195]. In relating these studies to the enhancement of damage by oxygen in whole cells or tissues, one must recognize that in the absence of the normal cellular architecture and biochemistry, markedly different physicochemical processes may dominate (see §II.D).

3. Characteristics of Oxygen Enhancement.

a. Dependence on Oxygen Concentration.

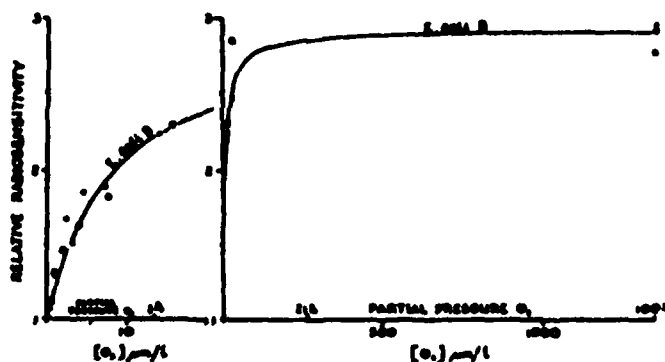
Soon after the presence of oxygen was recognized as an important factor influencing radiation sensitivity, the dependence of this effect on oxygen concentration was determined. Alper and Howard-Flanders [22] showed that for E. coli B irradiated in suspension, the sensitivity (S_p) of cells at oxygen partial pressure P relative to their sensitivity in anoxia (S_N) follows the relationship

$$(21) \quad \frac{S_p}{S_N} = \frac{mP + K}{P + K}$$

where m and K are constants. The factor m represents the maximum sensitization, which may be interpreted as the oxygen enhancement ratio at high doses

of radiation. The constant K relates the rate of increase in sensitivity to the increase in the oxygen partial pressure.

Graphically, equation 21 describes a hyperbola, with radiation sensitivity increasing rapidly as oxygen concentration increases from zero to about 0.5 - 1% O₂ (Figure 1). Further increases up to the concentration of oxygen in air (21%) or to 100% serve to increase radiosensitivity only marginally. For the conditions under which equation 21 applies, m has a value of about three and K (interpreted as the partial pressure of oxygen at which the effect is half maximal ($K = \frac{m+1}{2}$)) is about 5-10 $\mu\text{mol/l}$ [22]. The experimental determination of the applicability of this equation is difficult [13] and is subject to the errors associated with the manipulation of low oxygen concentrations [100]. Perhaps for these reasons, although earlier studies had shown the general applicability of equation 21 to bacteria [22], yeast [211] and mammalian cells [122,109],



(Figure 1)

more recent research has described some deviation from this hyperbolic relationship. Millar et al. [309] have shown that by careful measurement of oxygen tensions in the range of 1-10 μM , a biphasic relationship is obtained between oxygen concentration and enhanced radiosensitivity of Chinese hamster V79-7538 cells. This separation of the oxygen effect into components depending on oxygen concentration had been noted earlier in dry [358,359] and wet [152,436] bacterial spores and has been observed recently in yeast [314]. In an interesting re-analysis, Powers [357] has shown that even in data purporting to show a fit to the single component hyperbolic curve (equation 21) [274,483], transformations of the equation and a re-analysis of the data

according to a linearized relationship show two components to the oxygen effect. While non-linearity of this oxygen concentration-effect relationship may indicate multiple components which contribute to the oxygen effect, it is incorrect to attempt to deduce the parameters of these sub-components from a plot describing their combined effect [18].

b. Time Scale of the Oxygen Effect.

Investigations into the timescale in which oxygen acts to enhance radiation sensitivity can be categorized into two groups. Experiments on the pre-irradiation effect of oxygen, in which cells are allowed contact with oxygen for a fixed amount of time prior to irradiation, have provided evidence about the critical sites of oxygen-dependent radiation damage. Conversely, the admission of oxygen at fixed times post irradiation provides data on the lifetimes of that portion of anoxic radiation damage which can be altered by oxygen.

i. Pre-irradiation Oxygen Effects.

Howard-Flanders and Moore [213] studied the effect of transferring bacteria between gases of defined composition. Using an apparatus with a resolution time of 20 milliseconds (msec), they found that the bacillus Sigella flexneri exhibited a radiation response characteristic of the gas in which they were irradiated - irrespective of their incubation in a different gas more than 20 msec prior to irradiation. Thus, in bacteria, the radiosensitizing effect of oxygen is fully expressed within 20 msec. These results were confirmed by Shenoy et al. [408] using a rapid mixing technique for Serratia marcescens over a wide range of oxygen concentrations. However in experiments with mammalian cells in culture, two components to the oxygen effect were resolved in time [8,408]. At low concentrations of oxygen (1-10%), the cells required 40 msec contact with oxygen to achieve their full oxygen enhancement ratio. At higher concentrations of oxygen, the full O.E.R. was achieved at earlier times. These data were discussed in terms of several hypotheses, the most plausible of which is the existence of two sites within the cell at which oxygen may interact. Subsequent studies using a carefully designed technique of a similar concept [481] with another mammalian cell line have shown a similar timescale, though no evidence of time-resolvable components [482,483]. Thus, in mammalian cells, the effects of oxygen are expressed within several tens of msec after contact with the cells.

ii. Post-irradiation Oxygen Effects.

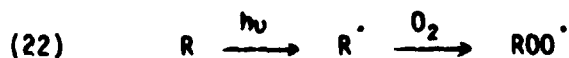
Oxygen added 20 msec after the anoxic irradiation of bacteria was without effect in altering the radiation response [213]. From this result, it was concluded that the reactive species, which are produced within these cells by radiation, decay in less than 20 msec to products which do not interact with oxygen. The refinement of fast response techniques has considerably shortened this estimate of the maximum lifetime of oxygen dependent damage. In fully hydrated bacterial spores, oxygen-dependent damage decays relatively slowly, following two parallel first-order reactions with half-lives of 9 and 120 sec [428]. In bacteria [149,478] and mammalian cells [273], the double pulse technique [150] yields an estimate of 0.1 msec for the maximum lifetime of oxygen-dependent damage. Conversely, the oxygen explosion method [302] consistently measures a half-life for decay of these species from 0.5 to 1 msec [301,303,477]. Although some disagreement has been noted, probably arising from the different techniques employed, it is clear that the transients produced upon irradiation which are induced in bacteria and mammalian cells under anoxic conditions are short lived, react rapidly with oxygen [303], and decay to products which do not interact with oxygen to increase radiation sensitivity.

4. Mechanisms of the Oxygen Effect.

The early theories of the mechanism by which oxygen increases the radiosensitivity of biological material involved the biochemical and physiological effects of oxygen which were known at the time [342]. However, as details of this sensitization were investigated, it became apparent that a physico-chemical mechanism of action was a more likely explanation for much of the oxygen effect. This view was championed by L.H. Gray and his colleagues whose arguments have been reviewed [356]. The temperature and concentration effects, the time of action of oxygen, and the variation of the oxygen effect with variations in radiation quality (LET) are all consistent with a physico-chemical mechanism.

The nature of this physico-chemical mechanism is the focus of the oxygen-fixation hypothesis [17,19,22]. In this theory, ionizing radiation is presumed to create free radicals within the target molecules of the cell which may undergo a number of reactions. If oxygen is present during or immediately after irradiation, this first reaction of the radiation-induced

radical (the "metionic" reaction [19]) will be to combine with oxygen, forming a species which prevents normal biologic functioning of the target (equation 22).



Since the lifetimes of most free radicals are short, oxygen must be present during or immediately after irradiation to be effective in fixing radiation damage; if oxygen is not present, the radical decays either to its original, biologically active form, or to an alternative damaged state [404]. To a first approximation, this theory fits some of the data recorded on the effect of oxygen in a wide variety of biological test systems. Thus, the requirement for oxygen to be present during or immediately after irradiation fits the observed lifetime of oxygen-dependent damage (§II.8.3.b). Also, the older measures of the dependence of radiosensitization on oxygen concentration described by equation 22 are consistent with one interpretation of that relation - the competition between oxygen fixation of radiation-induced radicals and their spontaneous decay or chemical repair by endogenous processes (§II.D).

Not all data fit such an idealized model of oxygen radiosensitization as the oxygen-fixation hypothesis. The effects of radiation on different endpoints of radiation damage (such as mutagenesis and the loss of reproductive capacity) were found to be differently modified by oxygen. In particular, the production of mutants by irradiation was found to be enhanced by oxygen to a lesser degree than the overall killing (reproductive sterilization) of the same bacterial strains [45,79]. Thus two types of damage were postulated [16]. One type, termed Type N, is relatively insensitive to oxygen and was identified tentatively as involving damage to the nucleic acid of the cell. The other component of damage, Type O, has a large oxygen enhancement ratio; no identification of the site of this damage was proposed. The experimental identification of multiple components to the oxygen effect (§II.8.3) presents the tempting possibility that Type N/Type O damage may have a physical explanation and may be amenable to direct observation. However, insufficient information is available on the relevant characteristics of these resolvable components to the oxygen effect to warrant speculation in this regard [14].

Whereas oxygen exerts much of its effect by interaction with radiation-induced free radicals, other effects of oxygen are also well known. Certainly the concentration of oxygen in the post-irradiation culture of cells affects their expression of radiation damage [109,110]. The influence of oxygen on the repair of radiobiological damage (widely interpreted as the recovery from sub-lethal or potentially lethal damage; §III.C.5) has received considerable attention [245]. Extremely hypoxic cells may be incapable of repairing sublethal or potentially lethal damage. This inhibition of repair probably results from metabolic deprivation and occurs at oxygen concentrations (< 50 ppm O_2) well below the radiobiological oxygen effect (< 1000 ppm O_2). Thus biochemical processes involving oxygen may also contribute to its radiobiological effects.

The significance of the mechanism of oxygen radiosensitization for chemical radioprotection lies in the interaction of the oxygen effect with other modifiers of cellular radiosensitivity. The pervasive distribution of oxygen and its profound influence on response to radiation sets practical limits to the maximum efficacy of some other modifiers, particularly in, but not limited to, those cases where the second modifier alters the oxygen effect. The elucidation of mechanisms of action of radioprotectors may be approached by studying their influence on the oxygen effect [357] or its components, in those test systems where oxygen has been shown to exert multiple effects.

C. Endogenous Radioprotective Substances.

1. Thiols.

a. Glutathione - Biosynthesis and Regulation.

Glutathione (L- γ -glutamyl-L-cysteinylglycine)(GSH) is a unique tripeptide that is characterized by a γ -glutamyl bond, which confers resistance to normal peptidase activity, and a thiol group, which is a good nucleophile, with a dissociation constant (pK_a) of 8.56 (for reviews see [53,184,295, 296,372,374,375] and [253]). At the normal redox status of cells, essentially all intracellular glutathione is present in the thiol form (reduced glutathione, GSH) with less than 5% present as glutathione disulfide (GSSG). The total cellular pool of glutathione also includes low molecular weight mixed disulfides, protein mixed disulfides and thioesters.

Extracellular space, including various body fluids such as bile, plasma and the glomerular filtrate, contains GSH, GSSG and mixed disulfides generally at very low (μM) concentrations [296,480]. These concentrations are two

or three orders of magnitude less than the glutathione concentration present in erythrocytes and body tissues in general. The glandular portions of the stomach and liver have the highest known concentrations of glutathione followed by the spleen, kidney, lung, and other organs and tissues [74,253]. The turnover of glutathione during normal physiological conditions is continuous with a wide variation of rates depending on the organ or tissue. The half-life of glutathione varies by tissue, being about one to three minutes in the plasma compartment, one hour in the kidney, two to three hours in the liver, and several days in the spleen, lung, nervous tissue and erythrocytes [253]. The liver is particularly susceptible to rapid and extensive depletion of glutathione by the formation of glutathione conjugates which are catalyzed by glutathione S-transferases.

Other thiols present in the liver include coenzyme A (1-2 mM in mitochondria; -15 μ M in cytosol [217,420]) and cysteine (0.1 to 0.4 mM); other thiols are thought to be of lesser concentration. The cysteine concentration is tightly controlled since a high concentration appears to be toxic to the cell. Cysteine dioxygenase is a highly inducible enzyme capable of rapid oxidation of cysteine to cysteine sulfinate which is rapidly converted to pyruvate and sulfite. Sulfite is then oxidized to sulfate within the intermembrane space of mitochondria by sulfite oxidase (for a review see [53]).

Depletion of liver glutathione is followed by a rapid resynthesis in which the cysteine pool turns over every two or three minutes. It has been firmly established that during a high rate of cysteine consumption, the liver utilizes the cystathionine pathway for its de novo synthesis of cysteine. In this pathway, the sulfur atom of methionine and the carbon skeleton of serine are utilized with the intermediate formation of cystathionine [376]. Exogenous sources of cysteine such as N-acetylcysteine and L-2-oxothiazolidine-4 carboxylate promote glutathione synthesis.

Whereas the regulation of the cystathionine pathway is not well understood, the rapid response to lowered glutathione levels is well demonstrated. Often, extensive resynthesis is accompanied by a so called "overshoot" in glutathione with a higher level after resynthesis than prior to depletion. This phenomena remains unexplained and potentially could be of value in maximizing cellular protection against the effects of ionizing radiation.

An extremely important aspect of glutathione is its interorgan status and function. Since it appears that the liver is largely responsible for

maintenance of the supply of plasma glutathione, and with the rapid turnover of plasma glutathione (1 to 3 minutes), the mechanism and regulation of the efflux of liver glutathione into this compartment is of considerable interest (for reviews see [53,295] and [184]). While much remains to be understood, it is clearly established that the efflux is almost exclusively as GSH and not GSSG. Some controversy exists concerning the relationship between the intracellular level of glutathione and the rate of its efflux [9,133].

The degradation of glutathione is initiated by γ -glutamyltransferase (EC 2.3.2.2)(5-glutamylpeptide:amino acid 5-glutamyltransferase) which catalyzes the removal of the γ -glutamyl moiety of glutathione (for a review see [295]). The enzyme can catalyze the transfer of the γ -glutamyl moiety to water or to certain γ -glutamyl acceptor amino acids and dipeptides if these acceptors are at millimolar concentrations. However, only under very specific conditions does it appear that this enzyme utilizes such amino acid substrates in place of water [295]. γ -Glutamyltransferase is located almost exclusively in the membranes of certain cells with its active site exposed to the extracellular space [448]. The kidney enzyme activity is localized in the brush border of the proximal tubular epithelium [413]. Only extracellular substrates containing the γ -glutamyl moiety appear susceptible to hydrolysis or transpeptidation. The rate of efflux of cellular glutathione, mainly from the liver, governs the rate of plasma glutathione degradation principally by the extracellular γ -glutamyltransferase of the kidney. Thus, under normal physiological conditions, the rate of turnover of liver glutathione is dependent almost exclusively on the rate of efflux of glutathione into the plasma compartment [299]. It has been estimated that about 80% of the total glutathione effluent from the liver is into this compartment while the remaining 20% is excreted into the bile [375]. Extracellular γ -glutamyltransferase in the biliary and intestinal epithelial cells degrade rapidly any GSH, GSSG, mixed disulfides or glutathione S-conjugates excreted via this route. However, millimolar concentrations of GSH and GSSG are present in the bile at the point of entry into the bile and nearly one half of such glutathione can be degraded in the bile duct under certain conditions [Reed and Ellis, unpublished data, 1982].

Recent evidence suggests that the kidney has the ability to alter the redox status of extracellular glutathione as well as all other thiols that have been examined. An early observation [25] on the oxidation of GSH to

GSSG found that this reaction was catalyzed by an enzyme in kidney homogenate which was distinct from γ -glutamyltransferase. Renal thiol oxidase activity has been characterized in detail and many of its properties established [328,329,331,334]. This oxidase is a component of the plasma membrane of the kidney tubular epithelium and catalyzes the oxidation of extracellular thiols only. Substrates include GSH, cysteine, N-acetylcysteine and dithiothreitol [328,329]. In contrast to γ -glutamyltransferase which is located in the brush border region, thiol oxidase is in the vasolateral part of the tubular epithelial plasma membrane. It has been concluded that its activity is probably restricted to thiols present in plasma [334].

Limited information exists on the uptake and reduction of low molecular-weight disulfides. It has been shown that freshly isolated renal cells are capable of the uptake and reduction of cystine to cysteine which probably occurs via a GSH-dependent sequence of reactions catalyzed by cytosolic thiol transferase and glutathione reductase [NAD(P)H](EC 1.6.4.2; NAD(P)H:oxidized glutathione oxidoreductase) [327,334]. Some evidence exists that renal cells [330] and lung utilize extracellular GSSG in a manner that does not involve extracellular degradation prior to cellular uptake.

Isolated cells appear to be useful in studying the metabolism of therapeutically important disulfide drugs. 2-Mercaptoethane sulfonate, a uroprotective agent [83] against oxazaphosphorine cytostatics, can be detected as the disulfide form in the plasma. However, the pharmacologically active form, the thiol, is excreted in the urine [334]. The disulfide form is readily taken up by isolated renal cells and reduced to the thiol [332, 334]. Freshly isolated hepatocytes do not take up the disulfide form and do not accumulate either the thiol or the disulfide form. Freshly isolated hepatocytes also fail to take up appreciable amounts of cystine or to accumulate either cysteine or cystine [373]. These cells accumulate momentarily both cysteine and cystine in the presence of high concentrations of cysteine [52,53]. Hepatocytes isolated aseptically and placed in culture adapt within hours to greatly enhanced uptake and utilization of cystine [Klingensmith and Reed, unpublished data, 1984].

The failure of freshly isolated hepatocytes to take up and reduce low molecular weight thiols appears to be a failure of transport and not reduction. Evidence for this conclusion comes from cell-free experiments with liver and kidney homogenates that represent a reconstituted system containing

thiol transferase and glutathione reductase [NAD(P)H]. This system, under a N_2 gas atmosphere, readily converted 2-mercaptoethane sulfonate (disulfide form) to the thiol form by both liver and kidney preparations [334]. Therefore, a deficiency in disulfide uptake capability appears to exist with hepatocytes but not renal cells. It can be assumed that maintenance of the thiol/disulfide redox status in the plasma compartment is complex and related to several important processes. Initially the efflux of GSH from the liver provides the redox potential to convert cystine (which is the predominant form of the total cysteine/cystine in plasma) to cysteine and the mixed disulfide of cysteine and glutathione [373]. Cysteine and, in turn any remaining GSH, can convert other disulfides to mixed disulfides and their respective thiol forms. Utilization of disulfide and mixed disulfide by the kidney also contributes to an overall decrease of disulfide and mixed disulfide in plasma. Other cell types will also cause a decrease by uptake, but again, variations in ability for uptake and possible limitation in rate of reduction of mixed disulfide is observed [84]. In vivo oxidation of plasma thiols by renal thiol oxidase to disulfides remains to be demonstrated at the presumed concentrations of thiols in plasma because of the low affinity of this enzyme and the resulting high K_m value [328,329].

In mammals, GSH appears to be an important physiological reservoir for cysteine. The rapid response of the cystathionine pathway for converting methionine sulfur and serine carbon atoms to cysteine appears limited largely to the liver.

The half-life of GSH in the blood is very short (1-3 minutes) because of the high degree of activity of extracellular enzymes in the kidney. These enzymes function in the degradation of GSH, GSSG and related mixed disulfides of GSH (for a review see [184]). Extracellular release of cysteine and cystine (from GSH and GSSG, respectively) is initiated by γ -glutamyltransferase followed by the action of one or more dipeptidases located primarily extracellularly in the kidney and intestines. This process may be essential to provide the cysteine and cystine that certain cell types require for growth and maintenance of intracellular GSH. A constant efflux of GSH from the liver, coupled with these extrahepatic enzymes functions to provide a constant cysteine supply; a portion of this released cysteine and cystine returns to the liver to help maintain the liver GSH content.

Separation of the mitochondrial and cytoplasmic compartments in isolated hepatocytes by digitonin disruption has led to the demonstration of the metabolic independence of the mitochondrial pool of GSH from that of the cytoplasm [299]. Hepatocytes subjected to acute oxidative challenge have shown a greater correlation of cell viability with the mitochondrial GSH pool than with that in the cytoplasm (for a review see [374]). Such depletion is without appreciable loss of cell viability unless accompanied by the additional stress that can occur in the presence of many drugs [374].

Reduced oxygen species ($O_2^{\cdot-}$, $\cdot OH$, H_2O_2) may be derived from the consequences of ionizing radiation, the redox cycling of chemical agents, or endogenous production during normal metabolism. The deleterious effects of these species are collectively known as oxidative stress and may lead to cell death. Oxidative stress is known to be limited by the glutathione redox cycle. Metabolism of cytosolic and mitochondrial hydrogen peroxide by glutathione peroxidase is firmly established (for a review see [235]). GSH provides the required reducing equivalents, and glutathione reductase utilizes NAD(P)H reducing equivalents to maintain a continuous redox pathway to limit the hydrogen peroxide concentrations to steady state micromolar levels. There is scant evidence to establish the rate limiting step during a high level of oxidative stress.

b. Thiols and Free Radical Reactions.

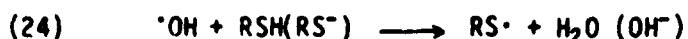
As we have discussed in previous sections, free radical reactions play a major role in radiation-induced cellular damage. Consequently, many schemes for the protection of cell constituents from radiation damage involve protection by free radical mediated processes. Relevant to this topic, we briefly review the large body of literature on the types of free radicals formed from glutathione and other thiols, their mechanisms of formation and their subsequent reactions. Finally, theories of thiol-assisted radioprotection by free radical processes are presented as a stimulus to further experiments in this research area.

i. Formation of Sulfur-centered Radicals.

The most prominent sulfur-centered radical is $RS\cdot$, the thiyl radical. Other sulfur-centered radical species include perthiyl radicals ($RSS\cdot$), the radical anion ($RSSR)^{\cdot-}$, and the radical cations $R_2S^{\cdot+}$, $(R_2S)_2^{\cdot+}$, and $(RSSR)^{\cdot+}$. The production and disposition of all these radical

species is a complex process involving reactions which occur at rates close to their diffusion-controlled limit. Whereas much evidence has accumulated indicating that thiyl radicals are formed as transient species in cellular systems, the identification and biological role for these other radical species is not as well understood.

Thiyl radicals may be produced by hydrogen atom abstraction from the corresponding thiol either by carbon-centered radicals (equation 23) or by hydroxyl radicals (equation 24).

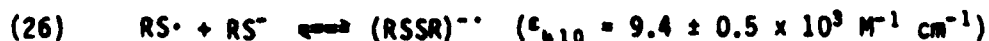


Furthermore, thiyl radicals may be formed upon reduction of transition metals by thiols (equation 25).



These three equations serve to place thiyl radicals at the center of molecular "repair" of direct radiation damage (equation 23), the scavenging of water radiolysis products in the indirect effects of radiation (equation 24) and the possible production of toxic products upon the autoxidation of thiols (equation 25).

Estimates of the rate of molecular "repair" of cellular targets by thiols have been obtained by measuring the rates of reaction of various thiols with model carbon-centered radicals. In solutions containing methanol and cysteamine, pulse radiolytic experiments show that the rate constant for equation 23 (in which $R^\cdot = \cdot CH_2OH$ and $RH = CH_3OH$) is $k = 6.8 \times 10^7 M^{-1} s^{-1}$ [6]. This rate constant holds true (within an order of magnitude) for a variety of thiols and a small number of aliphatic carbon-centered radicals, measured with either the equilibrium



at a pH close to the pK_a of the thiol [6,7] or with the probe 2,2'-azino-di-(3-ethylbenzthiazoline-6-sulfonate) (ABTS, $\epsilon_{415} = 3.6 \times 10^4 M^{-1} cm^{-1}$)

[484]. However, under the experimental conditions required to measure molecular repair by the reaction shown in equation 26, the extent of the repair reaction (equation 23) varies widely with even minor changes in the structure of the carbon-centered radical. Thus, Baker et al. [44] found (a) nearly 100% repair by the reaction shown in equation 23 to occur with glutathione and carbon-centered radicals from simple aliphatic alcohols, (b) lower repair for biological materials such as glucose and deoxyribose, and (c) no measurable repair for adenosine-5'-phosphate. With more complex target molecules, the carbon-centered radicals may undergo competing reactions [437], and the demonstration of molecular repair is constrained by the measurement techniques which have been employed. Perhaps with the probe ABTS [484], estimates of the molecular repair by thiols will be extended to more complex biomolecules [See §V.1].

Similar pulse radiolysis experiments have measured the rate constants of the reaction between thiols and the hydroxyl radical (equation 24). For RSH = glutathione, the rate constant for reaction 24 (k_{24}) is $1.3 \times 10^{10} \text{ M}^{-1} \text{ s}^{-1}$ [367]; the formation of the thiyl radical from the reaction of a number of thiols with $\cdot\text{OH}$ approximate this value [204]. However, thiols may differ in their contribution to molecular "repair" by their susceptibility to alteration at other sites in the molecule, as may be the case for glutathione [416]. This susceptibility may influence their capacity for radical scavenging.

Thiyl radicals may also be produced by the one-electron reduction of transition metals accompanying thiol oxidation to the disulfide [192] or to those oxygenated forms which identification has been hampered by instability. The autoxidation of cysteine has been reported to produce toxic metabolites, presumably reactive forms of oxygen [394], which may be responsible for the toxicity associated with the administration of cysteine [394,470].

Disulfides also produce thiyl radicals during irradiation through their interaction with organic carbon-centered radicals (equation 27), inorganic radicals (equation 28) and the hydroxyl radical (equation 29).





It has been suggested that for disulfides such as cystine or penicillamine, reaction 30 may be quite important [33]. This



reaction certainly operates for bis(t-butyl) disulfide in which the t-butyl fragment is relatively stable [71] and contributes to the spectrum of products produced during the irradiation of cystine [363], penicillamine [364], and cystine-penicillamine mixed disulfide [365]. However, evidence from pulse radiolysis [367] and product analysis [336,337,338,363,364,365] experiments suggests that for many biologically relevant disulfides, reaction 29 predominates.

As mentioned above, the radical anion $(\text{RSSR})^{\cdot-}$ is formed by the reversible equilibrium of equation 26. Presumably, this species may also arise from direct electron capture of e^-_{aq} , a fact which has been exploited in measuring the rate of decay of this ion in anaerobic experiments [367]. The radical cations formed from sulfides and disulfides $[(\text{R}_2\text{S})^{\cdot+}$, $(\text{R}_2\text{S}\cdot\cdot\text{SR}_2)^{\cdot+}$] and $(\text{RSSR})^{\cdot+}$ have quite interesting properties [33], but the formation and structure of these species have unknown relevance to radiation biology.

11. Reactions of Sulfur-centered Radicals.

By definition, the hydrogen donation (or electron transfer) from sulfur-containing species to carbon-centered target molecules (equation 23) may only be thought of as repair of radiation damage if the sulfur-centered radicals produced in the reaction are less damaging than the original target radical. Given the somewhat lower reactivity of sulfur-centered radicals compared with their carbon-centered congeners, this requirement may be met. However, sulfur-centered radicals still are very reactive, and may undergo a variety of reactions. Although these reactions (generally) serve to detoxify the radical from which they were produced, notable examples may be found of the production of toxic species involved in the disposition of sulfur-centered radicals.

The thiyl radical reacts in a variety of ways that may allow restoration of, or may destroy, the original state of the thiol. The thiyl radical

may dimerize with radical decomposition, forming the disulfide (equation 31). Alternatively, addition of molecular oxygen to the thyl radical



(equation 32) proceeds with a rate dependent on the structure of the thiol, being high for cysteine and glutathione (8 and $1.6 \times 10^9 \text{ M}^{-1}\text{sec}^{-1}$, respectively) [48,367,400] and somewhat lower for simpler thiols (e.g., ethanethiol, penicillamine). Addition of oxygen to thyl radicals results in products (RSO_2^\cdot), a portion of which may react to regenerate the original thiol. One product of this oxidation is the sulfinic acid ($\text{GRSO}_2\text{H} = 1.8$ for glutathione [260]) which may dimerize and subsequently react with a thiol to yield RSSR, O_2 and the sulfinic acid (equations 33, 34). Thus a disulfide is produced by the radiolysis of glutathione which may be reduced



to the thiol by the action of enzymes such as glutathione reductase in the presence of NAD(P)H. Other stable products of the radiolysis of glutathione at neutral pH include γ -glutamylserylglycine, GSO_2H , and the disulfide GSSG [260].

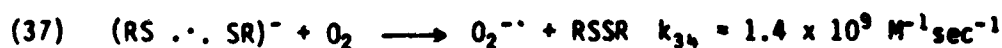
Thyl radicals may also interact with certain biological materials which are classified as antioxidants, reducing agents, or electron acceptors. The electron transfer from α -tocopherol (vitamin E) or ascorbate (vitamin C) has been proposed to dispose of the thyl radicals formed during molecular "repair" of cellular targets (equation 35 and 36)[484]. This reaction



follows the general order of radical reactivities ($\text{C} > \text{S} > \text{O}$) since it is likely that these products are initially oxygen-centered radicals which may subsequently form resonance-stabilized structures with delocalization of the electron density at the oxygen atom [292]. Subsequent electron transfer to

biologic acceptor molecules (§II.C.2,3,4) will detoxify the radicals and complete the cascade of electron transfer from ultimate acceptor to target radical (§II.C.1.c).

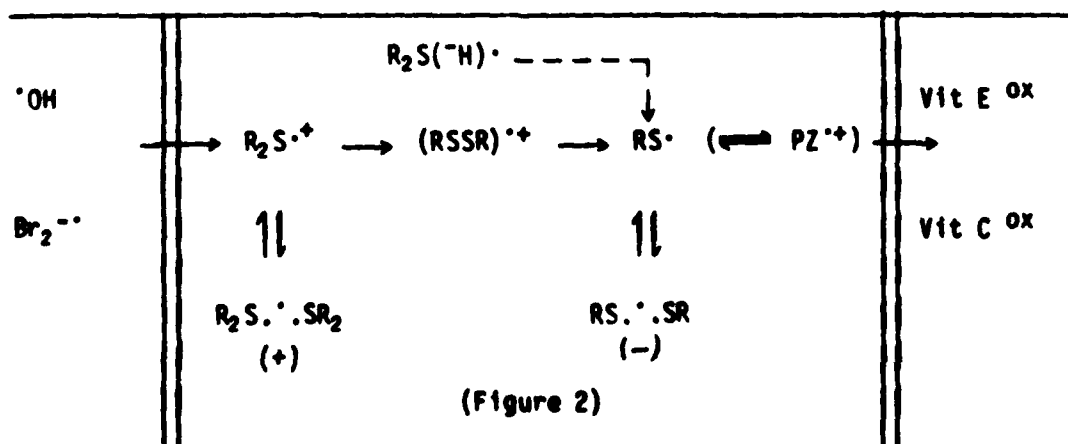
Whereas the sulfur-containing radical cations and anions may be of less radiobiologic importance, they undergo several interesting reactions. The radical anion (RSSR)^{-•} reacts with molecular oxygen to generate superoxide radical anion and the disulfide (equation 37)[97]. Also, the radical cation of



methionine is subject to an intramolecular reaction which results in decarboxylation and the formation of a carbon-centered radical [203] (equation 38). Thus not all sulfur-centered radicals are disposed without potentially harmful effects.

c. Overall Scheme of Sulfur-centered Radical Reactions.

The formation and disposition of sulfur-centered radicals can be summarized in several figures. Firstly, the chemical production and general order of reactivity of the sulfur-centered radical cations, anions and neutral species are shown in Figure 2. Highly oxidizing inorganic radicals such as Br₂^{••} and the hydroxyl radical may cause the formation of



sulfide radical cations. Sulfide radical cations are more oxidizing than the disulfide radical cations which, in turn are more powerful oxidants than the thyl radicals.

The reaction scheme from left to right is equivalent to electron transfer from right to left in the figure. In this figure, $PZ^{\bullet+}$ refers to the radicals produced upon oxidation of phenothiazine drugs. Several drugs of this class have been found to participate in radical reactions similar to those of the thiyl radicals [43]; their known antioxidant effects have been ascribed, at least in part, to their radical transfer properties [452].

A strong case is presently being made for thiol participation in coupling hydrogen donation reactions, as in the molecular "repair" of radiation damage, with electron transfer reactions leading ultimately to non-toxic biochemical reactions. The scheme of this coupling of hydrogen and electron transfer is shown in Figure 3 [484]. The initial step of molecular

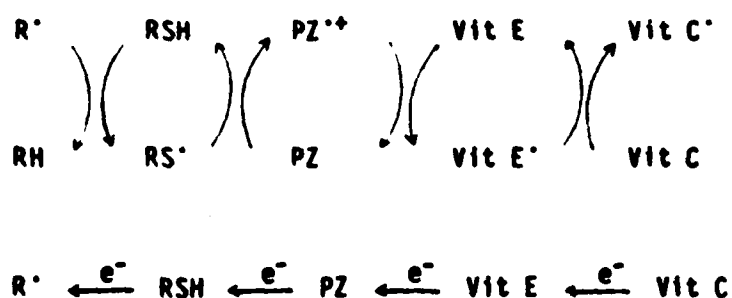


Figure 3

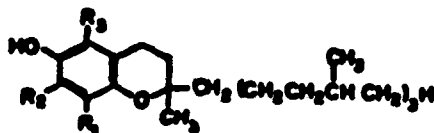
"repair" is hydrogen donation by a thiol; if this reaction occurs *in vivo*, RSH would be mainly glutathione. Except for thiyl radical formation, these reactions are envisioned as electron transfer reactions [160]. Obviously, in the absence of drug treatment, phenothiazine radical cations would not participate; recently the direct reaction of thiyl radicals with ascorbate anion has been observed [159]. The precise nature of the ultimate electron donor is speculative; reduced nicotinamide dinucleotide (NADH) and reduced cytochrome c may react at rapid rates with the glutathione thiyl radical [159].

Figure 3 presents an attractive picture for the disposition of radiation-induced free radicals. However, it rests on some limited data collected in highly purified model systems under controlled conditions. Several problems concerning the general applicability of this scheme must be resolved. First, the initial reaction certainly occurs for simple aliphatic carbon-centered radicals (§11.C.1.b). However when a variety of structures

are tested and the extent of reaction is determined, it has been noted that when the target radical is more biologically relevant, this reaction is quantitatively less important [44]. Furthermore, kinetic treatment of these data suggests that when competing reactions vie for the initially formed target radical, including intramolecular reactions, only a subset of the reaction products may be susceptible to this "repair" reaction [437]. Once thyl radicals are formed from the target carbon-centered radicals, the extent of their participation (as outlined) in the electron transfer reactions outlined must be determined. As yet, no studies have been undertaken to address this point (See §V.5). Until these questions are resolved, the hypothesis for sequential free radical repair to progressively less noxious radical species, although conceptually (chemically) possible, must be considered somewhat (biologically) speculative.

2. Vitamins and Antioxidants.

Vitamin E is an efficient inhibitor of radical based reactions including lipid peroxidation in vivo (for a review see [439].)



$R_1 = R_2 = R_3 = \text{CH}_3$

α Tocopherol (α T):

$R_3 = \text{CH}_3; R_2 = \text{H}$

β -Tocopherol (β -T): $R_1 =$

$R_1 = R_2 = \text{CH}_3; R_3 = \text{H}$

γ Tocopherol (γ T):

$R_1 = \text{CH}_3; R_2 = R_3 = \text{H}$

δ Tocopherol (δ T):

(Vitamin E)

Autoxidation, in simple terms, is a chain reaction as described below in a reaction scheme of Burton and Ingold [90]. RH represents the organic substrate and initiation:

- (39) Initiation: $RH \longrightarrow R\cdot \text{ or } ROO\cdot$
 (40) Propagation: $R\cdot + O_2 \longrightarrow ROO\cdot$
 (41) $ROO\cdot + HR' \longrightarrow ROOH + R'\cdot$
 (42) $ROO\cdot + R'H \longrightarrow ROOR'\cdot H (\neq R\cdot)$
 (43) Termination: $ROO\cdot + ROO\cdot \longrightarrow \text{non-radical products}$

$ROO\cdot$ the peroxy radical as the product.

Several individual tocopherols constitute vitamin E, and only recently has their relative and the absolute antioxidant effectiveness in vitro been clarified [90]. These chain-breaking phenolic antioxidants, $ArOH$, shorten the oxidation chain. Whereas chain termination by reaction 43 is suppressed, termination may occur by reactions 44 and 45 with n being the stoichiometric factor for the antioxidant.

- (44) $ROO\cdot + ArOH \longrightarrow ROOH + ArO\cdot$
 (45) $(n-1) ROO\cdot + ArO\cdot \longrightarrow \text{nonradical products}$

In an inhibited reaction in which all $ArO\cdot$ are destroyed by reaction 45, the rate of autoxidation has been described by the following equation:

$$\frac{-d[O_2]}{dt} = \frac{k_3 [RH] R_i}{nk_5 [ArOH]}$$

where R_i is the rate of chain initiation.

The abstraction by peroxy radicals of the phenolic hydrogens from these tocopherols has been described as the rate constant k_{45} . The values of k_{45} for α -, β -, γ -, and δ - tocopherols are 23.5, 16.6, 15.9 and $6.5 \times 10^5 \text{ M}^{-1} \text{ s}^{-1}$, respectively, at 30°C [90]. Each tocopherol was found to react with exactly two peroxy radicals and all the tocopherols appear to be exceptionally good chain-breaking antioxidants in vitro. Further, the data of Burton and Ingold [90] are in agreement with in vivo tests of the relative biological activities of these tocopherols; $\alpha\text{-T} > \beta\text{-T} > \gamma\text{-T} > \delta\text{-T}$ [96].

Rate constants have been reported for the reaction of superoxide radicals with ferricytochrome c, $k = 2.6 \pm 0.2 \times 10^5 \text{ M}^{-1} \text{ s}^{-1}$ at pH 9.0 and ascorbate, $k = 1.52 \pm 0.1 \times 10^5 \text{ M}^{-1} \text{ s}^{-1}$ at pH 9.9 [65]. It has been suggested that the facile oxidation of ascorbate by $O_2^{\cdot -}$ probably occurs via hydrogen atom transfer [399].

In aqueous media, reduced paraquat (methyl viologen MV^+) combines with O_2 to give a stoichiometric yield of $O_2^{\cdot -}$. In an aprotic solvent such as

dimethylformamide, MV^+ and O_2^- combine in a 1:1 stoichiometry to form irreversibly a peroxy zwitterion adduct [$MV^+ O_2^-$] with the -OO- group at the 2-position [320]. Rapid decomposition via ring rupture and oxidative reactions yield a multitude of products [320].

Interestingly, no evidence has been obtained to indicate that O_2^- acts as an initiator of radical chain reactions [399]. The powerful nucleophilic properties of O_2^- in aprotic solvents do not exist in aqueous media [399].

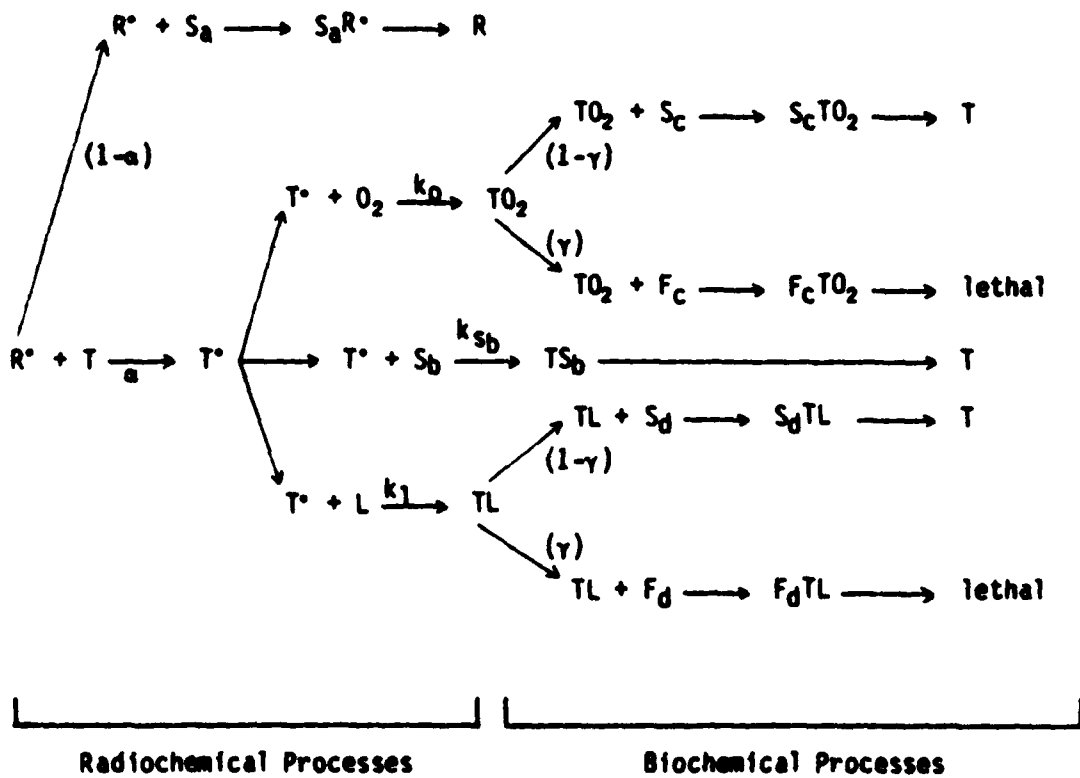
D. The Competition Model.

For nearly 30 years workers have extended the original observation of Alper and Howard-Flanders [22] on the role of oxygen in modifying the radiosensitivity of E. coli. Although molecular oxygen has the ability to increase the sensitivity of living cells to ionizing radiation more than any other agent, compounds containing the thiol moiety are by far the most active protective agents known. Thus, the quantitative relationship between ionizing radiation injury and oxygen supply continues to provide a useful means of describing the interactions of a variety of endogenous and exogenous agents that modify such injury. There is general agreement that the oxygen effect is mainly the reaction of oxygen with radiation induced free radicals at target sites which can result in permanent damage. Competition for these target site free radicals involves a large number of compounds with thiols having the greatest effectiveness.

Further understanding has led to the idea that an additional type of radiation damage occurs which is independent of oxygen [120]. Révész and coworkers [380] have extended the model to consider the initial reaction of radiation induced radicals with oxygen as being reversible and subject to biochemical alterations. The chemical events of ionizing radiation damage and biochemical processes are described in Figure 4 (1984, Lazlo Révész, personal communication).

Much of the recent work of Révész and coworkers involves the effects of ionizing radiation on glutathione deficient and proficient cells. The in vitro clonogenic survival of human fibroblasts with a genetically defined glutathione deficiency have been studied along with genetically related fibroblasts without glutathione deficiency [121]. The survival curves, obtained in an oxygen atmosphere, of both cell lines were similar but the

Figure 4. Schematic illustration of the radiochemical and biochemical processes postulated by the theory. R^\cdot = unspecific radical; T = functional target; T^\cdot = target radical; S_a, S_b, S_c and S_d = repairing species; O_2 = molecular oxygen; L = reactive species in absence of O_2 ; F = species which fixes damage irreversibly; α, β, γ = constants indicating proportions; k_0, k_{sb} and k_1 = constants indicating reaction rates.



survival curves obtained in anoxic (argon) atmospheres indicated an oxygen enhancement ratio (OER) of about 1.5 for glutathione deficient cells. An OER of 2.9 was found when comparing the oxic and anoxic survival curves of the control cell line.

This evidence was used to support the theory of a competition model for oxygen and glutathione specifically since other thiols (cysteine and γ -glutamylcysteine) were present in the glutathione deficient cells [121]. Furthermore, these studies suggest that the major effect of exogenous thiols may be their scavenging action whereas endogenous glutathione exerts its major effect in the radical competition process with oxygen. Glutathione appears to be extremely efficient in the repair of radiation damage due to its high ability to eliminate free radicals by hydrogen donation. Revesz [377] has proposed a qualitative difference between GSH^+ and GSH^- cells in their ability to repair oxidically induced DNA damage even though no difference was observed in GSH^+ cells rejoining DNA single strand breaks (SSb) induced by hypoxia and radiation. However, GSH^- cells had a decreased capacity to repair oxidically induced injuries which could indicate that the repair of SSb induced under oxic conditions requires GSH [377]. Exogenous thiols including GSH and dithiothreitol (DDT) could promote rejoining of SSb. On the other hand, GSH depletion with diethylmaleate does not change the rate of SSb repair [151]. The role of thiols in DNA repair is quite unclear and needs careful evaluation (See §III.C.5.b).

III. Chemical Radioprotection.

A. Physiological Responses to Chemical Modulation of Cellular Radioprotection Systems.

Genetic and somatic alterations of cellular constituents occur during exposure to ionizing radiation. The extent of these alterations is related to the status of the cellular defense systems that protect cellular constituents and stabilize their functions. This section examines the general nature of radioprotectors and outlines the physiological responses involved in cellular radioprotection. Pertinent to "built-in" radioprotection at the cellular level during irradiation is the status of naturally occurring substances. Additionally, compartmentation of cellular protective systems must be considered since its role is beginning to be placed more in perspective relative to cell viability during chemical intoxication.

Cell viability and even cell survival is dependent upon the various inherent protective features. The protection of vital cellular constituents appears dependent on the structural integrity of the cell, the compartmentation of both functions and constituents, and the presence of certain enzymes. These enzymes include glutathione S-transferases, epoxide hydrolases, superoxide dismutases, catalase, glutathione peroxidases and glutathione reductase. Essential low molecular weight constituents include water, thiol compounds (particularly glutathione), vitamins C and E and the vitamin A precursor, β -carotene, although an absolute requirement for any one of these agents for cellular radioprotection has not been ascertained.

1. General Concepts.

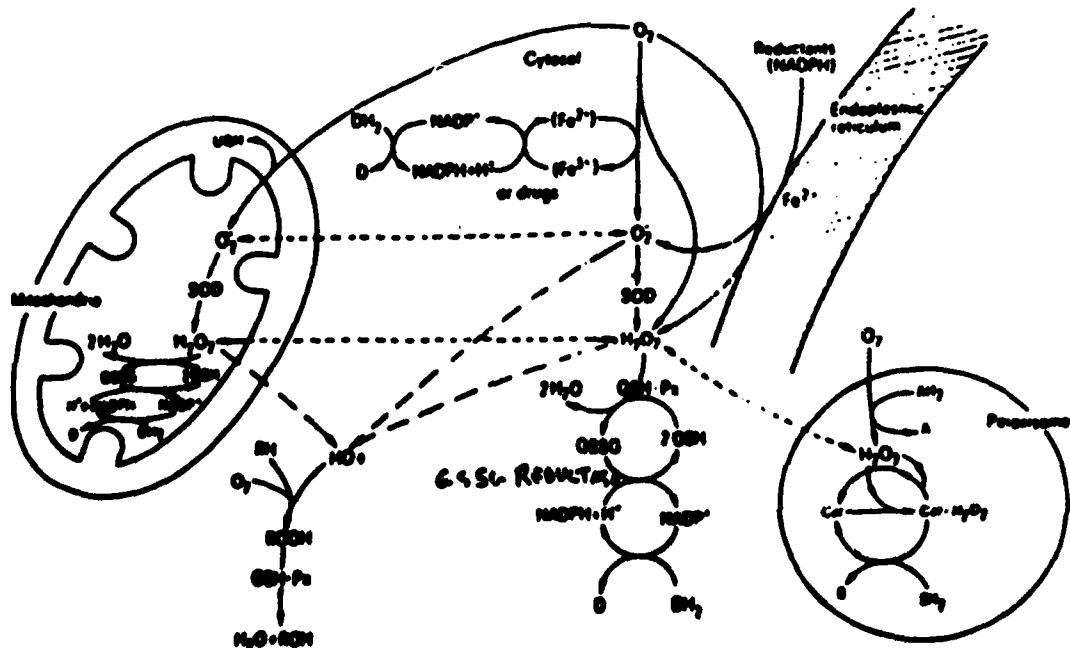
Cellular defense against injury can be defined in terms of the nature of the species causing the injury. In the case of ionizing radiation, at least a portion of that injury results from such highly reactive intermediates as the hydroxyl radical. These agents possess an inadequate electron density and attack cellular constituents at positions of higher electron density. The rates of such reactions are less dependent on the (relatively minor) variations in the inadequate electron density of the injurious species as they are on the electron density of the damaged cellular constituent. Reactions of this type are known to be susceptible to the presence of small amounts of agents that either liberate or scavenge radicals [433]. The importance of agents such as Fe^{2+} iron (for liberation) and vitamin E (for

scavenging of radicals), continues to be a subject of lively polemics among toxicologists.

Reduced species of dioxygen (including those that are free radicals) are endogenous to cells and tissues. However, ionizing radiation can result in a magnification of the total cellular content or the subcellular concentration of these reactive intermediates.

Cellular constituents that protect against free radical-mediated cellular damage reside in the subcellular compartments. These subcellular organelle compartments are important, but attention must also be paid to the distribution characteristics of both the prooxidants and antioxidants between the aqueous and lipid phases. Additionally, oxidation-reduction (redox) potentials vary with the degree of complexation with metal ions, macromolecules, etc. Thus the general nature of these reactions and even the protective systems are influenced by the particular milieu of the cellular interior.

Specific enzymes have a major responsibility for cellular protection against radical-mediated toxicity. The glutathione peroxidase/reductase redox cycle enzymes, catalase, and superoxide dismutases (SOD) catalyze reactions that are capable of realizing very rapid decreases in the concentration of reduced oxygen intermediates (Fig. 5).



(Figure 5)

Glutathione (GSH) is a substrate for the glutathione peroxidase/reductase redox cycle (an enzymic reaction), but in non-enzymic reactions the cell primarily utilizes β -carotene, α -tocopherol, ascorbic acid and possibly uric acid [24] as important cellular protective agents.

2. Cellular Aspects of Radioprotection Systems.

a. Compartmentation.

The concentration and nature of nonprotein thiols and protein sulphhydryl groups has been a topic of long-standing interest. Vital cellular functions of protein sulphhydryls are numerous and cannot be enumerated here. However, the dynamic nature and relatively high concentration of protein sulphhydryl groups, which may exceed the concentration of total nonprotein thiols, (6-10 mM in liver) are closely related to the status and functions of nonprotein thiols. Protection of protein thiols from alterations (including the homeostasis oxidation state) involves the total cellular thiol:disulfide potential [494]. Subcellular distribution and concentrations of both non-protein thiols and protein sulphhydryls may relate closely to their respective functions. More than 90% of the total non-protein thiols present in cells appears to be glutathione. The presence of a discrete mitochondrial pool of glutathione was proposed by Vignais and Vignais [466]. Mitochondria retained GSH during experiments involving nonaqueous media [224,225]. Isolated rat mitochondria contain about 10% of the total hepatic glutathione with about 90% of it being present as reduced glutathione [225]. Wahllander *et al.* [472] reported the mitochondrial glutathione content to be 13% of total liver content by a nonaqueous extraction procedure.

Meredith and Reed [299] suggested that based on compartment water space [140,472], the mitochondrion maintains a higher glutathione concentration than the cytoplasm, 10 mM versus 7 mM, respectively. The apparent impermeability of the inner membrane of the mitochondrion led to the speculation that mitochondria maintain intramitochondrial glutathione by in situ synthesis [472]. Higashi *et al.* [199] have suggested that liver glutathione is a two-compartment physiological reservoir of L-cysteine. A labile compartment serves as a cysteine reservoir and as a more stable compartment, which is not readily available even during starvation. Cho *et al.* [102] have provided confirmatory evidence in that fasted and re-fed rats maintain a constant level of plasma cystine.

Studies on glutathione biosynthesis demonstrate separate pools of glutathione in the cytosol and the mitochondria with the in vivo turnover half-lives being 2 and 30 hr, respectively [299]. Short-term starvation depleted the cytosol pool but not the mitochondrial pool.

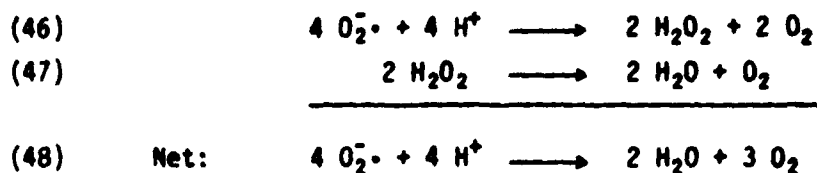
Differential depletion of cytosolic and mitochondrial glutathione of freshly isolated hepatocytes with glutathione depleting agents has permitted an evaluation of the protective role of intracellular glutathione. Chemical intoxication observed with ethacrynic acid [299], acetaminophen [298] or bromobenzene, suggests that short-term depletion of cytosolic glutathione does not cause a significant loss of cell viability. If depletion of cytosolic glutathione was accompanied by partial depletion of mitochondrial glutathione, then a rapid increase in loss of cell viability was observed. The effects of thiol depletion on cellular radiosensitivity have recently been investigated (e.g., [246]). Much more needs to be understood about the consequences of depletion of the pools of intracellular glutathione.

Hill and Burk [200] have speculated that vitamin E-deficient hepatocytes are more susceptible to oxidative stress than normal hepatocytes. Also, other oxidant defenses were unable to prevent lipid peroxidation that occurred under the incubation conditions employed in their experiments. Loss of cell viability during incubation was not accompanied by depletion of glutathione which indicates that some aspect of membrane fragility may relate to a specific function of vitamin E. Compartmentation may have an important role in these observations.

b. Redox Cycling.

A second role for glutathione is in a powerful radioprotection system against ionizing radiation damage which is mediated via the glutathione redox cycle. The cellular effects associated with reduced oxygen metabolism and subsequent redox cycling and lipid peroxidation have been reviewed by Kappus and Sies [235]. We are just beginning to understand and assess the energy required by the consumption of reducing equivalents that result from redox cycling.

The combined effects of protection by superoxide dismutase, glutathione peroxidase and glutathione reductase is:



Since superoxide anion radicals can migrate across artificial lipid bilayer membranes at temperatures above the lipid phase-transition [393], they may traverse membranes in general. However, their crossing membranes of erythrocytes [283] and granulocytes [170] is thought to occur via anion channels. This point could be important since most quinones are in membrane and the concentration of O_2 in the lipid plasma membrane is 8 times that in the aqueous medium [362]. Thus, superoxide anion radicals may be migrating in both directions across membranes from their site of formation. The rapid reaction of semiquinones with oxygen would indicate that semiquinones would not diffuse far in the presence of oxygen [360]. Protection by superoxide dismutase may indicate some superoxide anion production outside of cells [360].

Protection from reduced oxygen species therefore may occur in membranes by specific membrane-associated proteins which are capable of membrane protection and therefore can be shown to limit lipid peroxidation of membrane-associated polyunsaturated lipids.

An excellent example of the complexity of redox cycling has been discussed by Biaglow [61] concerning the reduction of nitro compounds that are radiosensitizers. Reduction of the nitro functional group to nitro radical anions is catalyzed by reductases including NADPH cytochrome P-450 reductase (AYH Lu, personal communication, 1982). The fate of such radicals depends on many factors including O_2 concentration and GSH. O_2 and GSH compete for the nitro radical anion electron and in turn form superoxide anion radical and glutathione thyl radical, GS^{\cdot} , which then forms glutathione disulfide (GSSG). Decreasing the concentration of either O_2 or GSH appears to increase macromolecular damage. Such damage has been shown to be coincident with radiation damage and currently is being investigated extensively for therapeutic application in cancer treatment with nitro compounds such as misonidazole [89].

Protection against quinones appears to involve several aspects of cellular function involving oxygen reduction. Quinones can undergo either two-

electron reduction to corresponding hydroquinones or one-electron reduction to the corresponding semiquinone radicals [219]. However, the main cytotoxic effects of quinones are thought to be mediated through one-electron reduction to the semiquinone radical [35]. This radical is known to be capable of the formation of the superoxide anion radical by the one-electron reduction of molecular oxygen [165].

It has been suggested that, whereas the rate of NADPH formation is not limiting for monooxygenase activity, it may be rate-limiting for quinone-stimulated superoxide formation [360]. Simple quinones stimulate the formation of $O_2^{\cdot-}$ by isolated rat hepatocytes at rates up to 15 nmoles/min per 10^6 cells. Destruction of $O_2^{\cdot-}$ and water formation would require the consumption of 15 nmoles/min per 10^6 cells of intracellular GSH or nearly a complete turnover of GSH to GSSG and reduction back to GSH in two minutes. An equal quantity (7.5 nmoles) of NADPH must be furnished. However, Sies *et al.*, [410,411] have calculated the maximum rate of NADPH production to be equivalent to 15 nmoles/min per 10^6 cells.

Sies *et al.*, [411] have reviewed the metabolism of organic hydroperoxides and concluded that enzymatic reduction of organic hydroperoxides is the result of the activities of two GSH-requiring enzymes, glutathione peroxidase [EC 1.11.1.9] and glutathione transferase [EC 2.5.1.18]. Additional protection against hydroperoxides is afforded by endogenous "antioxidants" including α -tocopherol, ascorbic acid and β -carotene. Synthetic antioxidants such as butylhydroxytoluene (BHT) are thought to act primarily as mimics of α -tocopherol in the termination of the free radical reaction sequence.

The rate of cellular generation of NADPH from $NADP^+$ appears to be rate limiting for monooxygenase reactions. In intact liver, cytochrome P-450-dependent drug metabolism is decreased when an organic hydroperoxide is being reduced to the corresponding alcohol by glutathione peroxidase and, in turn, GSSG consumes NADPH-reducing equivalents in the conversion of newly generated GSSG to GSH [171].

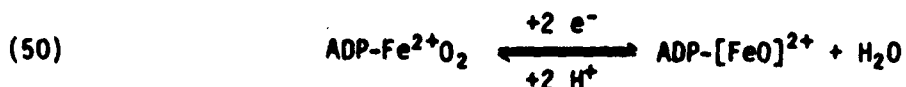
A serious question has been raised concerning the role hydrogen peroxide may have in microsomal lipid peroxidation. Hydrogen peroxide reacts with reduced transition metals, especially ferrous iron, to generate the most oxidative oxygen species, the highly reactive hydroxyl radical, $\cdot OH$. This radical is thought to predominate in initiation of microsomal lipid peroxidation. However, Morehouse *et al.* [317] have concluded that hydroxyl radicals

generated from hydrogen peroxide do not initiate microsomal lipid peroxidation.

NADPH-dependent lipid peroxidation, which is initiated by NADPH-cytochrome P-450 reductase, may occur by hydroxyl radical formation through an iron-catalyzed, Haber-Weiss reaction [158]. Such lipid peroxidation may arise also from the formation of a reactive ADP-Fe-oxygen complex [442]. Possible events include the reduction of perferryl ion to the ferryl ion for initiation of lipid peroxidation. Superoxide anion may be the reductant:



followed by



In contrast, NADPH-cytochrome P-450 reductase-dependent lipid peroxidation with EDTA-Fe may occur through a hydroxyl ion-dependent mechanism rather than an ADP ferrous ion-oxygen type of complex [88].

The effect of redox cycling can now be extended to calcium. Hydroperoxides can modulate the redox state of pyridine nucleotides and the calcium balance in rat liver mitochondria via the participation of the glutathione redox cycle involving glutathione peroxidase and glutathione reductase [280]. These workers have proposed that the redox state of mitochondrial pyridine nucleotides can be controlled in part by glutathione peroxidase and glutathione reductase and that oxygen metabolites are a factor in the balance of Ca^{2+} between mitochondria and extramitochondrial space.

A calcium-dependent process has been described as the common final pathway of toxic chemical cell death. Using primary cultures of adult rat hepatocytes, Schanne *et al.* [401] demonstrated that toxic cell death caused by ten different chemicals was dependent on extracellular Ca^{2+} . Similarly, Chenery *et al.* [101] showed that cultured hepatocytes exposed to CCl_4 , and the calcium ionophore, A23187, were dependent on extracellular Ca^{2+} for the expression of toxicity. These investigators proposed a two-step mechanism for toxic cell death. The first step is the disruption of the integrity of the plasma membrane by widely differing mechanisms followed by a common final step: the influx of extracellular calcium across the damaged plasma membrane.

More recent experiments cast doubt on the commonality of this pathway for cell death. Recent studies by Acosta and Sorenson [2] have demonstrated that the toxicity of $CdCl_2$ is accelerated in cultured hepatocytes incubated with calcium-free media. These results are in direct conflict with those reported by Schanne et al. [401] and Chenery et al. [101]. In addition, Smith et al. [418] have demonstrated in freshly isolated hepatocytes that three different liver cell toxins, CCl_4 , bromobenzene, and ethylmethane sulfonate (EMS), are far more toxic to hepatocytes in the absence of extracellular Ca^{2+} than in its presence. These studies suggest that certain aspects of toxic cell injury are not dependent on extracellular Ca^{2+} .

The reasons for variability in cellular responses to extracellular Ca^{2+} and chemical toxicants are presently unknown. One can only speculate that differences in media conditions play an important role. Reed and Fariss [374] have shown that the entry of extracellular calcium is not a prerequisite for cell death in isolated rat hepatocytes.

It is interesting to speculate that the susceptibility to cell injury afforded cells in calcium-free media may be the result of inadequate intracellular Ca^{2+} concentrations since A23187, permits the influx of extracellular calcium but does not cause cellular damage [374]. Indeed, these studies support the contention that the entry of extracellular calcium is not the cause of cell death but, more likely, the result of cell death.

A puzzling result of the extracellular Ca^{2+} studies is the accelerated toxic cell injury afforded hepatocytes incubated in calcium-free media. This phenomenon has been observed with numerous compounds including adriamycin + bis-(2-chloroethyl)-nitrosourea (ADR-BCNU), CCl_4 , bromobenzene, and EMS which are depleters of glutathione [418]. Babson et al. [374] have demonstrated that ADR-BCNU toxicity is dependent on the level of intracellular glutathione. That is, cell death occurs once the level of intracellular GSH falls below 20% of its initial value. Accelerated cell death of hepatocytes treated with Ca^{2+} -free media resulted from an enhanced loss of intracellular glutathione [374]. This accelerated loss of glutathione has recently been shown to be the result of a rapid efflux of GSH which occurs regardless of the toxin used [374]. Consequently, the accelerated loss of intracellular glutathione in hepatocytes treated with Ca^{2+} -free media may explain the enhanced toxicity observed with ADR-BCNU or any other compound that relies on GSH depletion as its mechanism of toxicity.

Recent developments suggest that chemically induced cell injury results from changes in intracellular Ca^{2+} homeostasis as opposed to the influx of extracellular Ca^{2+} . These studies have demonstrated the depression of Ca^{2+} sequestration in liver microsomes and mitochondria after treatment with a variety of hepatotoxins. Furthermore, this loss in calcium retention appears to be related to alterations in the status of glutathione and reducing equivalents.

B. Theories of Radioprotection.

In the forty years since the research of the Manhattan Project suggested the possibility of chemical radioprotection, numerous theories have been proposed to account for the actions of radioprotectors. These theories range from molecular interactions between radioprotectors and the target molecules, which are damaged by ionizing radiation, to events at the organ level which influence the state of radiosensitivity of the organism. A theory of radioprotector action differs from the mechanism of action in that a single mechanism of action may be involved in several different theories by which radioprotectors exert their beneficial effects. This relationship should become clear in this section, in which we review the historical context of the theories of radioprotector action and explain which mechanisms may be involved in each theory. The individual mechanisms of action will be described more fully in the following section (§III.C.). Please keep in mind that several of these theories of radioprotection are mutually exclusive; however, in the absence of conclusive proof that they are not involved in chemical radioprotection we have chosen to present them in a historical context. This overview of theories is presented to orient the reader and to unify the mechanistic concepts to be presented in §III.C. in a field in which the lines between opposing theoretical frameworks have been quite heavily drawn.

1. Radical Scavenging.

The radical scavenging theory of radioprotection involves solely the indirect effect of radiation. The interaction of ionizing radiation with the solvent in biochemical systems, water, has been described in §II.A. The radicals produced from water radiolysis ($\cdot\text{OH}$, $\cdot\text{H}$, e_{aq}^-) exert damaging effects on critical constituents of model cellular systems and may be damaging in the whole organism, contributing to the sum of radiation damage.

Therefore, the removal of these water radiolysis products before they can interact with critical targets in cells should confer protection from radiation. This theory of radioprotection was first described when the free radical nature of radiation damage was first understood in the 1950's. It has survived to the present largely because at least a portion of the damage caused by ionizing radiation is likely the result of indirect action, and many very efficient radioprotectors are very good scavengers of water-derived radicals. The evidence for and against radical scavenging as a mechanism of radioprotector action is discussed in §III.C.3.a.

2. Hydrogen Donation to Target Radicals.

Both the direct and indirect effects of ionizing radiation produce free radicals in biological materials. Hydroxyl radicals, hydrogen atoms, and products derived from the aqueous electron, react with organic molecules to abstract hydrogen atoms from the molecule. Direct effects may also contribute to the formation of species in which a hydrogen atom is removed from the starting structure. In these circumstances, restitution of the original structure requires donation of a hydrogen atom. This hydrogen atom transfer has been observed between thiols and carbon-centered radicals (see §II.C.1. b.1.). In simple systems containing model carbon radicals (derived from aliphatic alcohols) and biological thiols (*i.e.* glutathione and cysteine), hydrogen atom donation with formation of thyl radicals has been observed. However, these highly purified systems cannot be considered as directly comparable to those of cells or tissues, and the relevance of such reactions to biological target molecules is unknown. The literature on the pros and cons of hydrogen transfer as a mechanism of radioprotector action is discussed in §III.C.3.b.

3. Mixed Disulfide Formation.

The mixed disulfide theory was proposed by Eldjarn and Pihl in the mid-1950's and applies only to sulfur-containing radioprotectors which can form mixed disulfides with protein sulfhydryl groups. The effects of ionizing radiation may be expressed to a certain degree by the loss of biological function of critical protein molecules. These critical proteins may be protected from damage by the formation of temporary mixed disulfides in an exchange reaction which can be expressed as in equations 51 and 52. The formation of mixed disulfides



serves to protect the labile sulfhydryl and disulfide groups on proteins from oxidative damage due to direct or indirect effects of radiation. The reversal of equations 51 and 52 would regenerate the original protein molecule after the ionization and free radical reactions initiated by radiation have been completed. In this way, enzyme active sites, the conformation of structural proteins, or critical ionophores may escape radiation damage at their thiol or disulfide moieties. Thus, the targets of radiation action are stabilized by mixed disulfide formation; since mixed disulfide formation is reversible, biologically-competent molecules may be reformed after the passage of radiation. The evidence for and against this mechanism of radioprotector action is discussed in §III.C.4.b.

4. Release of Endogenous Radioprotectors.

Révész and co-workers have proposed that exogenously administered radioprotective thiols and disulfides act by releasing endogenous radioprotectors which are responsible for the beneficial effects. This theory is restricted to exogenous radioprotectors having a thiol or reducible disulfide group, since the released endogenous radioprotectors (principally glutathione) are contained in naturally occurring mixed disulfide forms with cellular proteins. In a fashion similar to the mixed disulfide theory, the proponents of this theory have shown that the efficacy of radioprotection by exogenous agents correlates with their glutathione-releasing potential. The released glutathione is thought to prevent radiation damage by the other mechanisms of protection, *i.e.*, by hydrogen transfer reactions, radical scavenging, etc. This theory is supported by the finding that glutathione may exert protective activity in ways that may not be mimicked by other thiol-containing radioprotectors [380]. However, more recent research on the nature of those thiols present in naturally occurring protein-thiol mixed disulfides tends not to support the theory, because only a small fraction of the low molecular weight thiols bound to protein have been identified as glutathione [81,278]. The evidence for and against this theory of radioprotection is discussed further under the title "enhanced protection against oxidative stress" in §III.C.3.c.

5. Biochemical Shock.

A theory of radioprotection, which was first proposed in the mid-1960's, and which has received little further direct experimental support. This theory was proposed by Bacq and associates [36,40,42] to overcome what they viewed as the inadequacies of the mixed disulfide and free radical scavenging theories of radioprotection. They proposed that radioprotectors (principally thiol radioprotectors) bind to cell membranes and induce the formation of lesions in the regulatory processes of the cell which leads to a radioresistant state. The hypothesis would explain the correlation of mixed disulfide formation with radioprotector efficacy since the formation of mixed disulfides was the first step in their proposed cascade of reactions that led to increased radioresistance. Consequently, no explicit mechanisms for the increased radioresistance were proposed at the time the hypothesis was formulated. However, the concept of "stress" reactions to a variety of environmental stimuli has recently been the subject of considerable investigation. Cells subjected to a brief hyperthermic treatment become more resistant to subsequent heat treatments (review [196]) and this thermotolerance is accompanied by specific biochemical changes. In the hour following heat shock, protein synthesis is virtually halted and, as translation function returns, the synthesis of a specific group of proteins is induced (Heat Shock Proteins, HSP) [226,236]. The synthesis of these proteins appears to be correlated with the development of thermotolerance [263,270]. These proteins are also regulated by environmental conditions other than heat shock [233, 264,479] and may be induced by chemical agents such as sodium arsenite or ethanol [269]. Concomitant with the development of thermotolerance, the yeast Saccharomyces cerevisiae acquires a resistance to radiation damage possibly by the induction of its DNA repair capacity [313]. The mechanisms by which thermal and radiation tolerance is increased by heat or these chemical agents is unknown. Recent work shows that altered glutathione metabolism is associated with the early stages of this effect [312,315]. Thus it is tempting to speculate that exogenously supplied thiols may be interacting with this stress response in some way - either by triggering induction (although in certain cell lines the response requires 8 - 10 hours to achieve its maximal effect) or by mimicing step(s) further down the pathway toward increased resistance. Paradoxically, other experiments have shown that exogenous thiols sensitize cells to thermal stress. It should be noted that

these studies [234,315] were all done in the presence of the exogenous thiol, rather than by treating the cells and washing out the thiol prior to the second application of heat stress. As heat may increase the autoxidation of exogenous thiols, this sensitization may be explained by invoking a heat-induced increase in the toxicity of the exogenous thiol. However, thiols may exert effects on cell constituents which result in observable increases in radiation resistance after they are washed out of cells [14,15,463]. Indeed, a recent report shows that the brief oxidation of GSH with diamide results in brief thermosensitization followed by the development of sustained thermotolerance [197]. Thus the induction of a stress response leading to radiation resistance by thiols or other radioprotection compounds needs to be investigated (see §V).

6. Hypoxia.

One of the major factors determining the radiosensitivity of a tissue is the degree of oxygenation during irradiation. As discussed in §II.B., oxygen contributes to the resulting damage by interacting with free radicals produced in both target molecules and in the solvent; it thereby increases the radiation damage which is measured. Consequently, a drug or procedure which decreases the extent of oxygenation should exhibit a relative radioprotective effect when compared to the fully oxygenated situation. When the oxygen effect was first recognized as an important factor in radiobiology in the 1950's, the concept was immediately applied to explain the radioprotective effect of a variety of radioprotectors. Two means by which hypoxia may be produced in tissues in vivo are by (1) reducing the delivery of oxygen to tissues either by altering oxygen transport or by redirecting blood flow to specific organs or portions of organs, or (2) by consuming the oxygen which is delivered to tissues in chemical or biochemical reactions, thereby limiting the oxygen available for participation in free radical reactions. Several hormonal agents may exert at least a portion of their radioprotective effect by altering blood flow in irradiated organs, thereby causing hypoxia. Also, at first, the radioprotection shown by sulfhydryl compounds was explained by the known consumption of oxygen during thiol oxidation. While a portion of the radioprotective efficacy of thiols may be attributed to this mechanism, other factors must certainly also be considered. The evidence for hypoxia by either mechanism is considered in §III.C.2.

7. Hypothermia.

The effects of temperature change on biochemical processes are well known. Consequently, temperature is a variable which has been employed to alter the radiosensitivity of cells and tissues. Hyperthermia is a promising adjuvant technique in cancer therapy, as it increases the susceptibility of cells to the toxic effects of chemotherapeutic drugs. Acute hyperthermia also increases the amount of damage produced by a given dose of ionizing radiation. However, as discussed above (§III.B.5. Biochemical Shock), the stress of hyperthermia is accompanied by adaptive processes which increase the resistance of cells to radiation. In contrast, the effects of suboptimal temperatures have been shown to result in a radioprotective effect [209]. Presumably, this protective effect may be explained by mechanisms which are different from the induced resistance resulting from prior hyperthermic exposure. The reduced metabolic activity accompanying hypothermia may allow more complete and efficient repair of radiation damage [239]. Alternatively, damage-producing reactions following the absorption of radiation energy may be slower or less complete and this effect may account for the reduced sensitivity [55]. Drug effects have only infrequently been explained by their action in causing hypothermia. A portion of the radioprotective activity of one drug, chlorpromazine, may be due to its ability to lower the body temperature; the protective effect and the profile of body temperature after chlorpromazine administration are coincident [60]. However, studies suggest that other drugs which produce hypothermia, including cysteamine, cysteine, serotonin, sodium fluoroacetate [39], cholinomimetics [424], and cyanide [458] may not produce the majority of their radioprotective effect by this mechanism [311].

C. Biochemical Mechanisms of Radioprotector Action.

1. Prevention or Reduction of Radiation Dose.¹

- a. Physical shielding of biological tissue.
- b. Administration of blocking drugs or chelators.

2. Suppression of the Formation of Reactive Species.

When oxygen was recognized as an important factor governing the radiation sensitivity of biological materials, this concept was soon applied to the mechanism of chemical radioprotectors. Since the maximum dose-reduction factor which can be obtained for cells in culture or in vivo is approximately equal to the magnitude of the oxygen effect (§II.B), the reversal of the oxygen effect was a potential explanation of chemical radioprotection. Similarly, pharmacological agents known to alter hemodynamics in vivo were thought to be radioprotective by interfering with the delivery of oxygen to irradiated tissue [461]. It was shown early on that sulfhydryl radioprotectors incubated in closed vessels can rapidly deplete the solution of its oxygen content [183]. The evidence for these two mechanisms of action is reviewed below.

a. Cardiovascular Hypoxia.

The importance of a normally maintained blood flow and concomitant oxygen delivery mechanism in the maintenance of tissue radiosensitivity has long been appreciated [183]. Indeed, this topic has recently been the subject of investigation by radiation oncologists endeavoring to protect normal tissues within the radiation field from dose limiting side effects. These investigators have used physical limitations in blood perfusion [207] and more recently microsphere embolization of the intestine [279] or the kidney [161], perfusion with deoxygenated dextran-hemoglobin [202], and other techniques. While promising, these techniques are both very experimental and by definition will be limited to radiation therapy.

¹ These topics will not be considered at the specific request of the agency sponsoring this review. The topics are listed in this report only to indicate their logical place in the full spectrum of possible mechanisms of action of radioprotective drugs.

Alterations in tissue oxygen delivery by altering distribution of blood supply has also been proposed as a mechanism of action of chemical radioprotectors [461]. Compounds to which this mechanism has been applied include the biogenic amines (histamine, serotonin, norepinephrine and epinephrine) which exert specific pharmacological effects which were well recognized prior to the recognition of their anti-radiation potency. Also included in this group are thiols and disulfides, although the evidence for the production of hypoxia by this mechanism is slim. A third chemical which likely protects by inducing cardiovascular hypoxia is cyanide, operating by a vasomotor stimulatory mechanism [458].

Of the biogenic amines, the most widely studied compound in this group is serotonin, whose radioprotective effect was first described in 1952 [41, 182]. The early studies on the interrelationships between serotonin and radiation effects have been reviewed [423]. In the period 1952 to 1965, the determination of the mechanism of action of these substances was the focus of intense investigation; radiochemical (§III.C.3) and biochemical mechanisms were championed against the local hypoxia mechanism. In particular, evidence concerning the protection afforded chemical polymer model systems [11] was used to refute earlier claims that serotonin and other aromatic amines acted by local or systemic tissue hypoxia. In this experiment, the depolymerization of polymethacrylate is used as a model of radiation damage. Histamine, serotonin and epinephrine all exerted a "protective" effect in this system which cannot be due to their pharmacologic effect on oxygen delivery, since a non-biological system was employed.

However, since the biological radioprotective effect is the one whose mechanism we seek to explain, data from biological experiments should be given more weight. In this respect, the evidence for radioprotection as a property of the cardiovascular pharmacology of the biogenic amines is striking. Firstly, thymocytes irradiated in vitro are unprotected by histamine, epinephrine and β -phenylethylamine, at doses which offer good protection in vivo [454]. Correlations between the spleen oxygen tension and radioprotective efficacy are high for the drugs of this group and also help to explain differences in efficacy of histamine between strains of mice [460, 461]. Conversely, the oxygen tension in the spleens of mice and rats after injection of the thiols cysteine, cysteamine or aminoethyl isothiuronium (AET) shows a variable and inconsistent response, tending to increase, rather

than decrease the oxygen content [459]. Radioprotective tryptamines inhibit uptake of the dye neutral red into the spleen of mice, while non-protective congeners and amino thiols do not have this property [493]. Also, specific pharmacologic antagonists abolish the radioprotective effects of histamine, epinephrine, carbamoylcholine [461] and serotonin [455,456]. If these drugs are acting to reduce the delivery of oxygen in radiosensitive tissues, then physically increasing the amount of oxygen available for delivery should reverse this effect. Indeed pure oxygen respired at pressures up to 60 p.s.i. reverses the radioprotective effect of serotonin, histamine, and epinephrine but causes much less reduction of cysteamine or cysteine radioprotection [457]. Finally, the state of intracellular oxygen tension in intestinal mucosa, estimated by measuring the oxidation state of the pyridine nucleotides $\text{NAD(P)}^+/\text{NAD(P)H}$, may be altered by serotonin, although these results were not clear cut [220].

Not all evidence favours hypoxia as the mechanism of radioprotection by the biogenic amines. As mentioned previously, indolealkylamines are protective in model polymer systems [11] and a recent report suggests that serotonin and 5-hydroxytryptophan protect mastocytoma P815A cells *in vitro* under conditions which preclude hypoxic radioprotection [398]. Protection of cells *in vitro* by β -adrenergic agonists may involve β -adrenergic receptors and the cyclic AMP system [419]. The data from the intracellular $\text{NAD(P)H}/\text{NAD(P)}^+$ reduction were equivocal, suggesting that intestinal radioprotection by serotonin may operate by a non-hypoxia mechanism. Also, inasmuch as most biological processes are interrelated, one can interpret serotonin or other biogenic amine radioprotection by other mechanisms. As examples, the enhancement of post-irradiation recovery/repair processes [32,57,180] (§III.C.5) or the effects of biogenic amines on endogenous thiols and their influence on radiosensitivity [179,310] (§III.B.4) have been proposed to account for biogenic amine radioprotection. However, the bulk of experimental evidence suggests that biogenic amines protect against ionizing radiation by affecting the cardiovascular system so that hypoxia is produced in tissues, exhibiting radiation damage.

b. Chemical/Biochemical Hypoxia.

An alternative means by which hypoxia may be induced in cells or tissues is by local consumption of oxygen by chemical or biochemical reactions. This mechanism of radioprotection is limited to the sulfhydryl (or

disulfide) containing radioprotectors which undergo oxidation reactions in which molecular oxygen is consumed. The chemical and biochemical oxidation of thiols has been reviewed [95,223] and efficient catalysts for the reaction between thiols and molecular oxygen have been identified. These catalysts include metal ions or their chelated forms in biological systems including haemin, cytochromes, and other metalloproteins. The metal ion catalyzed oxidation of thiols by molecular oxygen always follows the stoichiometry:



For many years, the biochemical hypoxia mechanism was thought to be restricted by definition to thiols which can participate in reactions 53-54 either with or without catalysis [37,459]. As a result of drug disposition studies on cystamine (2-aminoethyl disulfide), *in vivo* reduction to the active thiol was recognized [142,464,465]. Furthermore, a "futile cycle" (Figure 6) has been proposed whereby there is oxidation of thiols by thiol-oxidizing enzymes (flavin-containing monooxygenase) and reduction of the resulting disulfides by the glutathione redox system [495], possibly with the assistance of thiol-transferase [288].

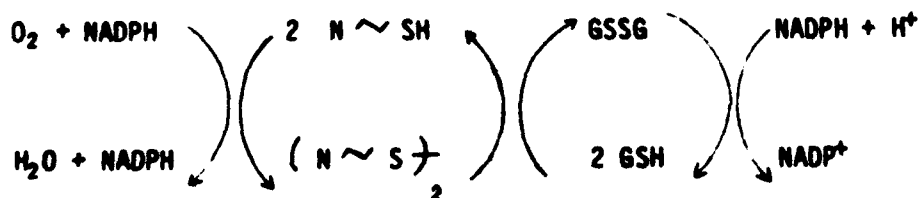


Figure 6: Redox cycle of aminothiol consumption of oxygen.

Evidence for and against this mechanism of radioprotection has been accumulating steadily since its suggestion by L.H. Gray [183]. Gray observed that unpurified cysteine (likely to contain traces of iron or copper) in buffer at $\text{pH} > 6$ rapidly removed oxygen from closed vessels. This effect was shown to operate in at least a part of the protective effect of cysteine. As

has been cautioned [14], reports on the importance of hypoxia in radioprotection from this period are difficult to interpret because the accurate measurement and control of low oxygen tensions in vitro were not often achieved [123]. Nevertheless, many reports were published either for or against the importance of hypoxia in sulfhydryl radioprotection. These early reports have been summarized [406,486]. Although most reports on sulfhydryl radioprotection acknowledge a contribution of protection by hypoxia, the extent to which this mechanism accounts for the sum of a radioprotector's actions remains controversial.

Early reports on hypoxia by sulfhydryl oxidation attributed the entire protective action of this class of radioprotectors to their tendency to produce this effect [183,205]. However, the effects of cysteamine, cystamine or cysteine are additive to the effects of severe hypoxia in vivo (breathing 5% oxygen) [123,391] although brief periods of respiring pure nitrogen produced effects which were not entirely additive [487].

Numerous investigations have shown (albeit reduced) radioprotection by sulfhydryl compounds under strict anoxia in vitro [99,210]. Measurement of oxygen content of tissues or blood in vivo show conflicting results: reports of a lowering of venous O_2 -tension without change in the arterial O_2 -tension after cysteine or cysteamine [389] conflict with reports of the variable or unchanged effect of thiols on tissue oxygen content [178,459]. As discussed in the previous section, the radioprotective effect of thiols was unchanged in animals breathing oxygen at high pressure [457]. If one accepts the reduction of pyridine nucleotide fluorescence as indicative of reduced intracellular oxygen tensions, sulfhydryl radioprotectors exert little influence on intracellular oxygen concentrations [220].

Recently, interest has again been focussed on thiol-induced hypoxia as an important factor in the radioprotection of mammalian cells by WR-2721 [S-2-(3-aminopropylamino)ethylphosphorothioic acid]. This compound is one of a group of compounds whose radioprotective actions are dependent on the hydrolysis of the material (in this case, a phosphoric ester) to liberate the thiol, which is the true radioprotective substance [248,250]. This agent has been investigated for clinical application because of its reported selectivity in protecting normal versus tumor cells [490]. The involvement of hypoxia in the mechanism of action of WR-2721 is important because one wants to selectively protect relatively well oxygenated normal tissue without

altering the already compromised radiosensitivity of relatively hypoxic (but not necessarily anoxic) tumor cells. Investigators at the Gray Laboratories have published an interesting series of reports [116,117,427] (also reviews [118,119]) whose collective impact is to question whether WR-2721 has any effect other than local tissue hypoxia. Experimental investigation on radioprotection in V79 spheroids, which are known to contain cells exposed to partial hypoxia, suggests that WR-2721 exerts both an oxygen-independent mechanism and an oxygen-dependent mechanism which is best expressed in these borderline-hypoxic cells [132]. Also Purdie *et al.* has shown that the product of WR-2721 dephosphorylation, WR-1065 [N-(2-mercaptoethyl)-1,3-diaminopropane] is capable of very rapidly depleting the oxygen content of suspensions of mammalian cells in culture [366]. The combination of oxygen identification as a critical factor in the clinical efficacy of WR-2721 coupled with experimental demonstration of its oxygen-depleting capability provides strong support for biochemical hypoxia as at least a large part of its mechanism of action.

All of these investigations are confounded by the lack of adequate ability to measure the oxygen concentration at the site of critical radiation effect, which likely is in or close to the nucleus. The pyridine nucleotide fluorescence measurements come the closest to achieving this objective, but these measurements reflect the oxygen tension in the sites of greatest flux of pyridine nucleotides, the mitochondria [220]. Furthermore, the observation of hypoxia or anoxia in closed vessels *in vitro* should be kept in perspective, as allowance must be made for factors *in vivo* which govern extracellular oxygen delivery and intracellular oxygen consumption.

3. Detoxication of Radiation-Induced Reactive Species.

When the physical interaction between ionizing radiation and the irradiated sample is complete (at $\approx 10^{-9}$ sec), radical species are present. Radical scavengers (reviewed in §a, below) may interact with water radicals to prevent damage to critical molecules in the cell which would otherwise have led to cell death. Radioprotectors may also react with organic or water radicals by hydrogen donation to "repair" these radical species (§b, below). Finally, since radiation damage approximates the "oxidative stress" which has been associated with active oxygen toxicity or the toxicity of compounds which undergo oxygen-dependent redox cycling, radioprotectors may support or

refurbish the natural cellular mechanisms of defense against oxidative stress (5c, below).

a. Free Radical Scavenging.

To the extent that radiation-induced radical formation occurs in the solvent (§II.A.), one mechanism of action of radioprotectors which must be considered is the removal of these products of water radiolysis before they are able to react with, and damage, the critical targets whose alteration leads to cell death. The extent to which the indirect (water radiolysis) effect is important in the expression of radiation-induced cell death remains a hotly debated topic among radiobiologists [349] cf. [12]. It seems reasonable to assume that products of water radiolysis do contribute to cell death and that the major damaging species is the hydroxyl radical ($\cdot\text{OH}$) since the rates of reaction of various radioprotectors with $\cdot\text{OH}$ correlate with the magnitude of their protective effect [107,390,396]. Although the involvement of the hydroxyl radical has generally been accepted, the assignment of the fraction of radiation damage to a specific percentage remains debatable [99].

A class of compounds whose protective action is generally accepted as involving radical scavenging is that of the aliphatic alcohols, including methanol, ethanol, ethylene glycol, and glycerol. A common feature of protection by these compounds is the large concentration required to achieve maximum radioprotection in vitro (1 - 3 M) [124,390] although by measuring parameters other than cell death, protective effects of radical scavengers may be noted at much lower concentrations [49,186]. Since their toxicity exceeds their radioprotective potency, the alcohols are not generally very effective in vivo. However, a compound whose maximum effect in vitro is similarly exerted at concentrations > 2 M is dimethyl sulfoxide (DMSO) [99]. DMSO is effective in vivo at a dose of 4.5 g kg^{-1} , which can be administered only because of the extremely low toxicity of the compound [30,31] As more is understood about the nature of the events interposed between free radical formation and cell death, the role of antioxidants has similarly been refined. Thus, classification of radical scavengers by the type(s) of radicals with which they interact is now possible, as is their protection against the initiation or sequelae of lipid peroxidation [370, 371].

Thiols may also participate in radical scavenging reactions, at rates which are close to the diffusion controlled limit (see §II.C.1.b.1). Even at these high rates of reaction, calculations show [349] that cysteamine (a very good scavenging thiol) would be required at a concentration of 30 mM to produce a dose reduction factor of only 1.3. Yet, cysteamine is effective to a greater degree at doses in vivo which would produce a concentration of 3 mM if the compound were distributed evenly throughout the body. This discrepancy is rationalized by suggesting that thiols are concentrated in the vicinity of critical radiation targets by electrostatic interaction or binding to the target molecule. This binding effectively raises their local concentration to a level at which their radical scavenging ability matches their protective potency (see §III.C.4.a.). On the other hand, thiols may also protect by mechanisms unrelated to radical scavenging.

One difficulty with the idea that radical scavenging plays a major role in radioprotection is the anomaly encountered with radiations of different biological effectiveness. As mentioned in §II.B.2, the oxygen enhancement ratio decreases with increasing linear energy transfer (LET). In concert with this observation, the yields of both $\cdot\text{OH}$ and e^-_{aq} decrease with increasing LET [258]. If the major mechanism by which radioprotectors act is to scavenge these radicals, and the contribution of these radicals to the total amount of radiation damage decreases, one would expect the effectiveness of radioprotectors to decrease in parallel with the radical yield. Glycerol protection of both bacteria and haploid yeast is relatively constant over a wide range of LET [23,289] and cysteine is equally effective in protecting against 5.2 and 27 MeV α -particles [20]. While it does not seem logical that a radioprotector should act by different mechanisms of action against the effects of radiation of different quality, these observations do not necessarily disprove the scavenging mechanism thought to operate with "soft" X- and γ -rays.

b. Hydrogen donation to target radicals.

A hypothesis of the mechanism of action of sulphhydryl radioprotectors, which has gained popularity in recent years, is the hydrogen donation hypothesis. This theory seeks to explain the radioprotection of this class of compounds by the reaction of thiols with carbon-centered radicals formed in critical target molecules (equation 23). In contrast to the radical

(23)



scavenging hypothesis, this theory takes into consideration both the direct and indirect actions of radiation, *i.e.*, target radicals may be produced by direct deposition of energy within the target or by the reaction of target molecules with the products of water radiolysis (primarily $\cdot\text{H}$ and $\cdot\text{OH}$). The theory lies at the heart of the competition model of radiation protection (§II.D.) in that the molecular repair reaction shown in equation 23 is in competition with oxygen addition to the target radical (§II.B.4; equation 22).

Direct evidence for the validity of the hydrogen donation hypothesis is scant. Although the reaction shown in equation 23 has been observed [5,6,7, 159] (reviewed [484]), at present such observations can be made only indirectly in highly purified model systems. Thus, it is not possible to measure this reaction in whole cells, cell fractions, or even with biologically relevant molecules such as proteins or DNA. Furthermore, since this mechanism is limited to thiols, most of which are also efficient free radical scavengers, one has difficulty in distinguishing in biological systems between radical scavenging and hydrogen donation. Estimates of the contribution of hydrogen donation to radioprotection have been made in model systems in which indirect effects are diminished or eliminated (*e.g.* dry or frozen biological preparations). Under these conditions, sulfhydryl compounds are effective in protecting DNA [76] and enzymes [172]. Also, radical transfer between carbon-centered radicals in salmon sperm DNA irradiated at -196°C and cysteamine has been shown by electron spin resonance spectroscopy [326].

Based on the presumed competition between hydrogen donors and oxygen for the target radicals, one would expect that radioprotectors which are thought to act by hydrogen donation should be more effective when oxygen is excluded from the test system. This result was indeed observed for the protection by cysteamine [210] and mercaptoethanol [212] of bacteriophage DNA irradiated in aqueous suspension. However, in aqueous suspension, at least a portion of this protection may have been produced by the radical scavenging effects of these thiols, as the precautions against indirect effects may have been inadequate [14].

Difficulties with the hydrogen donation theory also hinge on the differential protection of hypoxic and well oxygenated cells. In contrast to results with bacteriophage, thiols are much more effective in protecting oxic than anoxic cell suspensions. This differential protection may be explained

either by invoking the theory of thiol oxidation resulting in oxygen consumption (which would tend to show a greater effect in well oxygenated cells [See §III.C.3.b]) or by the argument that hypoxic cells are already protected to their maximum degree by endogenous thiols and therefore derive little benefit from additional exogenous thiol. Furthermore, estimates of the rates of the reaction between model target molecules and either oxygen or thiols have shown that oxygen reacts with carbon-centered radicals as much as 200 times faster than the hydrogen-donating reaction [4]. Thus under physiological conditions and in the absence of any chemically induced hypoxia, the relative contribution of the hydrogen donating reaction is questionable. However, some experimental evidence does suggest that this reaction may account for a share of the somewhat modest radioprotective activity of thiols in the absence of oxygen.

c. Enhanced Protection from "Oxidative Stress".

The adverse effects of reduced oxygen species ($\cdot\text{OH}$, $\text{O}_2^{\cdot-}$, H_2O_2) on cells or tissues are collectively known as "oxidative stress" (for overview, see [409]). Since these reactive compounds are produced during the irradiation of cells and tissues, one may refer to radiation as producing oxidative stress. Whereas acutely lethal effects of radiation may be mediated to a large degree by the indiscriminate and highly reactive hydroxyl radical ($\cdot\text{OH}$) [107,396], other oxidants may also contribute to both acute and delayed effects. Perhaps as a result of the involvement in certain reactions of intermediary metabolism, cells have developed enzymes to provide protection against certain oxidants. Superoxide dismutase is effective in the destruction of the superoxide anion radical, converting two molecules of $\text{O}_2^{\cdot-}$ to one molecule each of O_2 and H_2O_2 [323]. Catalase [98] removes hydrogen peroxide, and glutathione peroxidase is a good catalyst for the detoxification of both hydrogen peroxide and lipid hydroperoxides [157]. Thus an intricate network of defenses has evolved to protect against oxidative stress.

Certain of these cellular defenses may be augmented by radioprotectors. We have previously noted the possible release of reservoirs of glutathione by exogenous thiol radioprotectors (§III.B.4); the released glutathione may function partly as the cofactor for either glutathione peroxidase or the

recently described glutathione-dependent labile cellular factor which protects against lipid peroxidation [188,201]. Alternatively, direct administration of the defensive enzyme may in some cases provide radioprotection. In vitro, added superoxide dismutase (SOD) is reported to protect erythrocytes [268] and DNA [492] from damage due to ^{60}Co γ -rays. SOD and catalase have been shown to protect certain enzyme activities associated with erythrocyte energy metabolism from γ -radiation in vitro [230]. Administration of exogenous SOD to mice [131] and rats [414] prolonged survival after lethal doses of radiation. In the most promising report to date, Petkau reported a dose reduction factor of 1.56 ± 0.04 after intravenous administration of SOD to mice [345]. This reduction of radiation lethality was attributed to protection of the proliferative capacity of bone marrow cells. On the other hand, radiation-induced inhibition of human lymphocyte blastogenesis was not protected by SOD or catalase, and indeed exogenous SOD and catalase depressed lymphocyte proliferation in vitro [242]. Other reports suggest that the protective effect of SOD may not be so striking [1,51]. In view of the many factors involved in the distribution and metabolism of enzymes administered in vivo [397], perhaps these conflicting reports should not be too surprising.

The possibility that chemical radioprotectors act by stimulating or inducing this enzyme seems even more remote. Indeed cysteamine in radioprotective doses is reported to inhibit activity of the enzyme in the bone marrow in vivo [255], and prior X-irradiation does not induce the activity of the enzyme in Drosophila [50]. Thus, the role of SOD in natural radioprotection and its possible therapeutic use as a radioprotective agent is unclear.

4. Target Stabilization.

Thus far, we have described means by which radioprotectors interact with the products of radiation to prevent or ameliorate radiation damage. Radioprotectors may also exert their action by interacting with the target for radiation damage. In this section we describe ways by which protective agents may stabilize the target to prevent or allow restitution of radiation damage.

a. Binding to DNA.

The idea that radioprotectors are effective by binding to DNA and stabilizing its structure was well summarized by Brown in 1967 [86]. This theory has been developed most extensively for the aminothiols radioprotectors, of

which cysteamine is the prototype. According to this theory, aminothiols radioprotectors bind to DNA and stabilize its secondary structure. This increased stability has several benefits.

With increased stability, the radioprotector-DNA complex is less susceptible to unwinding and subsequent loss of secondary structure that can occur when the DNA chain is broken by ionizing radiation or its products. Also, an increase in stability reduces the rate at which the DNA may be unwound for transcription or replication. In both of these cases, the increase in stability allows for a greater possibility that lesions produced in the DNA molecule can be repaired.

Evidence for the involvement of this theory in the mechanism of radioprotector action is mostly circumstantial. Cystamine, the disulfide form of cysteamine, was shown by Jellum in 1965 [221,222] to bind to DNA and the mode of binding has recently been shown to involve electrostatic forces [275]. The binding of cyst(e)amine² is almost entirely accounted for by binding to the sugar-phosphate backbone of DNA [82], interaction which involves binding between the cationic amino groups on the aminothiol or dithiodisulfide and the anionic phosphate groups of DNA [462]. Upon binding, the melting point (T_M) of the nucleic acid-radioprotector complex is raised, relative to the T_M of the nucleic acid alone [287,387,462]. Protection of DNA by cyst(e)amine² was found to be complete at low doses (< 20 Gy) of γ -radiation and high concentrations of cyst(e)amine²; at higher radiation doses, increasing concentrations of cyst(e)amine² protected against the destabilizing effect of radiation [387].

The correlation between DNA binding and radioprotective activity is only partial. It appears that DNA binding is not the sole requisite function. In contrast to the cystamine, guanidoethyl disulfide (GED), glutathione disulfide (GSSG) series, where DNA binding paralleled radioprotective potency, other diamines, such as cadaverine or diguanidines such as pentamethylene diguanidine, show good DNA binding but no radioprotective activity [249]. This result was explained by the possibility of localized radical scavenging by

² In much of this work, cysteamine was dissolved in water or buffer and the interaction with DNA was monitored over a finite time period. In view of the capacity of cysteamine to be oxidized to cystamine, some question remains as to which material actually was bound to the nucleic acid in these studies.

the disulfides; alternatively, the disulfides may be easily reducible and therefore the DNA may be more accessible once the repair is complete.

Finally, the DNA binding hypothesis serves to readily explain some observed structure-activity relationships among the aminothiols (See §VII.A). Generally speaking, the presence of a thiol group in a molecule is not sufficient to express radioprotective activity; an amino group is required for highest activity, and the amino group cannot be separated from the thiol by more than three carbon atoms [128,431]. Presuming that the aminothiol is oxidized to the diaminodisulfide in vivo [494,495], an aminothiol having four carbon atoms between amino and sulfhydryl groups would result in a diaminodisulfide with ten atoms between the amino groups. In a study of DNA binding and stabilization by a series of α, ω -diamines having various carbon chain lengths, maximum stabilization was found with 1,5-diaminopentane and very low binding was observed with 1,10-diaminodecane [285,286]. Thus at the first inactive diaminodisulfide in the series, the relative binding is probably very low. However, this correlation does not hold up uniformly, since a series of N-(alkyl)-disulfides and thiosulfates were found non-concordant for DNA binding (measured using equilibrium dialysis) and radioprotective activity [164].

b. Mixed disulfide Formation.

This hypothesis, presented in the mid-1950's by Eldjarn and Pihl [141] involves the reversible formation of disulfide bonds between proteins and administered sulfur-containing radioprotectors. Following on the observation of mixed disulfide formation in vitro, the interconversion of cysteamine and cystamine in vivo was demonstrated. Eldjarn and Pihl also noted that after administering ^{35}S -labelled cysteamine or cystamine, most of the radioactivity was bound to protein in mixed disulfide linkage at the time of maximum protective activity [141]. Subsequently thiol/disulfide exchange reactions (equations 56 and 57) were documented, and the presence of substantial amounts



of mixed disulfide (RSSR') were found to be present in such a system at equilibrium [142,144]. A positive correlation between the rate and extent of

mixed disulfide formation and radioprotective activity was demonstrated for a variety of thiol compounds [143]. The regeneration of native protein may be accomplished by thiol-disulfide exchange (in which GSH functions as RSH in equation 57, possibly catalyzed by thiol transferase) and by subsequent action of the glutathione redox system coupled with glutathione reductase and NADPH [348].

Certain enzymes, especially those requiring an essential sulfhydryl group, were found to be protected from X-rays by forming mixed disulfides [350]. Other studies failed to show appreciable change in enzyme radioresistance upon mixed disulfide formation with a radioprotector [368]. The mechanisms behind enzyme protection were originally proposed to involve radiation-induced heterolytic cleavage of the disulfide bond of the mixed disulfide (equation 58). Such a reaction would theoretically yield low



molecular weight thiol radicals and protein thiols in one half of these radiation-initiated reactions [347]. However other experiments indicated that this heterolytic reaction may not occur [126], but rather that the mixed disulfide prevents interaction of the critical thiol with other radiation-damaged portions of the molecule [127]. The hypothesis of Pihl *et al.* suffers from several flaws. First, the measurement of equilibrium constants and rate constants has been criticized on the basis of the lack of consideration which was given to pH effects. Critics contend that inadequate attention was given to differences in the degree of ionization of the various radioprotectors when correlations were made between the equilibrium formation of mixed disulfides and radioprotector efficacy [176]. When one removes from consideration those candidate thiols which are widely different in degree of ionization and in steric hindrance to the reaction, little difference in rate or degree of mixed disulfide formation is observed. In defense of Pihl's correlations, it should be mentioned that all his measurements were made at 37°C and pH 7.4, conditions which are likely to approximate the situation in vivo. Thus candidate thiols, which do not exhibit ionization or steric factors under these conditions, are likely to exhibit similar behavior also in vivo, and so they should not be excluded from consideration a priori.

Perhaps the most serious fault with the mixed disulfide hypothesis is its failure to explain the radioprotection of nucleic acid, which is thought

by many to be the prime radiation target. Sulfhydryl groups are restricted to proteins, most of which are quite radioresistant relative to tissues, cells, or DNA in vitro. Identification of sulfhydryl-containing critical targets would support the hypothesis of protection by mixed disulfide formation. Some progress in this direction was made with the demonstration of X-ray inactivation of the initiation factor δ DNA-dependent RNA polymerase [429] and its protection by mixed disulfide formation [430]. However, the radiation-induced inactivation is produced at relatively high radiation doses, raising doubts about the relevance of this observation to the situation in cell inactivation studies. This type of experiment should be extended to other critical enzymes in DNA metabolism.

5. Enhancement or Protection of Recovery or Repair Processes.

After ionizing radiation has damaged cellular molecules, this damage may be expressed by the attendant biological consequences (cell death, mutagenesis, altered function) or it may be repaired, and the cell may recover from radiation-induced effects. For the purposes of this section, we have adapted the definitions of the terms "recovery" and "repair" as they are considered by Orr [333]. By these criteria, recovery [i.e. "Elkind recovery"; recovery from sublethal damage (SLD) or potentially lethal damage (PLD)"] refers to the whole cell and its response to radiation damage; recovery is measured as cell survival, death, or division time. On the other hand, repair ("DNA repair") refers to processes carried out on the molecular or sub-cellular organelle level. As pointed out by Orr, recovery and repair are related, though not necessarily always closely related.

The importance of recovery (and by inference, repair) lies in the end result desired. The observed decrease in radiotherapy efficacy with increasing dose fractionation [162] presents difficulties for cancer therapy presumably due to recovery from radiation damage in tumor cells; for increased radiotherapy efficacy, one would want to inhibit the processes governing recovery [231,319,438]. Conversely, for accidental radiation exposure, one would wish to enhance or stimulate this repair process to prevent radiation damage. The latter concept is the focus of our review.

a. Recovery from Radiation Damage.

Cellular recovery from radiation damage was described by Lea [266] in 1938, but the reports of Elkind and Sutton [145,146] stimulated interest in its effects and mechanism. Various metabolic factors are important in the

expression of recovery, including oxygen [87,277](for a review see [245]). The effects of radioprotective substances on the recovery process appear to have not been investigated extensively. Presumably thiols could be tested for their effect on the recovery process between doses of a split-dose experiment, provided they were removed from the medium prior to the second dose of radiation (without removal, the effect of radioprotective substances on the second dose of radiation might be misinterpreted as an effect on recovery).

The term potentially-lethal damage is used to denote circumstances under which, by appropriate treatment of irradiated cells, the expression of radiation lethality may be avoided. This term was coined by Phillips and Tolmach in 1966 [346] to describe their observation that cells treated immediately following irradiation with cycloheximide to inhibit cell division were more resistant to the radiation damage. Similar results have been observed for the holding of cells at temperatures suboptimal for growth [56]. While some work has been performed on the identification of substances which inhibit the recovery from potentially lethal damage, little investigation has been done on the stimulation of this biological phenomenon.

b. Repair of Radiation-damaged Structures.

Macromolecular structures damaged by radiation may be repaired by enzymes. DNA repair is a well-researched function of bacterial and mammalian cells [191], and this process has recently been the subject of numerous reports in radiation biology [21]. The involvement of ADP-ribosylation in repairing DNA strand breaks produced by radiation is under investigation, and the suggestion has been made that such repair of DNA strand breaks is necessary for cellular recovery from radiation damage [281]. Glutathione (GSH) may also be involved in the repair of DNA single-strand breaks (SSb) as has been suggested using cells genetically deficient in GSH synthesis [137,378] or in which GSH deficiency was produced by D,L-buthionine-S,R-sulfoximine (BSO) [378] or hypoxia/misonidazole treatment [135,379]. Interestingly, cells which are genetically deficient in glutathione synthetase [265] have increased intracellular amounts of γ -glutamylcysteine, cysteine, and other low molecular weight thiols [137], yet these thiols are unable to substitute for GSH in supporting DNA SSb repair [379]. In contrast to these results, Chinese hamster ovary cells whose non-protein thiols are depleted by diethylmaleate show no differences in the rate of repair of SSb induced by X-rays

[151]. Thus, the role of endogenous thiols in the repair of DNA damage must be studied further to clarify these conflicting findings.

Exogenous compounds have recently been investigated for their ability to induce the enzymes responsible for DNA repair. This property has been documented for a number of compounds which stress cells, including hydrogen peroxide [115], methylmethane sulphonate [62], nickel compounds [388], 1,6-dinitropyrene [91] and mercury [388]. The induction of DNA repair capacity has also been reported for the sulfur-containing radioprotector WR-2721 [384,385]. In contrast, cysteamine was found to inhibit DNA polymerase I-directed repair synthesis [66]. Cysteamine decreased the extent of rejoining of DNA SSB in GSH-proficient cells [316] but was able to substitute for glutathione in GSH-dependent SSB repair in GSH-deficient fibroblasts [136]. Thus, it appears that thiols are involved in certain types of DNA repair (though possibly not all types), and further research may point to new compounds able to stimulate the repair of radiation-induced DNA damage.

IV. Therapy of Radiation Damage.

In this section, the question: "What post-irradiation actions can be taken to ameliorate radiation injury?" is briefly considered. In general, therapeutic strategies after radiation exposure depend upon the dose received. At exposures above about 2000 rads, there is no effective treatment at the present time for the CNS-syndrome produced. At lower doses which can produce the acute effects of the gastrointestinal radiation syndrome, provision of symptomatic relief and physiological support must take priority over other considerations. If the patient survives this syndrome or does not experience it, then support of the functions and recovery of any hematopoietic injury can be provided. Beyond treating symptoms of these acute radiation syndromes, it should eventually be possible to provide therapeutic measures for enhancement of normal processes for DNA repair, including therapy to prevent expression of delayed effects of DNA lesions such as neoplasms.

A. Treatment of Gastrointestinal Failure.

Reviews of acute radiation syndromes and their supportive treatment are given by Bond *et al.* [70], Prasad [361], Pizzerello [351] and by Pizzerello and Witcofski [352]. As mentioned in Section I, the direct cause of radiation death depends on the dose absorbed. With whole body radiation doses from about 500 to about 5000 rads (above which the CNS syndrome causes more rapid death), gastrointestinal failure is typical. This syndrome is characterized by nausea, vomiting, anorexia, diarrhea, fluid electrolyte imbalance, increased vascular permeability, vascular collapse, and overwhelming infection as the gut wall is breached before destroyed mucosal cells can be regenerated. Spontaneous survival after such massive gastrointestinal injury is improbable.

Therapy for the gastrointestinal radiation syndrome should include:

1. Measures to combat infection (antibiotics, gamma globulin, sterile isolation, etc.);
2. Correction of fluid and electrolyte imbalances; and
3. Administration of other agents to ameliorate acute symptoms and treat tissue damage. Experimental work has identified certain agents which may eventually prove to be therapeutically useful. For example, Palladino *et al.* [339] described protection of chickens and mice from γ -irradiation mortality by use of certain proteolytic enzyme inhibitors. They suggest that the protection

was due to prevention of radiation-induced, protease-mediated increases in vascular permeability.

If the patient survives the gastrointestinal crisis (death can occur within a few days), then the more slowly expressed effects of hemopoietic failure can be treated.

B. Physiological Support during Recovery of Hemopoietic Functions.

Mammalian hemopoietic and lymphatic cells are quite radiosensitive compared to many other cell types. Whole body irradiation above approximately 200 rads (in humans) can severely depress the proliferating stem cell populations of these systems, with fatal results. Death is typically due to loss of the body's ability to combat infection and to blood loss consequences of acute depletion of the leukocyte and platelet populations. For doses below about 500 rads, therapeutic measures can be effective. Established therapeutic methods are designed to replace the impaired functions or cell populations until repopulation by surviving or administered cells can be accomplished. These measures include direct administration of fresh platelets, granulocytes, leukocytes, whole blood, bone marrow, spleen cells, etc. Antibiotics and sterile-tent isolation may be used during the period of increased vulnerability to infection.

These measures to sustain the patient during the bone-marrow recovery period can be supplemented by the administration of other agents which stimulate recovery of the hemopoietic system. Use of these agents, however, has been chiefly experimental. Agents with which some success has been achieved in irradiated animals include the following:

Interferon: Survival of hemopoietic tissue is reported to be enhanced by interferon [282,335] or by substances which can induce interferon synthesis, including sulfhydryl compounds, their phosphorylated derivatives, bacterial endotoxins, vasoactive amines (histamine, serotonin, mexamine), double-stranded RNA, and polysaccharides. With the currently increasing availability of microbiologically produced interferon, adequate evaluation of the utility of this agent in post-radiation therapy should now be feasible.

Tissue extracts: Active thymic polypeptides stimulate lymphocytopoiesis, increase immunological competence, stimulate metabolic recovery processes in thymus and liver of whole-body X-irradiated rats, and provide radio-protection [73,355,450]. In contrast, Czaplicki [111] reported that while embryonal calf thymus extract provided protection to mice if administered

before irradiation, it caused a rapid decrease in leukocyte count and decreased survival time if given after irradiation.

Glutaurine (γ -glutamyl-aurine), identified by Feuer *et al.* [156] as the radioprotective agent in parathyroid extract, partially prevents the radiation-induced decrease in bone marrow mitotic index. When injected as much as 3 hours after exposure, glutaurine supported 30-day survivals of 86%, compared with 50% for controls.

Endotoxin and Endotoxin Polysaccharides: Vigneulle and Baum [467] observed increased 30-day and 40-day survival rates in γ -irradiated mice given endotoxin immediately after exposure. The treatment caused an increase in the pool of myeloid precursor cells, allowing enhanced granulocytopoiesis.

Bacterial endotoxins consist of lipid and polysaccharide moieties, with the major endotoxic effects being due to the lipid. Nowotny *et al.* [322] have demonstrated that either the lipopolysaccharides or their hydrolyzed, non-toxic, polysaccharide-rich components are active inducers of bone marrow colony-stimulating factors in mice. They protect against lethal irradiation, have *in vitro* immune adjuvant activity, and show antineoplastic activity. However, the radiation protection with post-irradiation injection was markedly less than with administration before irradiation [322]. Work by this group (reviewed in [54]) indicated that the protective action is indirect, involving the release of mediators (by the lung and perhaps other tissues as well) into the serum. Thus, each of the four biological effects can be passively transferred by injecting serum from treated into untreated animals. Their work suggests that different fractions of the polysaccharide hydrolysates are responsible for the different biological activities. Injection of bacterial lipopolysaccharides after irradiation but immediately before bone marrow transfusion markedly improved spleen colony formation and erythroid differentiation in mice [426].

Hormones: Akoyev [10] emphasized the importance of the integrative functions of the endocrine system which aid recovery from radiation injury. He presented experimental results of treatment of irradiated animals with preparations from the thyroid gland, gonads, and adrenal cortex. He concluded that his and other data in the literature support the hypothesis that when post-irradiation endocrine deficiency begins to appear, administration of thyroid or adrenal cortical hormones can diminish hemopoietic deficits. Improvement of hemopoiesis, phagocytic capacity, and reaction to infectious

factors after hormonal treatment was demonstrated. Aggravated endocrine deficiency was correlated with increased expression of radiation injury whereas stimulation of endocrine function lessened that expression. Methyl-androstadienolone is reported to stimulate postirradiation structural and metabolic repair in rats [395].

Other Agents: Synthetic lysophospholipid analogs of the naturally occurring 2-lyso-phosphatidylcholine were reported [58] to improve significantly the survival of X-irradiated mice, with the improvement being detectable even when treatment was given 6 hours after irradiation. Effective doses have been found to be without toxicity in clinical pilot studies. Although the mechanism of action is unknown, it is speculated that the central role of phospholipids in cell membrane structure and function, the influence of the analogs on normal DNA metabolism, or the possible interaction of phosphatidylcholine with chemical radicals may be involved.

Glucan, a potent reticuloendothelial stimulant and immune modulator which is isolated from the cell wall of Saccharomyces cerevisiae, enhances hemopoietic recovery in sub-lethally γ -irradiated mice when injected 24 hours postirradiation, although pretreatment is markedly more effective [354]. The protection mechanism is believed to be the stimulation of granulocyte production. Takeda et al. [434,435] and Yonezawa [488] report that single injections of ginseng extract to mice, rats, or guinea pigs within 2.5 hours of irradiation provided protection from bone marrow death. For example, when the injection was within 5 minutes of irradiation, 30-day survival was 76%, compared with 15% for controls.

An improved survival rate is produced by injection of tocopherol immediately after irradiation; no improvement is observed if the injection was postponed until 5 hours after irradiation [392]. Reports showing experimental postirradiation therapeutic effects of a number of other agents have been reviewed [351]. These include imidazole, lipids (intraperitoneal or oral), lycopine, RNA, DNA, and erythropoietin. In each case, a large increase in survival rate for irradiated rats or mice was reported.

In most cases the clinical therapeutic potential of these various experimentally promising agents is yet to be evaluated. The variety of the agents found which can support hemopoietic recovery and the evidence [54] which suggests that the activity of the bacterial polysaccharides is mediated by the release of an endogenous agent encourages further efforts in identifying

such an endogenous agent which could prove to be therapeutically useful.

C. Reinforcement of Normal DNA Repair Processes.

Even if the absorbed radiation dose is low enough to preclude severe hemopoietic and gastrointestinal injury of the types discussed, radiation damage to DNA can produce serious delayed effects. Fortunately, precise and active DNA repair systems exist in cells. The subject of DNA repair has been reviewed [191,272,352] and is discussed in Section III.C.5.

Much investigation (summarized in [341]) has documented repair deficiencies in a number of heritable human disorders which are associated with increased cancer and/or increased sensitivity to radiation. The importance of DNA-repair to the normal organism is also made clear by the review of several human diseases associated with impaired DNA-repair activity by Friedberg et al. [166]. There can now be no doubt that repair processes are crucial to the determination of whether DNA lesions will ultimately be expressed.

At least some of the DNA repair processes are capable of responding to the stimulus of DNA damage with increased activity. The survival of irradiated cells has been shown in a number of cases to depend on postirradiation conditions [109]. Adjustment of these conditions to those which are optimal for repair of potentially lethal cellular damage therefore represents a therapeutic opportunity. Despite long-standing research attention to radioprotection through prevention of DNA injury, some radioprotective agents act in part, at least, through the enhancement of repair processes rather than by the prevention of DNA lesions. Indeed, work with repair-deficient mutant bacteria led Bresler [78] to postulate that repair enhancement is the main mechanism of radioprotectant action.

An experimental system in which repair of radiation-damaged DNA can be specifically studied (in the absence of complications introduced by effects of the radiation on the repair system itself) uses cultured mammalian cells which have been infected by radiation-damaged viral DNA. As reviewed by Defais [113], use of this system as a screening assay should allow identification of new candidate therapeutic agents and evaluation of DNA-repair enhancement by known radioprotectants (see §V.4).

Much of the available information concerning DNA repair and its modulation has been obtained with isolated cell systems. One can hope for, but not assume, clinical therapeutic potential for an agent which enhances repair

when added directly to cell cultures. Even in the experimental systems, the repair-enhancing agent usually must be added very soon after irradiation to be effective - too soon to seem practicable for treatment of most human exposures. Nevertheless, the accumulating evidence that carcinogenic and mutagenic DNA lesions are subject to repair by normal cellular mechanisms [191] is grounds for optimism. The results cited below, demonstrating that DNA repair can be stimulated by chemical intervention, may yield practical results since there are typically very long latent periods which extend between a mutagenic or carcinogenic transformation and its expression. Further work may eventually reveal practical approaches to DNA repair therapy of radiation injury. Specific agents showing experimental post-irradiation effects on DNA repair include:

Thiols: Riklis et al. [385] demonstrated that NR-2721 or mercaptopropionylglycine causes an increase in post-irradiation DNA repair, as represented by labeled thymidine incorporation by cultured hamster cells. Observations led them to conclude that these agents act not only as antioxidants and radical scavengers but also act by affecting repair processes.

Certain cellular repair systems may be thiol dependent. Research by Revesz and co-workers [135,137,383] shows that post-irradiation incubation of cultured GSH-deficient fibroblasts with dithiothreitol or 2-mercapto-propionylglycine supports increased DNA repair. Post-irradiation addition of 1,4-dithiothreitol to leukocyte cultures was reported by Bick and Brown [63] to decrease chromosomal damage in hamster and Potorous cells by 36% and 46% respectively. The most significant effect is in the first 30 minutes after irradiation. In view of the short half-lives of free radicals, the reports of post-irradiation protection (continuing in some cases for hours) by free radical scavengers is surprising and suggests that there may be a delayed, post-irradiation production of free radicals.

Exogenous enzymes: Superoxide dismutase, recognized as being radioprotective through its prevention of superoxide-induced lesions [323], was reported by Simonyan [414] to improve survival of X-irradiated rats when given intraperitoneally thirty minutes after irradiation. Surprisingly, postirradiation administration is more effective than was administration before irradiation.

Singh and Singh [415] suggest that the administration of exogenous repair enzymes, already demonstrated as effective in isolated cell systems,

and use of agents which induce synthesis of endogenous repair enzymes may have potential as therapeutic approaches to radiation injury.

Exogenous enzymes have also been shown to reduce the spontaneous aberrations in cells from Fanconi's and Bloom's syndromes [147], two of the heritable human conditions linked with increased radiation sensitivity and increased DNA damage. These observations led to the suggestion that the defect in the inherited conditions may be a decreased capacity for radical scavenging rather than deficient repair capabilities [147,169]. Presumably, an analogous hypothesis can be invoked as an explanation of the post-irradiation protection by radical scavengers: if irradiation injures the cell's basal radical scavenging capacity, neither a second generation of radiation-induced radicals nor impaired repair mechanisms need be hypothesized.

Other agents: Olontseva [325] attributes the protective effect of purified spleen extract, given one hour after irradiation of mice and hamsters, to the presence in the extract of highly active DNase I inhibitor. Borek [72] reported that selenium and retinoids, added to cell systems after radiogenic or chemically induced neoplastic transformation, suppresses the expression of that transformation.

D. General Principles.

Akoyev [10] reviewed some of the general hypotheses concerning radiation recovery processes (as of 1970) and reported additional experiments undertaken to explore some of the questions raised by these hypotheses. From his review of available information and his own work, Akoyev developed several general principles concerning mammalian recuperation from radiation injury. These include the facts that recovery occurs during, between and following radiation exposures and is proportional to the absorbed dose of radiation that does not inhibit the repair processes themselves. Radiation damage repair is proportional to the metabolic rate of the species and occurs on all levels of biological organization (molecular, cellular, tissue and organ levels). Finally, the rate of repair in various tissues parallels the rate of damage expression (i.e. bone marrow is faster than gastrointestinal tissue which is faster than nerve, muscle, etc.).

E. Summary.

Current treatment strategies for radiation injury can be said to be on a physiological basis. They are relatively effective for treatment of the bone marrow suppression and other symptoms of hemopoietic failure. However,

strategies appear merely symptomatic and supportive for treatment of the gastrointestinal syndrome, and are without effect in treatment of the CNS syndrome. Strategies remain in the realm of basic experimentation for reinforcement of DNA repair processes. The multiplicity of agents which have shown experimental promise for augmentation of bone-marrow recovery and DNA repair suggests that clinical advances in the near term can be expected in these areas.

V. Recommendations for Future Work.

In this section we present recommendations for future studies in the field of chemical radioprotection. We have identified six general areas in which we feel that additional work will lead to profitable advances in our understanding of the mechanisms of action of radioprotective drugs. These six areas are presented, according to our opinion, on a scale of decreasing priority.

1. Pulse Radiolysis.

The pulse radiolysis technique is providing information about the nature of the free radicals formed by ionizing radiation that is essential for the understanding of free radical interactions with cellular constituents. The measurement of radical yields, radical reaction pathways and rates of reactions in defined chemical systems provides data that aid enormously in understanding the biological effects of free radicals. Improvement of radioprotectors will require a biochemical and genetic understanding of these effects in defined systems as well as in more complex biological systems.

2. Protein Thiols and Mixed Disulfides.

A growing body of evidence indicates that protein thiols participate in the regulation of cellular metabolic and genetic processes. Ionizing radiation damage via reduced oxygen species can alter the oxidation reduction state (redox state) of the pyridine nucleotides and the thiol disulfide status. The glutathione redox cycle utilizes NADPH reducing equivalents in the reduction of GSSG back to GSH with glutathione reductase after the reductive transformation of hydrogen peroxide to water by the oxidation of GSH to GSSG which is catalyzed by glutathione peroxidase. The limiting rate in the glutathione redox cycle appears to be the rate of formation of NADPH via the pentose phosphate pathway. Failure to reduce GSSG rapidly results in the formation of protein glutathione mixed disulfides. These and other protein mixed disulfides have an undetermined effect on the rate of metabolism and genetic events including progression through the cell cycle.

Research is needed on several aspects of protein thiols. Improved measurement is needed on the quantity of these protein thiols that can form protein mixed disulfides with low molecular weight thiols and disulfides by thiol disulfide interchange reactions. With such information it would be

logical to determine the rates of thiol disulfide transferase activity with the protein mixed disulfide for the conversion to protein thiols and glutathione mixed disulfides followed by thiol and GSSG formation and the consumption of NADPH reducing equivalents for reduction of GSSG to GSH. It is important to have this information to understand better the radioprotective effects of thiol containing agents. Cells possess a very dynamic energy-dependent process for the maintenance of homeostasis of thiols and disulfides. The perturbation of this homeostasis by the administration of exogenous thiol- or disulfide-containing radioprotectors is likely to alter these protein thiol- or protein mixed disulfide-dependent processes. A key to developing better radioprotective agents may lie in the understanding of the physiological role of this process.

3. Metabolism and Distribution of Radioprotective Compounds.

Studies on the metabolism and distribution of radioprotective agents appear to be quite inadequate. In view of the long history of chemical radioprotection, it is surprising that certain aspects of the basic pharmacology of these compounds have not been investigated. The few studies of metabolism of sulfur-containing radioprotectors which have been attempted appear to be quite unreliable. Many early studies used radioactively labelled compounds which were used to investigate the tissue distribution of the compounds. However, only the presence of radioactivity was determined in most of these studies. Therefore, no information on the biochemical transformations and ultimate fate of the compound can be ascertained by such experiments. Without such information, meaningful structure-activity relationships are impossible to determine (See §VII.A). Furthermore, the development of radioprotectors in cancer therapy has been hampered by unexpected pharmacokinetics of promising drugs, sometimes leading to untoward responses in patients participating in clinical trials [69,174,240]. Therefore, an effort must be directed toward the investigation of the metabolism and tissue distribution of representative radioprotective drugs. Such investigations should focus on the biotransformation of representative drugs with the identification and quantification of metabolites both in vitro and in vivo. Investigations on the extent and kinetics of absorption, distribution, and excretion of the parent drug and its metabolites will assist in judicious clinical use of these drugs and in the development of more advanced radioprotectors.

4. DNA Repair Induction.

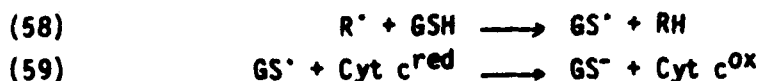
The human body continuously repairs DNA as expressed by excretion in the urine of 1-2 $\mu\text{moles day}^{-1} \text{ person}^{-1}$ of modified bases, principally thymine (Dr. Bruce Ames, personal communication, 1984). Since oxidative stress appears to modulate the level of these products in some instances, such indicators of DNA damage could be valuable indicators of level of DNA repair that may occur with individuals. If DNA repair induction occurs and tolerance to oxidative stress develops then urinary products could be biological markers for such changes.

The virus/cell system described by Defais [113] for studying DNA repair does not appear to have been utilized for screening of potential post-irradiation protectants. It would appear to be well adapted to this purpose. This system, involving irradiation and purification of the viral DNA before its use to infect non-irradiated cultured mammalian cells and observation of the viral-DNA repair by those cells, has a number of advantages for this application. Replicate samples of homogeneously damaged DNA preparations can be administered reproducibly to cells exposed to different agents and conditions. Repair success can be objectively measured by observation of repaired virus activity. Effects on repair of radiolesions, divorced from any effects on their prevention, can be observed. The method should allow convenient preliminary screening of potential therapeutic agents as well as evaluation of the repair component of the action of radioprotectants. Systematic testing by this method of previously identified radioprotectants should add significantly to our understanding of chemical radioprotection.

5. The Effect of Radical Acceptors on the Yield of Glutathione Radiolysis Products.

According to the scheme of Willson et al. [160,484] (see Figure 3, §II.C.1.c), glutathione thyl radicals formed during molecular "repair" of target radicals by hydrogen atom donation react with progressively less noxious radical acceptors to detoxify the sulfur-centered radical. If this hypothesis holds, one should be able to demonstrate, under conditions in which direct oxidation of the ultimate electron donor (e.g., cytochrome c or NADPH) does not take place by the ultimate oxidant ($\cdot\text{OH}$ or $\text{R}\cdot$), that the radiochemical yield of GSO_2H , GSSS and other glutathione radiolysis products

are diminished by the presence of the ultimate electron donor. For example, if the radical reactions



are thought to result in cycling of GSH between reaction 58 (hydrogen atom donation) and reaction 59 (electron transfer), then the yield of other products of the radiolysis of glutathione



should be reduced in the presence of reduced cytochrome c compared to the yield of these oxidation products in its absence. This experiment could be repeated at whatever levels of biological relevance the hydrogen donation reaction had been shown to occur (i.e. purified systems, DNA, whole cells, etc.).

6. Toxicity of Thiol Radioprotectors.

A large proportion of radioprotectors contain a thiol group or a potential thiol group. This class of compounds contains many of the most effective radioprotectors. As with many drugs, the utility of thiol radioprotectors is limited by their toxicity. The prototypic thiol radioprotector, cysteamine, cannot be used clinically because of this toxicity. However, few studies of the toxic effects of thiol compounds have been done which quantify these toxic effects. Little is known about the relationship, if any, between the toxic effects of thiol and their radioprotective activity. The mechanism of toxicity has recently been investigated for the thiol-containing amino acid cysteine [468,469]. These studies have recently implicated cysteine oxidation, with concomittant production of hydrogen peroxide, in the mechanism of cysteine toxicity [470]. Cysteine has been shown to be mutagenic in the Salmonella reversion assay [173], presumably by similar mechanisms. If the radioprotective efficacy of thiol compounds results from their consumption of oxygen during their oxidation, the toxicity of these compounds may be an extension of their therapeutic effect. On the other hand, should other mechanisms be implicated in the therapeutic limitations of these drugs, such as the ulcerogenic [85] and adrenocortical necrotic [293] actions of cysteamine or the hypocalcemic effects of MR-2721 [174], one may be able to

dissociate the radioprotective from the toxic effects of the drugs. A similar separation of the toxic from the radiosensitizing effects of congeners of misonidazole [3] has recently begun to yield some promising results [103]. An understanding of the factors contributing to the toxicity of thiol radioprotectors may yield similar benefits in the therapeutic indices of these drugs.

VI. Chemical Radioprotection: Research In Progress.

A. Major Topics and Current Principal Investigators.

Introduction. Because radioresistance and radiosensitivity are reciprocal variables, research directed toward one of these topics is also related to the other. Much current research, for example, is aimed at chemically increasing radiosensitivity of tumor cells. Since modification of radiosensitivity is equally a modification of radioresistance, research projects concerning radiosensitization were not uniformly excluded from this compilation: if results of such a research project might be expected to also provide information concerning radioresistance, it was included here. However, many radiosensitivity projects which were judged to have only marginal relevance to radioprotection (such as clinical trials of radiosensitizers or investigation of radiosensitizer toxicity and pharmacology) were omitted.

In this section, projects related to eight topics are referenced by the principal investigator's surname. Further information concerning specific projects can be found in Section B.

1. Radiation Damage: Basic Nature and Mechanisms.

Investigators: Adelstein, Bedford, Bernhard, Burns, Cole, Cress, Curtis, Denman, Dewey, Epp, Ewing, Fanburg, Geard, Gillette, Gregg, Griffiths, Griggs, Henner, Jose, Katz, Keng, Koval, Kubitschek, Lawrence, Leeper, Lett, Matney, Oleinick, Powers, Ramey, Remsen, Rich, Rodgers, Rosenberg, Roti Roti, Schneiderman, Setlow, Sinclair, Sowby, Smith, Stuart, R Sutherland, R Sutherland, Taylor, Tobias, Wallace, Wheeler, Withers, Zimbrick.

2A. Radiation Resistance/Sensitivity: Basic Nature and Mechanisms.

Investigators: Bedford, Biaglow, Ducoff, Gregg, Koval, Paterson.

2B. Radiation Resistance/Sensitivity: Temperature Effect.

Investigators: Bowden, Coleman, Cress, Denman, Dewey, Geard, Berner, Hahn, Hall, Hofer, Kim, Leeper, Lett, Plenk, Schneiderman, Song.

2C. Radiation Resistance/Sensitivity: Oxygen Effect.

Investigators: Agrawal, Biaglow, Epp, Geard, Gupta, Hofer, Kim, Ling, Meistrich, Moulder, Mulcahy, Plenk, Remsen, Rich, Song, Suit, Tobias.

2D. Radiation Resistance/Sensitivity: Other Chemical Modulation.

Investigators: Agrawal, Arthur D Little, Inc., Bardos, Barkley, Biaglow, Brown, Chil Hosp Philadelphia, Ciborowski, Cole, Coleman, Epp, Ewing, Fanburg, Fu, Geard, Gillette, Gregg, Hagan, Hall, Henner, Hickman, Hofer, Infante, Jordan, Kligerman, Krohn, Leeper, Megaw, Meistrich, Mitchell, Moulder, Mulcahy, No Calif Cancer Prog, Parthasarathy, Phillips, Powers, Ramey, Research Triangle Inst., Rich, Richmond, Rosenthal, Sanders, Savarese, Schneiderman, Sodicoff, Song, Sridhar, Stuart, Suit, R Sutherland, Urtasun, Utley, Yuhas, Zimbrick.

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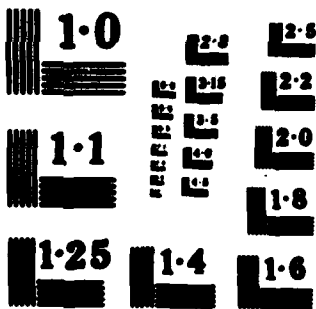
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3A. Radiation Repair/Recovery Processes: Basic Nature and Mechanisms.

Investigators: Brent, Burns, Cress, Denman, Ducoff, Evans, Fluke, Griffiths, Griggs, Hadden, Hanawalt, Henner, Howard-Flanders, Humphrey, Keng, Koval, Lawrence, Lett, Meyn, Oleinick, Paterson, Prakash, Ramey, Ramsen, Rich, Rupert, Setlow, Smith, B Sutherland, Taylor, Wallace, Wheeler.

3B. Radiation Repair/Recovery Processes: Chemical Modulation.

Investigators: Adler, Alving, Bardos, Brent, Gillette, Ling, Mulcahy, Remson, Setlow, Smith, R Sutherland.

4: Research on Methodology For Use In Radioprotection Studies.

Investigators: Brent, Ciborowski, Jordan, Lange, Matney, Megaw, Moss, Paterson, Wallace, Weinreb, Zimbrick.

B. Research Projects in Areas Relevant to Chemical Radioprotection.

Introduction: Listed on the following pages are some specific current or recent research projects relevant to chemical radioprotection funded by U.S. Government Agencies. It is emphasized that for some projects, the radioprotection component may represent only a secondary objective of the research. Entries given, when available, for each project are as follows:

PI/ORG: This entry identifies the principal investigator and organization with which the project is associated.

TITLE: This entry gives the title of the project.

SUMMARY: This entry gives brief characterization of that portion of the research project related to chemical radioprotection, to the extent that such information was available to us. In most cases, these entries consist of relevant selections and summaries from larger abstracts provided by the researchers or other sources.

SPONSOR: This entry indicates the source of funding for the research.

TOPICS: These codes refer to the eight major topics listed in section A.

SOURCES: The Sponsor names are followed by letters indicating the source of our information concerning the project. These sources are as follows:

A. CRISP (the U.S. Public Health Service's "Computer Retrieval of Information on Scientific Projects" file), a computer-based information system concerning all USPHS-supported grants and contracts and intramural research at the National Institutes of Health. We are grateful to Louis J. Parkhurst, Technical Information Specialist, for the search of CRISP on the topics "radioprotective agents" and "radiosensitizers", performed 2/23/84.

B. Federal Research in Progress (Unabridged) data base of Dialog Information Services, search performed 20 Feb, 1984.

C. RECON RIP data base of the Department of Energy. We are grateful to Axel Ringe, Science and Technology Division, DOE, for providing us with a search of this data base performed in February, 1984.

D. Commerce Business Daily (Dialog Data Base) - search performed Feb 22, 1984. The four contracts retrieved from this data base were listed in CBD as being in the process of negotiation. It is assumed that negotiations were successfully completed but no additional information is available for them. Therefore, they are listed separately here rather than in the main body of the following compilation.

CONTRACTS LISTED AS UNDER NEGOTIATION

PI/ORG: Arthur D Little, Inc., Cambridge, MA
TITLE: In vivo screening of radioprotectors.
SPONSOR: U.S. Army Med Res Dvlt Command, Fort Detrick, MD/D TOPICS: 2D

PI/ORG: Children's Hosp, Philadelphia, PA
TITLE: Development of central nervous system radioprotectors
SPONSOR: U.S. Army Med Res Dvlt Command, Fort Detrick, MD /D TOPICS: 2D

PI/ORG: Northern Calif Cancer Program, Palo Alto CA
TITLE: Screening of radiosensitizers and radioprotectors.
SPONSOR: Natl Cancer Inst, NIH /D TOPICS: 2D

PI/ORG: Research Triangle Inst., Research Triangle Park, NC
TITLE: Development of new prophylactic radioprotective agents.
SPONSOR: U.S. Army Med Res Dvlt Command, Fort Detrick, MD /D TOPICS: 2D

PI/ORG: Adelstein, S James; Shields Warren Rad Lab, Harvard Univ, Boston MA
TITLE: Macromolecular radiation effects.
SUMMARY: Radiochemical alterations of amino acids, protein, and DNA in cultured hamster lung fibroblasts are studied.
SPONSOR: Natl Inst Arth, Diab, Digest and Kidney Dis /B TOPICS: 1

PI/ORG: Adler, HI; Oak Ridge National Laboratory, Oak Ridge TN
TITLE: Microbial mutagenesis and cell division.
SUMMARY: One objective is to explain the previously observed promotion by membrane preparations of recovery of irradiated bacteria.
SPONSOR: Dept Energy /C TOPICS: 3B

PI/ORG: Agrawal, Krishna C; Tulane Univ. Sch. Med., New Orleans, LA
TITLE: Development of antitumor and radiosensitizing agents.
SUMMARY: An objective is to develop and test a radiosensitizer for hypoxic tumor cells. Nitroimidazole analogs are synthesized and tested in vivo and in vitro.
SPONSOR: Natl Cancer Institute /A TOPICS: 2C,2D

PI/ORG: Bardos, Thomas J; SUNY at Buffalo, Amherst NY
TITLE: Chemical and biological studies in cancer chemotherapy.
SUMMARY: Objectives include determination of structure-activity relationships for radiosensitizing agents, design of new agents, and study of interaction of selected agents with nucleic acids and with DNA-repair processes.
SPONSOR: Natl Cancer Inst, NIH /A TOPICS: 2D,3B

PI/ORG: Barkley, Howard T; Univ of Texas, Houston TX
TITLE: Radioprotective effects of prostaglandin inhibitors.
SUMMARY: This is a sub-project of a larger research program grant.
SPONSOR: Natl Cancer Inst, NIH /A TOPICS: 2D

PI/ORG: Bedford, Joel S; Radiology, Colorado State Univ, Fort Collins CO
TITLE: Dose and time factors in cellular radiosensitivity.
SUMMARY: The objectives are a better understanding of the nature of lethal lesions in irradiated cells and of the interrelationships of factors influencing radiosensitivity. Dose-rate and dose-fractionation effects are emphasized.
SPONSOR: Natl Cancer Inst, NIH /B TOPICS: 1,2A

PI/ORG: Bernhard, William A; Dept Radiation, Univ Rochester, Rochester NY
TITLE: Effects of ionizing radiation on nucleic acids.
SUMMARY: The objective is to determine the chemical mechanisms by which ionizing radiation causes alterations in the primary structure of DNA, initially by developing a set of rules for prediction of DNA/free radical events.
SPONSOR: Natl Cancer Inst, NIH /B TOPICS: 1

PI/ORG: Biaglow, John E.; Case Western Reserve Univ., Cleveland OH
TITLE: Modification of X-ray response of anoxic-hypoxic cells.
SUMMARY: The nature of radiosensitization by mitogenic hormones of hypoxic tumor cells is studied. The effect of cellular thiols on radiosensitization by insulin and effects of drugs which influence endogenous non-protein thiols are investigated. Agents studied include epidermal growth factor, phorbol esters, rotenone, antimycin A, metronidazole, and misonidazole.
SPONSOR: Natl Cancer Inst, NIH /A TOPICS: 2A,2C,2D

PI/ORG: Bowden, George T; Univ Arizona, Rad'n Oncology Div, Tucson AZ
TITLE: Interaction of hyperthermia with radiation and drugs.
SUMMARY: (see summary under Eugene Gerner).
SPONSOR: Natl Cancer Inst, NIH /A TOPICS: 2B

PI/ORG: Brent, Thomas P; St Jude Children's Research Hosp, Memphis TN
TITLE: Enzymes and reactions for repair of DNA in human cells.
SUMMARY: Objectives include identification and characterization of enzymes and reactions involved in excision-repair of DNA in human cells exposed to radiation or alkylating agents (using purified repair enzymes) and screening of cell extracts from individuals with "DNA repair syndromes" for repair enzyme deficiency.
SPONSOR: Natl Cancer Inst, NIH /B TOPICS: 3A,3B,4

PI/ORG: Brown, John M.; Stanford Univ., Stanford CA
TITLE: Experimental radiotherapy - Basis and modification.
SUMMARY: Two of the topics of this project are (a) the influence of common chemotherapeutic agents on radiation resistance of normal spinal cord, lung, and kidney tissue; and (b) the testing and enhancement of tumor cell radiosensitization by electron-affinic agents. The agents studied include BCNU, misonidazole, actinomycin D, adriamycin, bleomycin, cyclophosphamide, and cis-platinum.
SPONSOR: Natl Cancer Inst, NIH /A TOPICS: 2D

PI/ORG: Burns, FJ; NY Univ Med Ctr, Tuxedo NY
TITLE: Oncogenic action of proton and electron radiation on rat skin.
SUMMARY: Single and double strand DNA breaks are studied using single and multiple radiation doses with special reference to repair of oncogenic damage

and to a track theory of radiation damage.
SPONSOR: Dept Energy /C

TOPICS: 1,3A

PI/ORG: Ciborowski, Linda J; Massachusetts General Hospital, Boston MA
TITLE: Micronucleus screening of DDC and other radioprotectors.
SUMMARY: An in vitro assay based on observation of micronuclei formation is evaluated for quantifying radiation damage and for use as a screening assay for radioprotective effectiveness.
SPONSOR: Natl Cancer Institute /A

TOPICS: 2D,4

PI/ORG: Cole, A; Dept of Physics, Univ Texas System Cancer Ctr, Houston TX
TITLE: Radiation and biophysical studies on cells and viruses.
SUMMARY: Continuing objectives are to define the initial lesions induced by radiation and subsequent events leading to cellular responses, using cultured, synchronized mammalian cells, low and high LET radiations, and various drugs.
SPONSOR: Dept Energy /C

TOPICS: 1,2D

PI/ORG: Coleman, C Norman; Stanford Univ Sch Med, Stanford CA
TITLE: Stanford University participation in the NCOG.
SUMMARY: Stanford is a participant in the Northern California Oncology Group, whose major purpose is to design and conduct clinical trials, including trials involving radiosensitizers, radioprotectors, and hyperthermia.
SPONSOR: Natl Cancer Inst, NIH /A

TOPICS: 2B,2D

PI/ORG: Cress, Anne E; Radiation Oncology, Univ Arizona, Tucson AZ
TITLE: DNA protein crosslinks after hyperthermia and radiation.
SUMMARY: The molecular and cellular nature of the DNA protein crosslinks generated by hyperthermia and radiation are investigated, with testing of their relationship to lethality, replication, and repair.
TOPICS: Natl Cancer Inst, NIH /B

TOPICS: 1,2B,3A

PI/ORG: Curtis, Stanley B.; Univ Calif., Lawrence Berkeley Lab., Berkeley CA
TITLE: Response of rat tumor cells to heavy ions.
SUMMARY: The research measures responses of cellular processes to high- and low-LET radiation.
SPONSOR: Natl Cancer Inst, NIH /A

TOPICS: 1

PI/ORG: Denman, David L; Univ Cincinnati Hosp, Cincinnati OH
TITLE: Chromosomal damage induced by hyperthermia and radiation.
SUMMARY: Studies of molecular mechanism of killing of cultured hamster ovary cells by radiation and heat, including the roles of repair and cell cycle stage are carried out.
SPONSOR: Natl Cancer Inst, NIH /B

TOPICS: 1,2B,3A

PI/ORG: Dewey, William C.; Univ of Calif. San Francisco CA,
Colorado State Univ, Fort Collins CO
TITLE: Molecular basis of radiosensitization by hyperthermia.
SUMMARY: The research is to determine which heat-induced lesions are lethal in themselves and which radiosensitize by interaction with X-ray-induced lesions. Effects of heat on the number of radiation-induced single-strand DNA breaks are determined.
SPONSOR: Natl Cancer Inst, NIH; US Dept Agriculture /A,B

TOPICS: 1,2B

PI/ORG: Ducoff, Howard S; Univ Illinois, Urbana IL
TITLE: X-rays increase insect longevity - Possible mechanism.
SUMMARY: The objective is to test a model explaining the increase in longevity of irradiated insects. The model hypothesizes that radiation damage to DNA induces higher levels of DNA-repair enzymes.
SPONSOR: Natl Inst of Aging, NIH /B TOPICS: 2A,3A

PI/ORG: Epp, Edward R.; Massachusetts General Hospital, Boston MA
TITLE: Radiation sensitization applied to cancer radiobiology.
SUMMARY: Effects and mechanisms of radiation damage and of chemical radiosensitizers, including oxygen and its interaction with other sensitizers, are studied in mammalian cells. Certain "shoulder-modifying" compounds and compounds believed to alter indirect damage to RNA are also studied.
SPONSOR: Natl Cancer Inst, NIH /A TOPICS: 1,2C,2D

PI/ORG: Evans, HH; Dept Radiology, Case Western Reserve Univ, Cleveland OH
TITLE: Carcinogenesis in mammalian cells.
SUMMARY: The objective is to determine the role of DNA repair in mutagenesis and carcinogenesis. Reactions to radiation of repair-proficient and repair-deficient cells are compared.
SPONSOR: Dept Energy /C TOPICS: 3A

PI/ORG: Ewing, David; Hahnemann Univ School of Med, Philadelphia PA
TITLE: Lethal damage from O₂ and OH in irradiated cells.
SUMMARY: Earlier conclusions regarding hydroxyl radicals and their relationship to oxygen in lethal radiation damage are reevaluated. The conclusion that oxygen sensitizes by reacting at cellular sites formed by OH attack is tested.
SPONSOR: Natl Cancer Inst, NIH /A,B TOPICS: 1,2D

PI/ORG: Fanburg, Barry L; New England Med Ctr Hosp, Boston MA
TITLE: Radiation injury to pulmonary endothelium.
SUMMARY: Radiation damage to cultured lung endothelial cells is characterized and biochemical mechanisms of damage and protection are studied, using radioprotectants and radiosensitizers.
SPONSOR: Natl Heart, Lung, and Blood Inst, NIH /B TOPICS: 1,2D

PI/ORG: Fu, Karen K; Univ of Calif., San Francisco CA
TITLE: Chemical modification of low dose rate irradiation.
SUMMARY: An objective of the research is to obtain quantitative information on modification of low-dose irradiation effects by radiosensitizers and radioprotectors in normal and tumor tissue in vitro.
SPONSOR: Natl Cancer Inst, NIH /A TOPICS: 2D

PI/ORG: Geard, Charles R; Columbia Univ, New York NY
TITLE: Radiation cytogenetics.
SUMMARY: The overall research objective is the study of effects of low-dose ionizing radiation on mammalian cells and the biophysical interpretation of these effects. Studies of modification by environmental factors, including oxygen and temperature, of dose response relationships are included.
SPONSOR: Natl Cancer Inst, NIH /A TOPICS: 1,2D,2C,2B

PI/ORG: Gerner, Eugene W.; Univ of Arizona, Rad Oncology Div., Tuscon AZ
TITLE: Biochemical and cellular aspects of hyperthermia damage.
SUMMARY: The primary objective of the program of which this is a sub-contract is to determine efficacy in cancer therapy of hyperthermia, used alone and with radiation or chemotherapy. Molecular, physical, engineering, and clinical aspects of the problem are studied.
SPONSOR: Natl Cancer Inst, NIH /A TOPICS: 2B

PI/ORG: Gillette, Edward L; Colorado State Univ, Fort Collins CO
TITLE: Radiation repair of normal mammalian tissues.
SUMMARY: Quantitative responses of microvascular and other normal tissues to radiation, with or without other agents, are evaluated with specific attention given to the relative biological effectiveness of high-LET radiations and to loss of repair capability after high- or low-LET irradiation combined with other agents, including the radioprotector WR-2721.
SPONSOR: Natl Cancer Inst, NIH /A,B TOPICS: 1,2D,3B

PI/ORG: Gregg, Earle C; Case Western Reserve Univ, Cleveland OH
TITLE: Mutants and altered radioresponse of cells and tumors.
SUMMARY: Objectives include (1) determination of effects of very small doses and dose rates of both drugs and ionizing radiation and (2) identification of biochemical, biophysical, and cytological differences between established radioresistant mutant cell lines and their parental source.
SPONSOR: Natl Cancer Inst, NIH /B TOPICS: 1,2A,2D

PI/ORG: Griffiths, T Daniel; Northern Illinois Univ, DeKalb IL
TITLE: DNA replication after insult with UV.
SUMMARY: The time course of UV effects on DNA synthesis and of recovery from these effects, and molecular events responsible for the effects and recovery from them are studied.
SPONSOR: Natl Cancer Inst, NIH /B TOPICS: 1,3A

PI/ORG: Griggs, Henry G; John Brown Univ Biology Dept, Siloam Springs, AR
TITLE: Ultraviolet and ionizing radiation damage.
SUMMARY: Radiation-induced intracellular processes, chromosomal lethal lesions, and cell repair processes in synchronous cell cultures are examined.
SPONSOR: Natl Cancer Inst, NIH /B TOPICS: 1,3A

PI/ORG: Gupta, Vicram; Univ Texas Med Branch, Galveston TX
TITLE: Effect of physiological oxygen levels on tumor therapy.
SUMMARY: The effect in cultured tumor cells of physiological vs. 20% oxygen concentrations are studied in the hope that the results will aid interpretation of cytotoxicity data from drug and radiation exposures.
SPONSOR: Natl Cancer Inst, NIH /B TOPICS: 2C

PI/ORG: Hadden, CT; Univ Tennessee, Oak Ridge TN
TITLE: Repair and cell cycle response in cells exposed to environmental biohazards.
SUMMARY: Removal in bacteria of light-induced pyrimidine dimers as controlled by UVR genes is studied. UVR induced proteins and their properties are studied to clarify repair processes.
SPONSOR: Dept Energy /C TOPICS: 3A

PI/ORG: Hahn, George M; Stanford Univ School of Medicine, Stanford CA
TITLE: Modification of radiation response in vitro.

SUMMARY: Objectives include the development of information on how hyperthermia kills cells, on cell thermotolerance, and on the effects of thermotolerance on X-ray sensitivity in vitro and in vivo.

SPONSOR: Natl Cancer Inst, NIH /A,B

TOPICS: 2B

PI/ORG: Hall, Eric J.; Columbia Univ, New York, NY

TITLE: Radiobiological studies related to high LET radiotherapy.

SUMMARY: Purposes of the research include: study of the mechanism of action of radiosensitizing electron affinic compounds, including several newly synthesized ones; study of interactions with naturally occurring polyamines of several chemotherapeutic agents; and interaction of these agents with hyperthermia and with the electron affinic sensitizers.

SPONSOR: Natl Cancer Inst, NIH /A

TOPICS:2B,2D

PI/ORG: Hanawalt, PC; Herrin Biol Labs, Stanford Univ, Stanford CA

TITLE: DNA repair mechanisms in living cells exposed to ultraviolet light or environmental by-products of energy conversion.

SUMMARY: Bacteria are used for analysis of post-irradiation recovery processes.

SPONSOR: Dept Energy, NIH /A,C

TOPICS: 3A

PI/ORG: Henner, William D; Dana-Farber Cancer Inst., Boston MA

TITLE: Mechanisms of radiation carcinogenesis.

SUMMARY: The chemistry and enzymology of X-ray-induced DNA damage and of DNA repair in human cells are studied. Location and extent of strand breaks and the effects of oxygen and free radical scavengers are determined, as well as rates and extent of post-radiation repair.

SPONSOR: Natl Cancer Inst, NIH /A

TOPICS: 1,2D,3A

PI/ORG: Hofer, Kurt G; Florida State Univ., Tallahassee FL

TITLE: Tumor cell hypoxia as a factor in cancer therapy.

SUMMARY: Studies are made of the significance of the oxygen effect to radiotherapy; means of modification of the radioresistance of hypoxic cells including simultaneous application of radiation and hyperthermia or radiosensitizing agents; enhancement of by tumor cell pH reduction of hyperthermic radiosensitization; and the mechanism (damage enhancement vs repair inhibition) of synergistic radiosensitization.

SPONSOR: Natl Cancer Inst, NIH /A

TOPICS: 2B,2C,2D

PI/ORG: Howard-Flanders, Paul; Yale Univ, New Haven CT

TITLE: Crosslinking of nucleoproteins by radiation.

SUMMARY: The enzymatic mechanisms of post-replication repair and genetic recombination in *E. coli* are investigated.

SPONSOR: Natl Inst of General Med Sciences, NIH /B

TOPICS: 3A

PI/ORG: Humphrey, Ronald M; Univ of Texas System Cancer Center, Houston TX

TITLE: DNA repair and recovery in the mammalian cell cycle.

SUMMARY: Objectives include determination of the biochemical basis of cell cycle dependent variations in response to radiation and chemical agents; definition of the relationship of certain DNA repair processes to mammalian cell survival and mutagenesis; and isolation of mutagen-sensitive variant cell lines that could be used to investigate the molecular basis of DNA repair.

TOPICS: Natl Cancer Inst, NIH /B

TOPICS: 3A

PI/ORG: Gabriel A Infante; Catholic Univ of Puerto Rico, Ponce PR
TITLE: Radiation chemistry of biologically important compounds.
SUMMARY: One of the subprojects continues studies of radiosensitization.
SPONSOR: Div of Research Resources /A TOPICS: 2D

PI/ORG: Jose, Jule G; Sch Optometry, Univ Calif, Berkeley CA
TITLE: Aging and radiation effects on ocular metabolism.
SUMMARY: Alterations in UV-induced DNA, RNA, protein, mucopolysaccharide, and proteoglycan metabolism in lens, cornea, and conjunctiva of young and old rats are examined.
SPONSOR: Natl Eye Institute, NIH /B TOPICS: 1

PI/ORG: Jordan, Scott W; Univ of New Mexico, Albuquerque NM
TITLE: Computer-based analysis of renal radiation response.
SUMMARY: Studies include evaluation of computer-assisted morphometric analysis for demonstration of tissue radiation response and of effects of radiation sensitizing or protective agents.
SPONSOR: Natl Cancer Inst, NIH /A TOPICS: 2D,4

PI/ORG: Katz, R; Dept Physics, Univ Nebraska, Lincoln NE
TITLE: Theory of RBE.
SUMMARY: A model of track structure and relative biological effectiveness is being used in an attempt to understand biological effects of low dose ionizing radiation.
SPONSOR: Dept of Energy /C TOPICS: 1

PI/ORG: Keng, Peter C; Univ Rochester, Rochester NY
TITLE: Phase specific DNA repair in irradiated tumor cells.
SUMMARY: The objective is to investigate DNA damage and repair of irradiated synchronized tumor cells at different phases of the cell cycle to determine whether relative rate or extent of repair is responsible for variations in cell survival during the different phases.
SPONSOR: Natl Cancer Inst, NIH /B TOPICS:1,3A

PI/ORG: Kligerman, Morton M; Univ Pennsylvania, Philadelphia PA
TITLE: Clinical radiation and drug protection with WR-2721.
SUMMARY: Dosage and effectiveness of the radioprotector, WR-2721, in patients undergoing radiotherapy are tested, alone and in combination with cis-platinum and cyclophosphamide. Some pharmacologic studies with radiolabelled drug are included.
SPONSOR: Natl Cancer Inst, NIH /A TOPICS: 2D

PI/ORG: Kim, Jae H; Sloan Kettering Institute, New York NY
TITLE: Cellular response to heat and radiation.
SUMMARY: Interactive effects of glucose concentration, ambient oxygen concentration, and temperature on survival of HeLa cells are studied.
SPONSOR: Natl Cancer Inst, NIH /B TOPICS: 2B,2C

PI/ORG: Koval, Thomas M; George Washington Univ Sch Med, Washington DC
TITLE: Insect cells - A basis for radioresistance.
SUMMARY: The objective is to determine the basis of the extreme radioresistance of cultured TN-238 insect cells. Several aspects of radioresponse, repair, and recovery of the cells are studied.
SPONSOR: Natl Cancer Inst, NIH /B TOPICS:1,2A,3A

PI/ORG: Krohn, Kenneth A; Univ of Washington, Seattle WA
 TITLE: Radioprotective drugs - Mechanism and biological studies.
 SPONSOR: Natl Cancer Inst, NIH /A TOPICS: 2D

PI/ORG: Kubitschek, HE; Argonne Natl Lab, Argonne IL
 TITLE: Molecular, genetic, and cellular mechanisms of environmental and solar-UV mutagens.
 SUMMARY: The nature of DNA lesions produced by environmental and energy-related mutagens is studied using bacteria. Effects of ultraviolet light are emphasized.
 SPONSOR: Dept of Energy /C TOPICS: 1

PI/ORG: Lange, CS; Downstate Med Ctr, State Univ of NY, Brooklyn NY
 TITLE: Biological effects of ionizing radiation at the molecular, cellular, and organismal levels.
 SUMMARY: Studies of DNA breakage and repair depend on DNA size measurements. This project attempts to develop accurate methods for these measurements.
 SPONSOR: Dept of Energy /C TOPICS: 4

PI/ORG: Lawrence, CW; Dept Rad Biol and Biophys, Univ Rochester, Rochester NY
 TITLE: Molecular biology of radiation mutagenesis.
 SUMMARY: Among the objectives is the study of the effects of new mutations in Saccharomyces cerevisiae on DNA repair.
 SPONSOR: Dept of Energy /C TOPICS: 1,3A

PI/ORG: Leeper, Dennis B; Thomas Jefferson Univ, Philadelphia PA
 TITLE: Interaction of hyperthermia, radiation and drugs in vitro.
 SUMMARY: Cell response to hyperthermia and to drug/radiation combinations are studied, as well as studies of physics and dosimetry of high energy protons, electrons and neutrons.
 SPONSOR: Natl Cancer Inst, NIH /A TOPICS: 1,2B,2D

PI/ORG: Lett, John T; Biochem & Rad, Colorado State Univ, Fort Collins CO
 TITLE: Repair of radiation damage to cellular DNA.
 SUMMARY: Studies in hamster ovary cells of repair of X-ray induced DNA strand breaks as a function of cycle position and temperature and of responses of individual chromosomes are being carried out.
 SPONSOR: Natl Cancer Inst, NIH /B TOPICS: 1,2B,3A

PI/ORG: Ling, C Clifton; George Washington Univ, Washington DC
 TITLE: Oxygen radiosensitization at different dose rates.
 SUMMARY: The oxygen effect as a function of dose rate and of oxygen concentration is systematically studied. Measurements of split-dose recovery kinetics of mammalian cells at low oxygen concentrations are included.
 SPONSOR: Natl Cancer Inst, NIH /B TOPICS: 2C,3B

PI/ORG: Matney, TS; Univ of Texas Health Science Ctr, Houston TX
 TITLE: The effect of radiation-sensitive mutations and mutagens/carcinogens on bacterial recombination and mutagenesis.
 SUMMARY: The project deals with development of bacterial systems which quantify different types of radiation- and chemical-induced genetic recombination and mutation.
 SPONSOR: Dept of Energy /C TOPICS: 1,4

PI/ORG: Megaw, Judith M; Emory Univ, Atlanta GA
 TITLE: Liposomal intraocular drug delivery in vitro and in vivo.
 SUMMARY: Delivery of liposome-bound specific agents to intraocular tissues, including delivery of free-radical scavengers to protect the lens from development of radiation-induced cataracts, are investigated.
 SPONSOR: Natl Eye Institute /A TOPICS: 2D,4

PI/ORG: Meistrich, Marvin L; Univ. Texas System Cancer Ctr, Houston TX
 TITLE: Mutagenic action of cancer therapy on testis cells.
 SUMMARY: This project concerning the sterilizing and mutagenic action of drugs and radiation on male germ cells includes studies of factors influencing cell sensitivity; investigation of methods of protection against sterilizing effects; and testing of radioprotectors.
 SPONSOR: Natl Cancer Inst, NIH /A TOPICS: 2C,2D

PI/ORG: Meyn, Raymond E; Univ of Texas System Cancer Ctr, Houston TX
 TITLE: Repair of radiation damage in vitro and in vivo.
 SUMMARY: The objective is detailed understanding of mammalian cell DNA repair mechanisms for radiation damage.
 SPONSOR: Natl Cancer Inst, NIH /B TOPICS: 3A

PI/ORG: Mitchell, J B; Natl Cancer Inst, NIH, Bethesda MD
 TITLE: Response of human hematopoietic precursor cells to halogenated pyrimidines.
 SUMMARY: Data relevant to whether the radiosensitizing halopyrimidines act by being actually incorporated into cellular DNA to make the DNA less stable to radiation are experimentally obtained.
 SPONSOR: Div of Cancer Treatment, NIH /A TOPICS: 2D

PI/ORG: Moss, Alfred J; Veterans Administration Med Ctr, Little Rock AR
 TITLE: Post-irradiation repair of DNA by mammalian cells.
 SUMMARY: A sensitive oxygen assay for direct determination of oxygen concentration in suspensions of irradiated cells is being developed for use in studies evaluating DNA damage and repair.
 SPONSOR: Veterans Administration /B TOPICS: 4

PI/ORG: Boulder, John E.; Medical College of Wisconsin, Milwaukee WI
 TITLE: Optimization of radiosensitizer use in radiotherapy.
 SUMMARY: Effects of hypoxia, the radiosensitizer misonidazole, and radiation are studied and distinguished in neoplastic and normal rat tissues.
 SPONSOR: Natl Cancer Inst, NIH /A TOPICS: 2C,2D

PI/ORG: Mulcahy, R Timothy; Univ of Rochester, Rochester NY
 TITLE: Radiation sensitizers - Interactions with other modalities.
 SUMMARY: The research tests the hypothesis that repair inhibition by carbamoylation is correlated with radiosensitizer enhancement of effects of nitrosourea chemotherapeutic agents. Chemical structure (carbamoylating and alkylating properties), cellular environment (e.g., oxygen concentration), and cell proliferative status are among the variables studied.
 SPONSOR: Natl Cancer Inst, NIH /A TOPICS: 2C,2D,3B

PI/ORG: Oleinick, Nancy L; Case Western Reserve Univ, Cleveland OH
 TITLE: Radiation-induced modification in protein synthesis.
 SUMMARY: Radiation-induced DNA damage and repair are compared in active DNAs

of proliferating cells and less active DNAs of plateau-phase cells.
 SPONSOR: Natl Cancer Inst, NIH /B TOPICS: 1,3A

PI/ORG: Paterson, Malcolm C; Chalk River Nuclear Labs, Chalk River, Canada
 TITLE: Radiosensitivity and DNA repair in cancer risk.
 SUMMARY: Radiosensitivity and DNA repair in skin fibroblasts from patients known to be at high risk of cancer are evaluated.
 SPONSOR: Div Cancer Cause and Prevention /B TOPICS: 2A,3A,4

PI/ORG: Parthasarathy, Rengachary; Roswell Park Mem Inst, Buffalo NY
 TITLE: Stereochemistry of thiol-disulfide interchanges.
 SUMMARY: The role of thiol-disulfide interchanges in radiation protection and carcinogenesis are studied, using X-ray diffraction techniques to study crystal structures of thiols and related compounds and complexes. Results will be useful in designing radioprotective agents.
 SPONSOR: Natl Cancer Inst, NIH /A TOPICS: 2D

PI/ORG: Phillips, Theodore L; Univ Calif. Medical Center, San Francisco CA
 TITLE: Evaluation of radiosensitizers and radioprotectors for cancer therapy.
 SUMMARY: This is a sub-project of the general clinical research center grant.
 SPONSOR: Div Research Resources, NIH /A TOPICS: 2D

PI/ORG: Plenk, Henry P.; LDS Hospital, Salt Lake City UT
 TITLE: Radiation therapy oncology group.
 SUMMARY: Activities which this cooperative clinical research project helps support include pioneering programs in use of increased oxygen tension and of hyperthermia with radiotherapy.
 SPONSOR: Natl Cancer Inst, NIH /A TOPICS: 2B,2C

PI/ORG: Powers, Edward L; Lab Rad Biol, Univ Texas, Austin TX
 TITLE: Physico-chemical studies of radiation effects in cells.
 SUMMARY: The effects of added metal (Ag or Hg) on radiation sensitivity of bacteria and the behavior of a radical scavenger and oxygen are studied.
 SPONSOR: Natl Inst General Med Sci, NIH; Dept Energy /B,C TOPICS: 1,2D

PI/ORG: Prakash, Satya; Dept Biology, Univ Rochester, Rochester NY
 TITLE: Repair of DNA damaged by psoralen + 360 NM irradiation.
 SUMMARY: Systems for repair of DNA damage induced by exposure of cell systems to psoralen plus UV light are characterized.
 SPONSOR: Natl Cancer Inst, NIH /B TOPICS: 3A

PI/ORG: Rasey, Janet S; Univ of Washington, Seattle WA
 TITLE: Neutron radiobiology in support of radiotherapy.
 SUMMARY: Biological dosimetry to determine RBE's for neutron beams are carried out in vitro and in vivo, with investigation of repair of sublethal and potentially lethal damage and protection by WR-2721 and related thiols.
 SPONSOR: Natl Cancer Inst, NIH /A TOPICS: 1,2D,3A

PI/ORG: Remsen, Joyce F; Univ Calif., Davis CA
 TITLE: Radiosensitizers and DNA damage.
 SUMMARY: The objective is to characterize effects of hypoxic-cell radiation sensitizers on formation and repair of radiation-induced DNA damage in mammalian cells. Thymine damage and DNA strand breaks are studied in aerobic

and hypoxic conditions.

SPONSOR: Natl Cancer Inst, NIH /A

TOPICS: 1,3A,3B,3C

PI/ORG: Rich, Tyvin A.; Harvard Medical School, Boston MA

TITLE: Hypoxic cell sensitizers - Radiosensitization, distribution, neurotoxicity.

SUMMARY: Damage interaction between radiation and cancer chemotherapeutic agents; development of a basis for use of hypoxic cell sensitizers during radiotherapy; genetic control of drug resistant cells and radiation response of those cells; long-term effects of radiation; and repair in mammalian cells of radiation damage are studied.

SPONSOR: Natl Cancer Inst, NIH /A

TOPICS: 1,2C,2D,3A

PI/ORG: Richmond, Robert C; Dartmouth-Hitchcock Med Ctr, Hanover NH

TITLE: Radiation-chemical induction of mutagenesis.

SUMMARY: Effects of sensitizers on radiation-induced mutagenesis are studied.

SPONSOR: Natl Cancer Inst, NIH /A

TOPICS: 2D

PI/ORG: Rodgers, Michael A; Ctr for Fast Kinetics Res, Univ Texas, Austin TX

TITLE: Electron transfer reactions in micro-heterogeneous media.

SUMMARY: Ways in which aggregates and interfacial regions in heterogeneous media influence one-electron transfers between free radicals are characterized. The results will have significance for understanding and control of health effects of high energy radiations.

SPONSOR: Natl Inst of General Med Sciences, NIH/A

TOPICS: 1

PI/ORG: Rosenberg, Robert C.; Howard Univ. School of Med, Washington DC

TITLE: Superoxide dismutase in normal and malignant cells.

SUMMARY: This is a sub-project of a biomedical interdisciplinary research project.

SPONSOR: Div of Research Resources, NIH /A

TOPICS: 1

PI/ORG: Rosenthal, C Julian; SUNY Downstate Med Ctr, Brooklyn NY

TITLE: Radiosensitization and treatment of malignant tumors.

SUMMARY: This is a sub-project of the general clinical research center grant.

SPONSOR: NIH /A

TOPICS: 2D

PI/ORG: Roti Roti, Joseph L; Univ Utah, Salt Lake City UT

TITLE: Radiation induced alteration of chromosomal proteins.

SUMMARY: The objective is to determine the role of chromatin in the radioresponse of mammalian cells.

SPONSOR: Natl Cancer Inst, NIH /B

TOPICS: 1

PI/ORG: Rupert, Claud S; Univ of Texas, Richardson TX

TITLE: Repair of radiation-damaged nucleic acid.

SUMMARY: DNA repair mechanisms in irradiated cells are studied.

SPONSOR: Natl Inst General Med Sciences, NIH /B

TOPICS: 3A

PI/ORG: Sanders, CL; Battelle Pacific Northwest Labs, Richland WA

TITLE: Inhaled transuranics in rodents.

SUMMARY: One objective is to examine anticarcinogenic factors that modify carcinogenic processes resulting from inhalation of transuranic elements. Anticarcinogenesis with vitamins is evaluated.

SPONSOR: Dept of Energy /C

TOPICS: 2D

PI/ORG: Savarese, Todd; Roger Williams General Hosp, Providence RI
TITLE: Differentiation-induction in human colon cancer cells.
SUMMARY: An objective is to determine whether differentiation-inducing compounds can alter sensitivity of cultured or in situ tumor cells to X-rays.
SPONSOR: Natl Cancer Inst, NIH /A TOPICS: 2D

PI/ORG: Schneiderman, Martin H
TITLE: G2 cell killing and arrest of X-ray and drugs.
SUMMARY: (see under Dennis Leeper)
SPONSOR: Natl Cancer Inst, NIH /A TOPICS: 1,2B,2D

PI/ORG: Setlow, RB; Brookhaven Natl Lab, Upton NY
TITLE: Radiation and chemical damage to DNA and its repair.
SUMMARY: Radiation damage to bacterial and vertebrate cells and kinetics of three types of repair are measured along with effects of chemical modulators of repair processes. The aim is to develop a molecular basis for biological dose-response curves at low doses.
SPONSOR: Dept of Energy /C TOPICS: 1,3A,3B

PI/ORG: Sinclair, Warren K; Nat'l Coun Rad Protec and Meas, Bethesda MD
TITLE: Radiation effects and exposure criteria.
SUMMARY: The research assesses available information in order to develop NCRP reports on (among other topics) biological aspects of radiation protection criteria and biological effects of magnetic fields.
SPONSOR: Food and Drug Admin, USPHS/A TOPICS: 1,2D

PI/ORG: Smith, Kendrick C; Dept Radiology, Stanford Univ, Stanford CA
TITLE: Repair of radiation-induced lesions in DNA.
SUMMARY: Objectives of these studies in E. coli include characterization of the processes for UV radiation mutagenesis; determination of the source and nature of spontaneous mutations; and molecular description of post-replication repair processes.
SPONSOR: Natl Cancer Inst, NIH /B TOPICS: 1,3A

PI/ORG: Smith, Kendrick C; Dept Radiology, Stanford Univ, Stanford CA
TITLE: Molecular basis of radiation lethality.
SUMMARY: Radiation-sensitive E. coli mutants are used to study various aspects of radiation-induced cell death, including the mechanisms and control for repair of DNA damage, interactions and possible radiation-induction of different repair pathways, and drug inhibition of repair.
SPONSOR: Natl Cancer Inst, NIH /B TOPICS: 1,3A,3B

PI/ORG: Sodickoff, Marvin; Temple Univ., Philadelphia PA
TITLE: X-ray therapeutic index for salivary glands.
SUMMARY: The objective is to widen the differences in sensitivities of normal and neoplastic salivary tissue by use of the radioprotector, WR-2721, and the radiosensitizer, Ro-07-0582. Effects of the compounds, alone and together, are studied. Other drugs, including isoproterenol and cyclic AMP, are evaluated as possible substitutes for the still-experimental WR-2721.
SPONSOR: Natl Institute of Dental Research /A TOPICS: 2D

PI/ORG: Song, Chang W.; University of Hospitals, Minneapolis MN
TITLE: Use of 5-thio-D-glucose in radiotherapy.
SUMMARY: Studies showing that 5-thio-D-glucose is specifically cytotoxic

toward hypoxic cells, that it sensitizes these cells to x-irradiation while protecting oxic cells from radiation damage, and that the hypoxic cell cytotoxicity of the compound is dramatically enhanced by moderate hyperthermia are extended.

SPONSOR: Natl Cancer Inst, NIH /A

TOPICS: 2B,2C,2D

PI/ORG: Sowby, FD; Internat Comm on Radiological Protection; Sutton, UK

TITLE: Recommendations on radiation protection.

SUMMARY: Fundamental radiobiological and other data are critically examined in reviewing the Committee's 1977 recommendations and (in the late 1980's) drafting its next recommendations for national and regional radiation protection programs.

SPONSOR: Natl Cancer Inst, NIH /B

TOPICS: 1

PI/ORG: Sridhar, Rajagopalan; Oklahoma Med. Res. Fndn., Oklahoma City OK

TITLE: Interactions of hypoxic cell radiation sensitizers.

SUMMARY: Interactions of electron affinic nitro radiosensitizers with certain mammalian enzymes are studied. Effects of catecholamines on their radiosensitization are measured.

SPONSOR: Natl Cancer Inst, NIH /A

TOPICS: 2D

PI/ORG: Stuart, Marie J; Upstate Med Ctr, State Univ NY, Syracuse NY

TITLE: Effect of irradiation on vascular-platelet interactions.

SUMMARY: Effects of radiation on arachidonic acid metabolism in blood vessels and their modification by radical scavengers and antioxidants are characterized to elucidate biochemical mechanisms involved in radiation effects on vascular/platelet interaction.

SPONSOR: Natl Cancer Inst, NIH /B

TOPICS: 1,2D

PI/ORG: Suit, Herman D; Dept Radiation Med, Mass General Hosp, Boston MA

TITLE: Modification of tumor response to local irradiation.

SUMMARY: Enhanced chemical radiosensitization by combination of sensitizer treatment with hyperbaric oxygen is evaluated in nine murine tumors.

SPONSOR: Natl Cancer Inst, NIH /B

TOPICS: 2C,2D

PI/ORG: Sutherland, Betsy M; Brookhaven Natl Laboratory, Upton NY

TITLE: UV transformation, DNA repair in human cells and skin.

SUMMARY: Roles of wavelength, age, cell origin, growth schedule, DNA and DNA repair on a UV-induced transformation process in human cell cultures are evaluated.

SPONSOR: Natl Cancer Inst, NIH /B

TOPICS: 1,3A

PI/ORG: Sutherland, Robert M.; Univ Rochester, Rochester NY

TITLE: Combined radiotherapy-chemotherapy studies.

SUMMARY: Experiments investigate the basic properties and responses of tumor and normal tissues to radiation and drugs, including the kinetics of repair processes.

SPONSOR: Natl Cancer Inst, NIH /A

TOPICS: 1,2D,3B

PI/ORG: Taylor, JH; Inst of Molec Biophys, Florida State Univ, Tallahassee

FL

TITLE: Repair of lesions and initiation of DNA replication in vertebrate cells.

SUMMARY: An objective is to study replicons and determine why these sites are

particularly sensitive to ionizing radiation using DNA cloning techniques in frog eggs or mammalian cell cultures.

SPONSOR: Dept of Energy /C

TOPICS: 1,3A

PI/ORG: Tobias, Cornelius A; Univ of Calif. Donner Lab., Berkeley CA

TITLE: Heavy ion radiobiology related to oncology.

SUMMARY: Responses of normal mammalian tissues and of tumor growth and kinetics to heavy-ion beams are studied. Modification of these responses by oxygen are also studied.

SPONSOR: Natl Cancer Inst, NIH /A

TOPICS: 1,2C

PI/ORG: Urtasun, Raul C; Cross Cancer Institute, Edmonton, AB, Canada

TITLE: R.T.O.G. phase I, and III clinical studies.

SUMMARY: Among the areas to which this project in a cooperative clinical research agreement will contribute is that of chemical modification of radiation response, with studies at both the basic and clinical research levels.

SPONSOR: Natl Cancer Inst, NIH /A

TOPICS: 2D

PI/ORG: Utey, Joella F; Univ Calif Medical Center, San Diego

TITLE: Biological analysis of sulphhydryl radioprotective drugs.

SUMMARY: A new, sensitive assay method for the radioprotective agent, WR-2721, is used to study: 1) the intracellular form and site of binding of the drug which may elucidate its mechanisms of action; 2) the rate of its reaction with radicals; 3) possible radiation-drug mutagenesis; 4) pharmacokinetics in normal and tumor tissues and their possible alteration by radiation.

SPONSOR: Natl Cancer Inst, NIH /A

TOPICS: 2D,4

PI/ORG: Wallace, Susan S; Dept Microbiol, New York Med Coll, Valhalla NY

TITLE: Modification of X-ray induced damages in phage T4.

SUMMARY: The objective is to define the molecular mechanisms involved in repair of X-ray induced DNA damage in bacteriophage.

SPONSOR: Natl Cancer Inst, NIH /B

TOPICS: 3A

PI/ORG: Wallace, Susan S; Dept Microbiol, New York Med College, Valhalla NY

TITLE: Repair of DNA damage induced by ionizing radiation.

SUMMARY: The objective is to elucidate molecular mechanisms involved in repair by *E. coli* and *S. cerevisiae* of radiation damaged phage DNA.

SPONSOR: Natl Cancer Inst, NIH /B

TOPICS: 3A

PI/ORG: Wallace, SS; Dept Microbiol, NY Med College, Valhalla NY

TITLE: Immunochemical approach to the study of DNA repair.

SUMMARY: The objective is to develop a simple immunochemical assay to quantify DNA lesions so as to facilitate the study of DNA repair.

SPONSOR: Dept of Energy /C

TOPICS: 3A

PI/ORG: Weinreb, Steven M; Pennsylvania State Univ, University Park PA

TITLE: Synthesis of securiniga alkaloids.

SUMMARY: Some alkaloids have shown antiradiation activity. Total synthesis of some of the Securiniga is proposed.

SPONSOR: Natl Inst of General Med Sciences, NIH /A

TOPICS: 4

PI/ORG: Weiss, Herbert; Sloan-Kettering Inst., New York NY
TITLE: Mechanism of radiation damage in cells.
SUMMARY: The early physicochemical events involved in radiation effects in cells are studied, using spores, bacteria, and mammalian cells plus radiation sensitizers and radioprotectors.
SPONSOR: Natl Cancer Inst, NIH /A,B TOPICS: 1,2D

PI/ORG: Wheeler, Kenneth T; Rhode Island Hosp, Providence RI
TITLE: DNA damage and repair in irradiated brain and brain tumor.
SUMMARY: The objective is to elucidate the molecular mechanisms differentiating DNA repair kinetics in normal cells and tumor cells after irradiation.
SPONSOR: Natl Cancer Inst, NIH /B TOPICS: 1,3A

PI/ORG: Withers, H Rodney; UCLA Ctr for Health Science, Los Angeles CA
TITLE: Radiobiology of normal tissues.
SUMMARY: Responses of normal tissues (bone marrow stem cells, hair follicle cells, and adrenal tubule cells) to multiple doses of radiation are quantified.
SPONSOR: Natl Cancer Inst, NIH /B TOPICS: 1

PI/ORG: Yuhas, John M; Children's Hosp of Philadelphia, Philadelphia PA
TITLE: Radioprotectants and radiosensitizers in radiotherapy.
SUMMARY: The objective is to determine whether WR-2721, given before radiation and radiosensitizers, increases therapeutic effectiveness.
SPONSOR: Natl Cancer Inst, NIH /B TOPICS: 2D

PI/ORG: Zimbrick, John D.; Univ. of Kansas, Lawrence KS
TITLE: Spin-labeled platinum complexes for radiochemotherapy.
SUMMARY: A series of such complexes are synthesized and tested for modification of cell response to radiation. Molecular mechanisms of their actions are studied.
SPONSOR: Natl Cancer Inst, NIH /A TOPICS: 2D

PI/ORG: Zimbrick, John D; Univ of Kansas, Lawrence KS
TITLE: Radiation biochemistry of DNA base damage.
SUMMARY: The overall objective is to obtain information on types of radiation-induced DNA base lesions in bacteria and the biological consequences of the lesions. Quantities and types of base lesions and effects on these of radiosensitizers and radioprotectors are determined.
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VII. Appendix B: Some Compounds Showing Radioprotective Activity.

This Appendix contains information on the types of compounds which have been tested for radioprotective activity. Included in Section A are some general comments on radiobiological structure-activity relationships (SAR) which have been deduced from tests of efficacy of a wide range of compounds. These tests have been performed by the Antiradiation Drug Development Program of the U.S. Army Medical Research and Development Command. The comments on SAR which are included here are an abbreviated version of a discussion of SAR included in reference [431]. Section B contains data extracted from literature reports which attempt to define the mechanisms of action of radioprotectors.

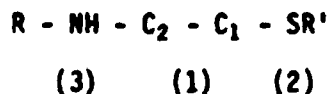
Several points should be kept in mind by persons using this Appendix. First, the bare conclusions of SAR derived from whole animal bioassay studies [431] provides no information on the absorption, distribution, metabolism and excretion of the test compounds, but is based only on the end effect radioprotective activity. Thus, some compounds judged in some assays to be without radioprotective effect may indeed exert radioprotective activity if adequately delivered to, or appropriately metabolized by, the radiosensitive tissue. Other compounds which are effective radioprotectors of cells may be metabolized or excreted before they can be delivered to the radiosensitive tissue and thus will appear to be without effect. Therefore, one must interpret bioassay-derived SAR with a note of caution when no data on the metabolism and pharmacokinetics are available. Secondly, for persons using Section B, it should be noted that many prominent radiobiologists have cautioned that such "objective" parameters as Dose Modifying Factors (DMF) obtained in tissue/cell culture systems and even in whole animal studies may vary greatly from one laboratory to another ([14] and references therein). The proper form of equations defining cell survival curves is a continuing controversy among radiobiologists. Even with data fit to the same equation, changes in the pre- or post-irradiation cell culture conditions markedly influences the observed cell survival [109,110]. Unsuspected variables which are uncontrolled [100] further complicate comparisons of data between laboratories. Thus comparison of data between different laboratories is generally ill-advised for quantitative purposes [14]. The table of compounds, rather than giving quantitative indications of absolute radioprotective activity, should be used to orient the reader to the types of compounds currently being tested and to

suggest references to begin further investigation about the work being done on that radioprotector.

A. Structure-Activity Relationships.

Since many non-thiol radioprotectors exert their effect through well-understood pharmacologic effects (e.g., serotonin, isoproterenol), the structure-activity relationships (SAR) of these compounds will not be discussed in this report. The finding of radioprotective activity for cysteine and cysteamine (2-aminoethanethiol) in the late 1940's and early 1950's stimulated an effort to identify structural analogs of these compounds which exhibit increased effectiveness and/or decreased toxicity. The general findings of these efforts [431] are summarized in this section.

The general rule which has emerged from intensive investigation of aminothiols radioprotectors holds that the necessary requirements for radioprotective activity are: (1) a two or three carbon backbone separating (2) a thiol or potential thiol and (3) a primary or secondary amino functional



group. While this "rule" is surely an oversimplification, its precepts have generally been upheld with few exceptions. Modifications of each of these requirements will be considered in turn.

(1) The Carbon Chain: The optimal size of the carbon chain separating the amino and thiol functional groups is two carbons. Separating these functional groups by more than three carbons abolishes radioprotective activity. In the series of 3-aminopropanethiols, few compounds showed more than low activity and many were without effect. Certain hydroxylated compounds, especially those carrying a hydroxyl group at the 2 position, were active when the amino group carried an alkyl chain. 3-Aminopropylphosphorothioates followed this generalization, with 2-hydroxy-3-alkylaminopropylphosphorothioates showing some activity.

Among the amino(alkylethane)thiols, most substitutions resulted in the diminution or abolition of radioprotective activity. Activity was retained in the series 2-alkyl-2-aminoethanethiols (up to propyl substitution) and varied results were obtained in the 2-alkyl-2-methyl-2-aminoethanethiols. However, more extensive substitution, including involvement of carbocyclic

structures at the 2 position, abolished radioprotective activity. Alkyl substitution at the C_1 carbon was more hindered in terms of the size of permissible substitutions, with no activity beyond ethyl substitution at C_1 . The involvement of both carbons of aminoethanethiol as part of a carbocycle (i.e., 2-aminocyclobutanethiol) retained activity, which diminished somewhat as the size of the carbocyclic ring was increased.

Functionalization of either R_1 or R_2 in the series $H_2NC(R_1R_2)CH_2SH$ dramatically altered the toxicity and/or radioprotective activity. Incorporation of thiol functions into these alkyl groups greatly increased the toxicity of the compounds. Hydroxylation of these alkyl groups increased the efficacy of the compound relative to the non-functionalized compound; the phosphorothioates of this series were generally highly active with relatively low toxicity.

(2) The Thiol Group: Early in the radioprotective drug development program, it became apparent that a thiol group or a potential thiol group was generally necessary for radioprotective activity. The nature of the "potential" thiol group influenced the relative activity and toxicity of the basic compound. Thus, blocking the thiol group in a manner such that it was metabolically unavailable (e.g., alkylation of the thiol to produce a thioether) eliminated radioprotective activity. However, blocked forms of thiols (e.g., thiosulfates (Bunte salts), phosphorothioates, disulfides³, or other derivatives from which free thiols may be formed metabolically) were active to varying degrees, both in absolute dosage and relative to the toxicity of the compound. Altogether, about 50 different sulfur blocking groups were tested in varying degrees for their ability to latentiate the thiol and alter the relative potency of the parent aminothiol. In general, the three thiol derivatives mentioned above were found to be most promising. The blocked thiols have generally been considered to be prodrugs; the free thiol was thought to be the active form at the site of action. One might assume that the function of the blocking group was to alter the pharmacokinetics or the rates of metabolism and excretion of the drugs. While this is a plausible hypothesis, extensive data to support this general

³ Note that hydrolysis of most pro-thiols yields one mole of thiol per mole of pro-thiol whereas on reduction, disulfides yield two moles of thiol per mole of disulfide.

conclusion is remarkably lacking; more detailed studies of the structure/activity relationships between the different series of blocked thiols must be compared with data on the pharmacokinetics of these drugs before this general conclusion can be accepted.

(3) The Amino Group: Various structures may be attached to the amino group of the basic aminoethanethiol structure with no deleterious effect on radioprotective activity. The N-(n-alkylamino)ethanethiosulfuric acid series ($\text{RNHCH}_2\text{CH}_2\text{SSO}_3\text{H}$) affords an interesting pattern of activity, with full activity where R includes a straight chain of up to three carbon atoms. The next four compounds (R = C_4 through C_7) were inactive, but modest activity returned when R = C_8 to C_{10} ; further extensions were inactive or exhibited only very low activity. Branched chain hydrocarbons attached to the amino functional group were generally representative of the activity of the unbranched homologue. Tertiary amines (dialkylaminoethanethiols) were without activity, including those compounds in which the nitrogen atom was part of a heterocyclic ring.

Introduction of a phenyl group onto the alkylaminoethanethiosulfuric acids (resulting in compounds of the series $\text{C}_6\text{H}_5(\text{CH}_2)_n\text{NHCH}_2\text{CH}_2\text{SSO}_3\text{H}$) produced inactive compounds for $n = 0 - 2$, but compounds showing good activity for $n = 4$ and 5. Incorporation of alkyl substituents on the phenyl ring of 4-phenyl-n-butylaminoethanethiosulfuric acid increased the toxicity of the compound dramatically, while substitution with a methoxy group produced higher radioprotective potency.

Hydroxylation of the alkyl chain in the N-alkylaminoethanethiols reduced the toxicity of the compound irrespective of the position of the hydroxyl group on the alkyl chain. In general, the introduction of this group had little effect on or reduced the radioprotective potency when compared to the nonhydroxylated homologue. Polyhydroxylation further reduced the toxicity, and in some cases allowed testing for potency at higher doses, revealing good activity.

Many other substituents on the amino functional group have been tested for radioprotective activity, including phenoxyalkyl-, cycloalkylalkyl-, heterocycloalkyl-, pyridylalkyl-, quinolyloxyalkyl-aminoethanethiols and their blocked thiol derivatives. Varying activity was encountered, not always in orderly sequence or in relation to their expected pharmacokinetic behavior.

Perhaps the best known alkylamino functionalization is the group of aminoalkylaminoethanethiols and phosphorothioates $[\text{RNH}(\text{CH}_2)_n\text{NH}(\text{CH}_2)_m\text{SR}']$, represented by the prototypic compound WR-2721 [S-2-(3-aminopropylamino)-ethylphosphorothioic acid, $\text{R} = \text{H}$, $\text{R}' = \text{PO}_3\text{H}_2$, $n = 3$, $m = 2$]. In general, the phosphorothioates in this group were more active than the thiols and were less toxic. Alkylaminoalkylaminoethanethiols or phosphorothioates were inactive when the terminal alkyl chain contained more than one carbon atom. Varying the length of the alkyl chain between the amino groups produced a peak of activity at $n = 3$. In contrast to the thiols, phosphorothioates in this class could be hydroxylated in the aminoalkylamino group without loss of activity. As noted above, the compounds in which $n = 2$ and $m = 3$ were of comparable activity when $\text{R}' = \text{H}$ or PO_3H_2 .

In view of the above requirements for a (potential) thiol and a primary or secondary amine, it is interesting that N,N'-bridged amino(bis(ethanethiols)) and derivatives $[\text{R}'\text{S}(\text{CH}_2)_2\text{NH}(\text{CH}_n)\text{NH}(\text{CH}_2)_2\text{SR}']$ were almost uniformly ineffective. The only exceptions were the diphosphorothioates ($\text{R}' = \text{PO}_3\text{H}_2$) where $n = 3$ or 4.

Other Compounds: Certain other compounds not patterned after the basic aminoethanethiol structure have also been tested for radioprotective activity. Mercaptoacetamidines, generally tested as the thiosulfates, are somewhat more effective than the corresponding aminoethyl analogs, but are also more toxic. In contrast to the aminoalkylthiol series, amidines containing more than 2 carbons in the primary alkyl chain were active, albeit with somewhat lower activity than the shorter chain compounds.

Guanidinoalkylthiols and derivatives $[\text{RNHC}(\text{=NH})\text{N}(\text{R}_1)(\text{CH}_2)_n\text{SR}' \text{ Y} = \text{H}, \text{SO}_3\text{H}, \text{ or disulfide}]$ showed little promise in terms of radioprotective activity. This result was somewhat unexpected, since the parent compounds $[\text{H}_2\text{NC}(\text{=NH})\text{NH}(\text{CH}_2)_n\text{SH}, n = 2 \text{ or } 3]$ are generally considered the active components of the isothiuronium compounds AET (Aminoethylisothiuronium) and APT (Aminopropylisothiuronium) which have the structure $\text{H}_2\text{N}(\text{CH}_2)_n\text{SC}(\text{=NH})\text{NH}$, $n = 2$ and 3, respectively. This result may demonstrate one of the hazards of inferring too much from the structure-activity relationships when pharmacokinetic behavior is not, or is only briefly, considered.

B. Compound List.

<u>Compound</u>	<u>Dose</u>	<u>Biological Material</u>	<u>Radiation</u>	<u>Effect</u>	<u>Reference</u>
Acetylthiourea	0.1M	<i>Shigella flexneri</i> Y6R	e ⁻ ; 20 kR/min	P-air 1.7, P-N ₂ 1.1	[106]
Aminoethane thiol	20mM	V79 cells in culture	near UV radiation	2x increase in D ₀ value	[189]
Aminoethylisothiuron- ium BrHBr (AET)	2-5mM	mouse fibroblast L929 cells	fast neutrons 4-5 MeV; 0.47-5.2 Gy	increased survival rate severalfold	[154]
Aminoethylisothiuron- ium BrHBr (AET)	0.45mM/kg	rat liver mitochondria	γ(76y) 30 min after treatment with AET	*antagonized radia- tion induced increase in protein synthesis	[167]
Aminoethylisothiuron- ium BrHBr (AET)	300mg/kg i.p. 15min before	mouse bone marrow cells <u>in vivo</u> irradiation	⁶⁰ Co-γ 50-250 R	reduced frequency of polychromatic erythrocytes	[168]
Aminoethylisothiuron- ium BrHBr (AET)	2, 4 or 5mM	mouse cells	⁶⁰ Co-γ 0.24 Gy/s 4-5MeV neutrons	DRF 2mM = 1.20 4mM = 1.27 5mM = 1.34 DRF 5mM = 1.00	[155]
Chloral hydrate	0.3mg/g i.p.	MT tumors (mice)	X-ray to TCD ₅₀	DMF 1.05	[407]
Cystamine	50moles/mole enzyme 50moles/mole enzyme 50moles/mole enzyme 50moles/mole enzyme	aldolase yeast alcohol dehydrogenase pancreatic α-amylase <u>B. subtilis</u> α-amylase	X-rays X-rays X-rays X-rays	enzyme inactivation (< 1) < DMF < 3 enzyme inactivation (< 1) < DMF < 3 enzyme inactivation (< 1) < DMF < 3 enzyme inactivation (< 1) < DMF < 3	[177]

<u>Compound</u>	<u>Dose</u>	<u>Biological Material</u>	<u>Radiation</u>	<u>Effect</u>	<u>Reference</u>
Cystamine	10 ⁻² M	E. coli RNA polymerase with σ -factor)	X-ray; 1.75 kR/min (220kV, 20mA, 0.5mm Cu filter)	DRF 2 (calf thymus template)	[430]
	10 ⁻² M	E. coli RNA polymerase with σ -factor)	X-ray; 1.75 kR/min (220kV, 20mA, 0.5mm Cu filter)	DRF 30 (T4 template)	
Cystamine	60mg/kg i.m. 20min before irradiation	adult male and female Wistar SPF rats (180-230g)	⁶⁰ Co- γ ; 0.78 Gy/min	DRF 1.46	[257]
	50mg/kg i.p. 15min before irradiation	adult male and female Wistar SPF rats (180-230g)	⁶⁰ Co- γ ; 0.386 Gy/min	DRF 1.79	
Cystamine	50mg/kg i.m. 15min before irradiation	adult male and female Wistar SPF rats (180-230g)	⁶⁰ Co- γ ; 0.386 Gy/min	DRF 1.65	[257]
	50mg/kg i.p. 15min before irradiation	adult male and female Wistar SPF rats (180-230g)	⁶⁰ Co- γ ; 0.369 Gy/min	DRF 1.44	
Cystamine	50mg/kg i.m. 15min before irradiation	adult male and female Wistar SPF rats (180-230g)	⁶⁰ Co- γ ; 0.369 Gy/min	DRF 1.24	[248]
Cysteamine	150mg/kg	endothelial cells of rat cerebral cortex	⁶⁰ Co- γ ; 3 Gy/min	1.3	[446]
Cysteamine	75mM	Chinese hamster V79 cells (synchronized)	50 kV X-rays, LET = (³ H) ₉₀ keV/ μ m	DMF (G ₁ /S) 4.8 DMF (late S) 3.2	[67]
	75mM	Chinese hamster V79 cells (synchronized)	50 kV X-rays, LET = (³ H) ₁₇₀ keV/ μ m	DMF (G ₁ /S) 1.6 DMF (late S) 1.5	

<u>Compound</u>	<u>Dose</u>	<u>Biological Material</u>	<u>Radiation</u>	<u>Effect</u>	<u>Reference</u>
Cysteamine	50moles/mole enzyme	aldolase	X-rays	enzyme inactivation 2 < DMF < 6	[177]
	50moles/mole enzyme	yeast alcohol dehydrogenase	X-rays	enzyme inactivation 2 < DMF < 6	
	50moles/mole enzyme	pancreatic α -amylase	X-rays	enzyme inactivation 2 < DMF < 6	
	50moles/mole enzyme	<u>B. subtilis</u> α -amylase	X-rays	enzyme inactivation DMF < 6	
Cysteamine	1.6 x 10 ⁻³ M	calf thymus DNA	¹³⁷ Cs;600 R/min	"weak protection"	[247]
	1.6 x 10 ⁻³ M	salmon sperm DNA	¹³⁷ Cs;600 R/min	"weak protection"	
Cysteamine chloride	10 ⁻³ M	microsomes from liver cells of male Sprague-Dawley rats (180-200g)	⁶⁰ Co γ -ray;80 kR	decreases V _{max} of ethylmorphine demethylation; increases V _{max} of cyt P-450-ethylmorphine interaction	[491]
Cysteine	50moles/mole enzyme	aldolase	X-rays	enzyme inactivation 2 < DMF < 6	[177]
Cysteine	50moles/mole enzyme	yeast alcohol dehydrogenase	X-rays	enzyme inactivation 2 < DMF < 6	[177]
	50moles/mole enzyme	pancreatic α -amylase	X-rays	enzyme inactivation 2 < DMF < 6	
	50moles/mole enzyme	<u>B. subtilis</u> α -amylase	X-rays	enzyme inactivation 2 < DMF < 6	
Cysteine	575mg/kg i.p.	rats	800R X-rays at 210 R/min	82% survival at 30 days vs. 10% survival in Controls	[343]

<u>Compound</u>	<u>Dose</u>	<u>Biological Material</u>	<u>Radiation</u>	<u>Effect</u>	<u>Reference</u>
Cysteine	0.1M	anoxic <u>Pseudo-</u> <u>monas</u> spp.	γ	DRF 1.8	[80]
L-Cysteine	40mg/day	male mice	$^{60}\text{Co-}\gamma$	DRF 1.19 ± 0.05	[475]
Cystine	50moles/mole enzyme	aldolase	X-rays	enzyme inactivation 1.3 DMF < 4	[177]
	50moles/mole enzyme	yeast alcohol dehydrogenase	X-rays	enzyme inactivation 1.3 DMF < 4	
	50moles/mole enzyme	pancreatic α -amylase	X-rays	enzyme inactivation 1.3 DMF < 4	
	50moles/mole enzyme	<u>B. subtilis</u> α -amylase	X-rays	enzyme inactivation 1.3 DMF < 4	
2-Di(n-butyl)- germathiazolidine	4mM	human kidney T cells (culture)	X-rays	DRF 2.0	[471]
Diethyl aminoreserpine (DL-152)	320mg/kg	mice	120 R/min (250 kV, 20mA hv1, 1.6mm Cu)	DMF intestine 1.15 skin 1.5 - 1.9 bone marrow 1.0 KHT tumor 1.7 ENT6 tumor 1.0	[267]
2-Diethyl-2- germathiazolidine	4mM	human kidney T cells (culture)	X-rays	DRF 2.7	[471]
Dimethylsulfoxide	1M	anoxic <u>Pseudo-</u> <u>monas</u> spp.	γ	DRF 1.6	[80]
2,2-Dimethyl- thiazolidine	250mg/kg	mouse bone marrow colony forming units	γ -radiation	reduced radiation- induced inhibition of CFU growth activity	[271]
Glycerol	2M	anoxic <u>Pseudo-</u> <u>monas</u> spp.	γ	DRF 2.0	[80]

<u>Compound</u>	<u>Dose</u>	<u>Biological Material</u>	<u>Radiation</u>	<u>Effect</u>	<u>Reference</u>
Guanylthiourea	0.3M 0.1M	<u>Shigella flexneri</u> Y6R <u>Shigella flexneri</u> Y6R	e ⁻ ; 20 kR/min e ⁻ ; 20 kR/min	P-air 2.3, P-N ₂ 1.14 P-air 1.9, P-N ₂ 1.3	[106]
bis-(2-Guanidoethyl) disulphide	1.6 x 10 ⁻³ M	calf thymus DNA	¹³⁷ Cs; 600 R/min	"strong protection"	[247]
bis-(2-Guanidoethyl) disulphide	1.6 x 10 ⁻³ M	salmon sperm DNA	¹³⁷ Cs; 600 R/min	"strong protection"	[247]
O-(8-Hydroxyethyl)-rutosides	450mg/kg 30min before radiation	neonatal rat brain microvasculature	1 Gy/min (Plotron)	DMF 1.3	[262]
Imidazolidine thione	0.1M	<u>Shigella flexneri</u> Y6R	e ⁻ ; 20 kR/min	P-air 2.1, P-N ₂ 1.7	[106]
Mercaptopropionyl glycine	20mg/kg	mouse liver nuclei	tritiated water 5μCi/gm B.W. 15-30 min after drug	44% reduction of abnormal mouse liver nuclei 3 days after radiation	[187]
2-(o-Methylphenyl)-thiazolidine	6mM	human kidney T cells (culture)	X-rays	DRF 1.6	[471]
1-Methyl-2-phenyl-thiazolidine	6mM	human kidney T cells (culture)	X-rays	DRF 1.8	[471]
D-Penicillamine	3gm/kg 60min before radiation	3-4 day old mice	⁶⁰ Co-γ; 6-10 Gy	increased LD _{50/30} from 6.77 Gy to 8.28 Gy	[259]
D-Penicillamine	10mg/day p.o.	male rats	⁶⁰ Co-γ; 25 Gy to right hemithorax	reduced lung pathology due to radiation	[353]
D-Penicillamine	10mg/day p.o.	male rats	⁶⁰ Co-γ; 25 Gy to right hemithorax	reduced radiation-induced arterial perfusion defects in lungs	[473]
D-Penicillamine	10mg/day p.o.	male rats	⁶⁰ Co-γ; 25 Gy to right hemithorax	prevented or reduced changes in lung enzymes caused by radiation	[474]

<u>Compound</u>	<u>Dose</u>	<u>Biological Material</u>	<u>Radiation</u>	<u>Effect</u>	<u>Reference</u>
D-Penicillamine	(1) 10mg/day (2) 100mg/day	male mice	$^{60}\text{C-}\gamma$; 500-1000 R	(1) DRF 1.04 ± 0.04 (2) DRF 1.13 ± 0.04	[475]
D-Penicillamine	2mg/day	male mice	$^{60}\text{Co-}\gamma$; 10-20 Gy	comparison of LD_{50} / 181-360 days gave DRF 1.2	[476]
Pentobarbital	0.06mg/g i.p.	MT tumors (mice)	X-ray to TCD_{50}	DMF 1.07	[67]
2-Phenylthiazolidine	8mM	human kidney T cells (culture)	X-rays	DRF 1.8	[471]
Structure 1	150mg/kg, LD_{50} =300	male mice	$^{60}\text{Co-}\gamma$; 40 R/min	DRF 1.4	[300]
Structure 2	600mg/kg, LD_{50} =1200	male mice	$^{60}\text{Co-}\gamma$; 40 R/min	DRF 1.3	
Structure 3	600mg/kg, LD_{50} =1200	male mice	$^{60}\text{Co-}\gamma$; 40 R/min	DRF 1.4	
Thiazolidine	8mM	human kidney T cells (culture)	X-rays	DRF 1.6	[471]
Thiocarbohydrazide	0.05M	<u>Shigella flexneri</u> Y6R	e^- ; 20 kR/min	P-air 1.8, P-N ₂ 1.1	[106]
5-thio-D-glucose	1.5g/kg	A/J female mice	2000-5000 rad	DMF 1.1 - 1.3	[402]
	1.5g/kg	A/J female mice	(220kV _p ; 15ma)	DMF 1.3 foot (0-40 days)	
	1.5g/kg	A/J female mice	117-124 rad/min	DMF 1.2 foot (60-90 days)	
Thiosemicarbazide	0.1M	<u>Shigella flexneri</u> Y6R	e^- ; 20 kR/min	P-air 2.4, P-N ₂ 1.7	[106]
Thiourea	0.3M	<u>Shigella flexneri</u> Y6R	e^- ; 20 kR/min	P-air 3.5, P-N ₂ 2.2	[106]
	0.1M	<u>Shigella flexneri</u> Y6R	e^- ; 20 kR/min	P-air 2.3, P-N ₂ 1.5	
Thiourea	0.2M	anoxic <u>Pseudo-</u> <u>monas</u> spp.		DRF 2.1	[80]

<u>Compound</u>	<u>Dose</u>	<u>Biological Material</u>	<u>Radiation</u>	<u>Effect</u>	<u>Reference</u>
WR-2721	400mg/kg i.p.	C57 BL/6J male mice (20-25g)	¹³⁷ Cs-γ; 117 R/min	DRF 1.75 (20min)	[248]
	400mg/kg i.p.	C57 BL/6J male mice (20-25g)	¹³⁷ Cs-γ; 117 R/min	DRF 1.32 (60min)	
WR-2721	220mg/kg 15min before radiation	weanling mouse	250kVp X-rays	DRF 1.16 - 1.20 for renal growth protection	[412]
WR-2721	3mg/ml 30min	V79 spheroids in culture	¹³⁷ Cs; 6.2 Gy/min	DMF 2.15 at 1% O ₂	[132]
WR-2721	400mg/kg 30min before radiation	male mice	¹³⁷ Cs-γ; 33-62 Gy at 917 R/min	DMF 1.5 for 5mm reduction in leg contractions	[214]
WR-2721	300mg/kg i.m. 15min before radiation	mice	⁶⁰ Co-γ; 0.33 Gy/min	hemopoietic death DRF 2.14	[256]
WR-2721	400mg/kg 15min before radiation	female mice	⁶⁰ Co-γ; 40 R/min	DRF 1.6	[238]
WR-2721	400mg/kg 30min before radiation	mice	¹³⁷ Cs-γ; 9.17 Gy/min	DRF for tumor cells: 1.11 - 1.24	[306]
WR-2721	400mg/kg 15min before radiation	mice	¹³⁷ Cs-γ; 9.17 Gy/min	DMF (jejunum) 1.64 (testis) 1.54 (fibrosarcoma) 1.28	[307]

<u>Compound</u>	<u>Dose</u>	<u>Biological Material</u>	<u>Radiation</u>	<u>Effect</u>	<u>Reference</u>
WR-2721	400mg/kg 30min before radiation	mice	¹³⁷ Cs-γ; 9.17 Gy/min	DMF (hair loss) = 1.24	[308]
WR-2721	4mM	human fibroblast cell culture	¹³⁷ Cs-γ	DMF for DNA strand breaks = 1.00	[386]
WR-2721	500mg/kg	EMT6 tumors in BALB/C mice	6 MeV X-rays 5 Gy/min	DMF 1.15 ± 0.04	[297]
WR-2721	500mg/kg	BALB/C mice	⁶⁰ Co-γ; 200 R/min	hematopoietic death	[104]
	300mg/kg	BALB/C mice	⁶⁰ Co-γ; 200 R/min	DMF 2.15 gastrointestinal death DMF 1.65	
WR-2721	400mg/kg	rat parotid gland	X-radiation	DMF 1.92	[421]
WR-2721	400mg/kg	rat parotid gland	300kVp X-rays	DMF 2.40	[422]
WR-2721	400mg/kg 35-45min before radia- tion	female mouse skin	240kVp X-rays	DMF 1.55 (in air) DMF 1.17 (in O ₂)	[427]

<u>Compound</u>	<u>Dose</u>	<u>Biological Material</u>	<u>Radiation</u>	<u>Effect</u>	<u>Reference</u>
WR-2721	400mg/kg 30min before radiation	mouse lung	240kVp X-rays	DMF (pneumonitis) 1.2-2.4 DMF (fibrosis) 1.5-1.6	[444]
WR-2721	400mg/kg variable time between drug and radiation	mouse skin	e ⁻ ; 20-60 Gy 13-17 Gy/min	DMF 1.1-1.3 (5min) DMF 1.7-2.1 (30min)	[443]
WR-2721	200mg/kg	rat hind limb	⁶⁰ Co-γ; 20-80 Gy 1.31 Gy/min	DMF (late skin reaction) 1.5 DMF (muscle damage) 1.5-2.0	[453]
WR-2721	(1) 125mg/kg (2) 250mg/kg 15min before radiation	mouse strains	300kVp X-rays	(1) DMF 1.34-1.40 (2) DMF 1.63-1.87	[489]
WR-2822	195mg/kg	C57B1/6J mice	(1) 4 MeV X-rays 250 R/min (2) 0.9 MeV neutrons 55 R/min	(1) survival DMF 1.23 (2) survival DMF 1.51	[104]
WR-2823	200mg/kg	C57B1/6J mice	(1) 4 MeV X-rays 250 R/min (2) 0.9 MeV neutrons 55 R/min	(1) survival DMF 1.32 (2) survival DMF 1.21	[104]

<u>Compound</u>	<u>Dose</u>	<u>Biological Material</u>	<u>Radiation</u>	<u>Effect</u>	<u>Reference</u>
WR-77913	2200mg/kg	BALB/C mice	^{60}Co - γ ; 200 R/min	hematopoietic death DMF 1.97	[104]
	1500mg/kg	BALB/C mice	^{60}Co - γ ; 200 R/min	gastrointestinal death DMF 1.95	
WR-109342	16.5mg/kg	C57B1/6J mice	(1) 4 MeV X-rays 250 R/min (2) 0.9 MeV neutrons 55 R/min	(1) survival DMF 1.17 (2) survival DMF 1.46	[104]

ABBREVIATIONS USED IN COMPOUND LIST

P-Air, P-N₂ = ratio of doses unprotected to give 10% survival S. flexneri added to solution 5-10 min before radiation.

DMF - Dose Multiplying Factor: The ratio of radiation doses required in the presence or absence of the drug to achieve the same level of effect.

DRF - Dose Reduction Factor: Synonymous with DMF, but specific for radioprotection.

D₀ - Slope of the cell survival curve.

i.m - intramuscular injection of drug.

i.p - intraperitoneal injection of drug.

kV_p - kilovolt peak: a measure of the intensity of X-rays.

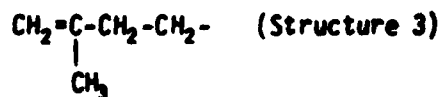
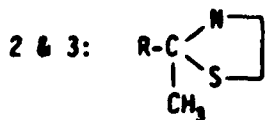
ma - milliamperes.

keV - kilo electron volts.

Gy - Gray, a unit of incident radiation (equal to 100 rads).

MeV - Million electron volts.

Structures: 1 = HC≡C-CH₂-NH-CH₂-CH₂-SH



VIII. References.

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