RADIATION BIOLOGY

I. Radiation, dualistic nature

Radiation may be defined as that process by which energy is transmitted or propagated.

A. Electromagnetic Radiation: Within our conceptual framework, electromagnetic radiation appears to have a dual nature, i.e., it travels as an electromagnetic wave and is absorbed or emitted as discrete "bundles" of energy. Maxwell (1831)[1] described by a series of equations the spatial behavior of the electromagnetic wave, which consists of an electric and magnetic field moving in phase at right angles to each other. The concept of "quanta" or "photons" of energy was formulated by Planck (1858) according to the equation $E=(hc)/\lambda$ where E is the amount of energy (ergs) per photon, h is Planck's constant (6.62×10^{-27} erg-sec), c the velocity of light (3×10^{10} cm/sec) and λ the wavelength (cm) of the radiation.

B. Particle Radiation: Of the number of identified particles which may be emitted from unstable (radioactive) atoms, only alpha particles, beta particles, and neutrons will be discussed in this outline. Alpha particles are doubly charged helium ions, beta particles have a mass and charge equal in magnitude to those of an electron, an a neutron is an electrically neutral particle with a mass similar to that of a hydrogen atom. Louis de Broglie (1892) theorized that in addition to waves behaving as particles, particles may behave as waves. He described this relationship by the equation $\lambda=h/(mv)$ where m is the mass (gm) of the particle, v the velocity (cm/sec), h planck's constant (erg-sec), and λ the wavelength (cm) of the particle. This has, in fact, since been demonstrated with a beam of electrons, the wavelength of which was determined to be approximately .05 A. As paradoxical as it may seem to us at the present, this dual (wave-particle) nature of radiation seems to be a fundamental property of nature.

II. Radiation, absorption

A. Electromagnetic Radiation: Absorption of electromagnetic radiation is dependent upon a number of factors which include (i) the nature of the absorbant material, (ii) the density of the absorbant, and (iii) the wavelength of the radiation. The logarithm of the intensity of a monochromatic beam (single wavelength) will decrease in direct proportion to the distance traversed in a homogenous medium. Expressed mathematically, $\log I/I_0=-kX$, where I is the

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[1]Dates given are birth dates.

intensity (# photons) of the radiation at thickness X (cm), I_o the intensity at 0 thickness, and k the "extinction coefficient" characteristic of the three aforementioned factors. The expression is commonly referred to as Lambert's law and applies throughout the electromagnetic spectrum (Fig.1).

In tissue there is considerable "specificity for absorption" of wavelengths from the far infrared through near ultraviolet. As an example, action spectra (experimentally determined curves in which are plotted the percent absorption vs wavelength of radiation for a particular substance) show that DNA and protein absorb radiation maximally at approximately 260 mμ and 280 mμ, respectively. From the far ultraviolet through gamma rays specificity for absorption is lost and continous absorption occurs with concomitant ionization. The "extinction coefficient" k falls off with shorter wavelengths, i.e., for a given intensity there is less absorption and greater penetration for the shorter wavelengths. In radiographic diagnosis, hard X-rays penetrate tissue more deeply than soft X-rays (longer wavelength) producing more definitive radiograms. In deep radiation therapy of tumors, gamma rays are on occassion preferentially used over X-rays because they are absorbed less and therefore penetrate more deeply. However, that there is less absorption (# photons/unit volume of tissue) of gamma rays than X-rays <u>does not</u> imply that, for an equal intensity of X-irradiation, gamma rays are less effective because they are absorbed less. The important factor to consider is the <u>total</u> energy absorbed per unit volume of tissue. A quantum or photon of gamma rays can be 1000 x greater than a quantum of X-rays such that to produce an equivalent amount of damage in tissue only 1/1000th of the gamma ray photons need be absorbed.

B. <u>Particle Radiation:</u>[2] Absorption of neutrons in tissue is similar to that of gamma rays and follow first order (exponential) decay. Approximately 50% of the neutron intensity is absorbed in the first millimeter of tissue, but the radiation can penetrate as much as a meter in tissue. Because of their electrical charge, beta and alpha particles are absorbed differently. The curve (fraction of intensity absorbed vs depth of penetration) for beta particle absorption would have less curvature than that described by an exponential relationship and would also reach a maximum depth of penetration in tissue of about 7mm. Absorption of alpha particles is essentially constant to a tissue depth of about .001 mm, then drops off almost instantly. For this reason alpha particles are not much of an external hazard, unless one were to have an open wound. Conversely, if an alpha emitter were taken internally it would produce considerable damage to the sensitive epithelial cells because of its extremely dense, although short, path of ionization.

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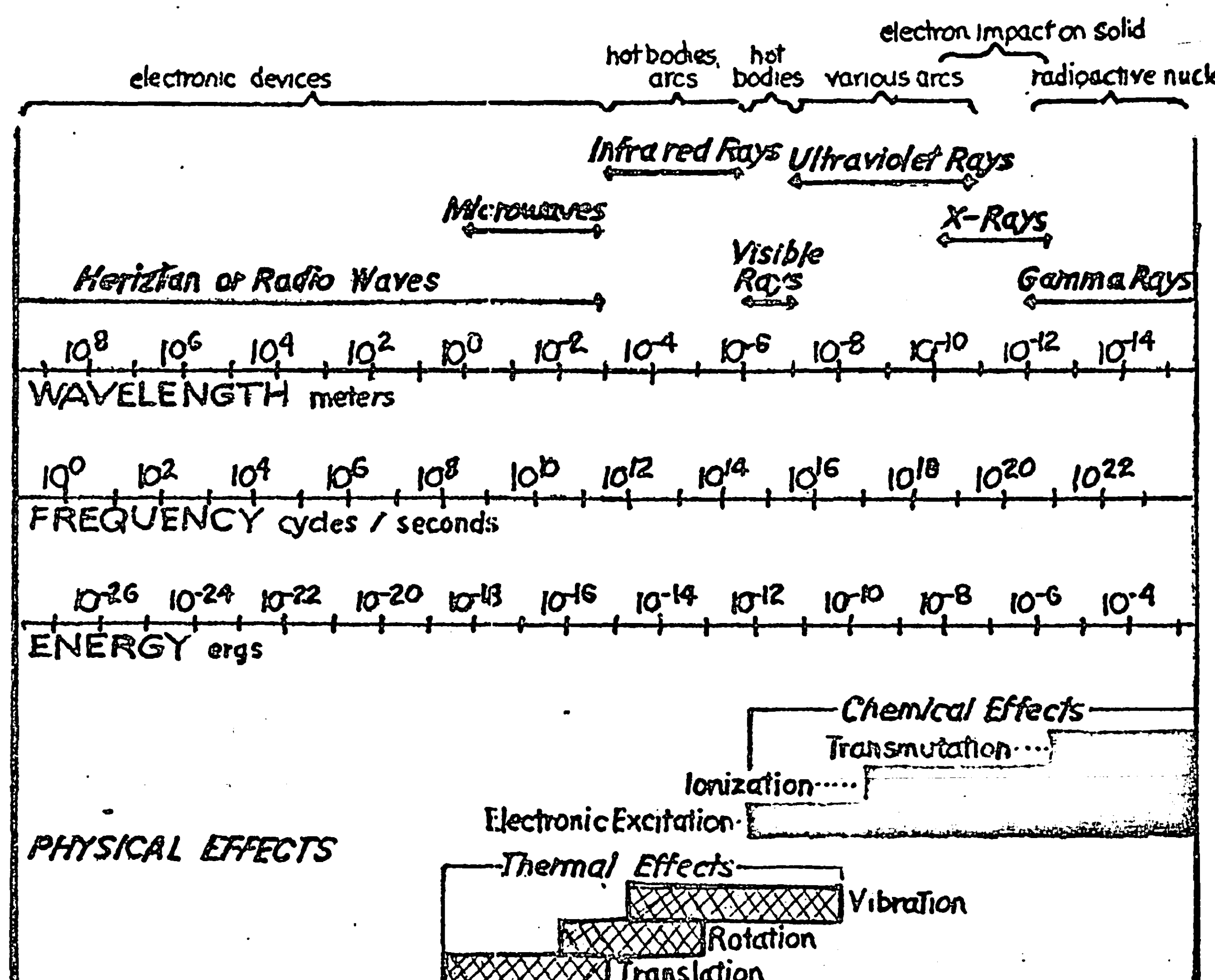
[2] In this discussion, assume all particles to have an initially equivalent intensity (I_o) of approximately 1 Mev

Figure 1.



The electromagnetic spectrum.

III. Radiation, physical effects

A. Thermal Effects: Thermal effects are usually associated with the longer wavelength (lower energy) portions of the electromagnetic spectrum (see Fig.1). Absorption of this energy will result in an increase in the translational, rotational, and/or vibrational energy states of the molecules. Figure 2 (a,b, & c) indicates generally, by means of a diatomic molecule, the three thermal energy states. Translation is the movement of the entire molecule, rotation the circular movement of the atoms about the common center of mass (c), and vibration the oscillation of the atoms in a straight line through their respective center of mass. As an example, the absolute temperature of a system is directly proportional to the translational kinetic energy of the molecules in the system. Quantitatively, this expression may be given by the equation, translational kinetic energy (KE)=$1/2\ mv^2 = 3/2\ kT$, where m is mass, v the average velocity of the molecules, k is a constant (Boltzman's), and T the absolute temperature. Therefore, any increase in the translational kinetic energy as a result of radiant energy absorption results in a consequent increase in the absolute temperature.

B. Chemical Effects: Chemical effects are usually produced with photons having sufficient energy to cause electronic excitation (electron "jump" from lower to higher orbital levels (Fig. 3a), ionization (electron emitted entirely from atom (Figs. 3b & 3c), and transmutation (also, at times, referred to as ionization and reflects a disruption of the nucleus, Fig. 3d).

Neutrons produce chemical effects by reacting with atomic nuclei, the products of which reactions leave dense paths of ionization. Because of their electrical charges, alpha and beta particles tend to produce ionization by interacting with the electrical fields of atomic orbital electrons "pulling" (He^{++}) or "repelling" (β^-) the electrons from their orbits.

IV. Radiation, biological effects

Microwave and infrared radiation result in an increase in tissue temperature. The water content (75-85%) of tissue accounts for the major thermal response. Water molecules (dipolar molecules: molecules which have a separation of negative and positive charges) tend to resonate in the electromagnetic field thereby increasing their respective thermal energy states. Microwave and infrared radiation are used extensively in diathermy.

Radiation from the visible and ultraviolet region result in photochemical effects by molecular (electronic) excitation. Vision ensues as a consequence of the absorption of visible rays by the rod pigment rhodopsin which is converted to "bleached" vitamin A, retinene, and energy (to nerve endings). Absorption of ultraviolet radiation in the tissue results in the chemical conversion

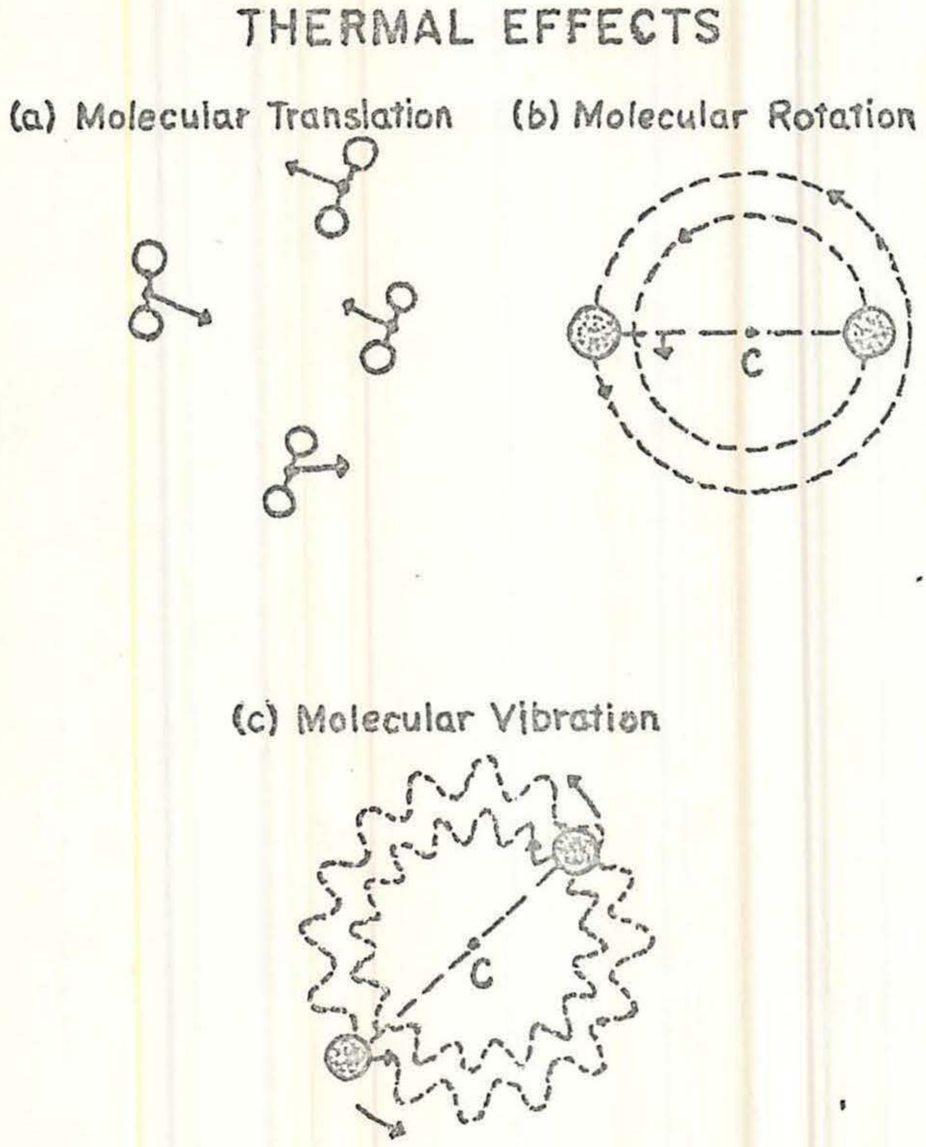
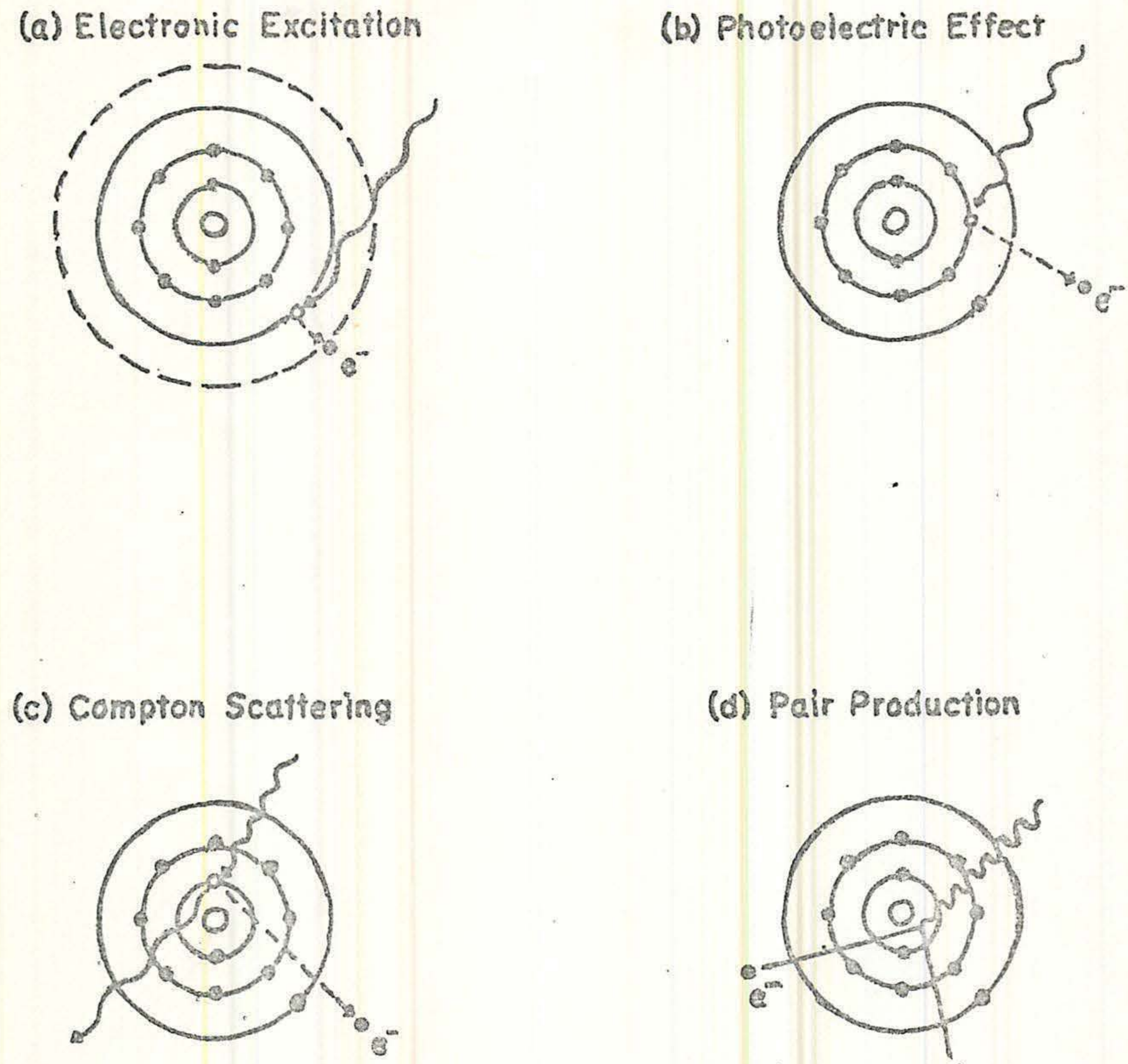

THERMAL EFFECTS
(a) Molecular Translation
(b) Molecular Rotation
C
(c) Molecular Vibration
C

Figure 2.

CHEMICAL EFFECTS



Note: Increased frequency of wavy lines designates greater photon energies.

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Figure 3.

(via excitation) of ergosterol to the anti-rickets vitamin D (calciferol).

High energy ultraviolet, X-rays, gamma rays, and particle radiation result in ionization. In general, the effects of ionizing radiation are characterized as "direct" and "indirect". The functions of the cells are felt to be integrated at the molecular level (consider especially DNA, RNA, and protein synthesis, and as such the action of radiation at this level is of vital importance. The "direct effect" of ionizing radiation is thought to result from the release of energy within the molecule itself. A simple generalization of this would be the induction of an ion cluster within the nucleic acids and/or proteins, releasing energy and thereby effecting their denaturation and consequent loss of function. An "indirect effect" of ionizing radiation results from the production of free radicals and other highly reactive agents (viz. $OH^{\cdot}$, $H^{\cdot}$, H_2O_2, and HO_2 from water) from cell constituents which act on sensitive sites within the cell. If one were to compare the biological effectiveness of the various forms of ionizing radiation discussed in this outline, one would find that, on the average, alpha particles are about 15 times more effective, neutrons 10 times, and beta particles twice as effective as X- or gamma radiation. Although there is no specificity for absorption of ionizing radiation, certain tissues in the body are more radiosensitive than others. The following biological structures are presented in order of decreasing radiosensitivity: bone marrow, lymph glands, intestinal epithelium, hair follicles, liver, kidney, nerve, brain, muscle, and connective tissue. Treatment of a patient with radiation sickness would essentially involve whole blood transfusions, antibiotic administration, and intravenous feeding. As a "rule-of-thumb" the law of Bergonie and Tribondeau describes several important factors which affect cellular radiosensitivity. In effect, it states that radiosensitivity increases with an increased rate of cellular division and metabolism and with an increase in the cellular oxygen concentration; radiosensitivity decreases with increased cellular maturity.

V. General References:

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4. Errera, M. and Forssberg, A. (eds.) Mechanisms in Radiobiology, Academic Press, New York, 1961.

Special Note: This material has been extracted almost in its entirety from a manuscript entitled "Concepts in Biophysics" Reference to the author of this report may be ~~may be~~ made if the contents of this report is otherwise quoted or copied. o/c

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