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Environmental Radioactive Pollution Sources and Effects on Man

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ABSTRACT

The sources of environmental radioactivity are essentially the naturally occurring radionuclides in the earth's crust and the cosmogenic radionuclides reaching the environmental ecosystems. The other sources of environmental radioactivity are the man made sources which result from the radioactive waste generated from the various extensive applications of radioactive materials in human life.

The naturally occurring environmental radioactivity is an integral component of the terrestrial and extraterrestrial creation, and therefore it is not considered a source of radioactive pollution to the environment. The radioactive waste from human activities is released into the environment, and its radionuclide content becomes incorporated into the different ecosystems. This results in a situation of environmental radioactive pollution.

This review presents the main features of environmental radioactive pollution, the radionuclide behaviour in the ecosystems, pathway models of radionuclides in the body and the probability of associated health hazards. The dose effect relationship of internal radiation exposure and its quantitative aspects are considered because of their relevance to this subject.

Key words : Environmental Radioactivity, Internal Exposure, Stochastic Effects.

INTRODUCTION

The sourcs and effects of environmental pollution by radioactive waste released into the ecosystems of the biosphere are intricate in complexity and depend on extensive multifactorial processes. These complicated mechanisms depend on the physical properties of the ecosystem recepient to the waste and the nature, amount, chemical and physical properties of the radionuclide composition of the radioactive waste released into the environment. All these parameters will control and influence the behaviour and fate of the radionuclide waste released into the water-air-soil-plant-animal-man pathways.

Radiation exposure of mankind from environmental radioactive pollution is mostly, but not totally by Internal Exposure after the intake of the radioactive material by the body through the processes of Inhalation, Ingestion, and via the Skin. The radionuclides are distributed within the body to the various body organs by translocation processes through biochemical and physiological mechanisms.

The ultimate issue is the absorption of energy of the radiations emitted from the radionuclide into the molecular constituents of the cell population of the volume of tissue exposed. The type and degree of the initial effect taking place after radiation energy absorption is the determining factor of the final health detriment. Internal exposure due to the incorporation of radionuclides in the body, results in low level radiation exposures. The various parameters dwling with low dose effect relationship and the probability of occurrence of delayed effects of radiation are considered.

NATURAL RADIOACTIVITY

Mankind and all forms of life on earth are exposed to radiation from natural sources of two different types. Sources from Extraterrestrial Environment as Cosmic radiations, and sources from Terrestrial Environment as the radioactive substances in earth's crust.Exposure of man to these natural sources vary little from year to year. The exposure dose from natural sources depends mainly on place of residence, type of dwelling, nature of earth's crust, altitude and other factors. The average global Annual Dose Equivalent from these Natural Sources is approximately 1.2 - 2.4 m.Sv at sea level.

The Extraterrestrial Radiation (Cosmic Radiation) include cosmic rays and cosmogenic radionuclides. The cosmic rays are primary and secondary ionizing components and neutron component. The cosmogenic radionuclides include:- Beryllium-7, Tritium H-3, Sodium-22, and Carbon-14. Chlorine, sulphur, phosphorus and other radionuclides also exist with relatively much shorter half life and less abundance. The Annual Dose Equivalent from Cosmic Radiations was calculated as 0.4 -1 m Sv.

The Terrestrial Radiation include premordial radionuclides of two types. The series premordial radionuclides include mainly Uranium-238 series, and Thorium-232 series. The Uranium series includes Radon-222 gas which contributes about 40 percent of the total Natural Radioactivity. The non-series premordial radionuclides include mainly Potassium-40 and Rubidium-87 as the most abundant of this group of about seventeen radionuclides. The other members of the group e.g. Vanadium-50, Cerium-142, Bismuth-209, Platinum-190, and Indium-155 are of no dosimetric significance.The Annual Dose Equivalent from Terrestrial Radiation for the most world average is 0.8 -1.4 m Sv at Sea Level.

MAN MADE ENVIRONMENTAL RADIOACTIVE POLLUTION

The advent, development and subsequent expansion of nuclear sciences and the proliferation of nuclear technology has resulted in the genration of radioactive waste which is released into the environment.These include:-

Technologically Modified Sources

- Airborne discharges of traces of U-238 and Th-232 fly ash from coal fired power plants.
- Airborne solid and liquid effluent waste from phosphate mining .
- Airborne solid and liquid effluent waste from processing operations of uranium.
- Tailings from Mining of Radioactive materials.
- Naturally Occurring Radioactive Materials (NORMS) in Petrolium Industry.
- Atmospheric discharges of large amounts of Radon -222 from geothermal energy production.
- Miscellaneous sources as Consumer products.

Nuclear Industry and Applications.

- Fall out from Nuclear Explosions
- Waste generated from Nuclear Industry and Nuclear Fuel Cycle.
- Milling of Radioactive Ores.
- Nuclear Fuel Fabrication and Reprocessing.
- Reactor Operation and Reactor Accidents.

- Radiological Incidents and Accidents.
- Radioactive Waste Disposal.
- Radioactive Waste generated from disciplines and applications of nuclear practices.

ENVIRONMENTAL ECOSYSTEMS.

Atmospheric Ecosystem.

The transport mechanisms of pollutants released in atmosphere depend on the physical properties of the atmospheric layer that control the diffusion and deposition of pollutants. These physical properties are:-

- *The Friction Layer " Planetary - Boundary Layer* which extends from ground surface to 200 - 3000 meter above, in which releases of radioactive gaseous and particulates take place.
- *Aerosol Formation.*
- *Atmospheric Dispersion Kinetics.*
- *Deposition and Resuspension.*

The above considerations apply to radioactive pollutants released into the Planetary Boundary Layer from ground installations. However, when radioactivity originates from nuclear or thermonuclear explosions, the problem involves knowledge of the physical properties of the stratosphere.

Aquatic Ecosystem.

This ecosystem constitutes all formations of water bodies, oceans, Seas, Rivers, Lakes, Estuaries and otherwise,subsurface aquifers are included.The basic physical properties of the Aquatic Ecosystem are:-

- Nature of the water body.
- Kinetics of Aquatic Dilution and Transport.
- Sediment Effect.
- Water Turbulence and Advection properties of water body.
- Mixing characteristics.
- Adsorption - Absorption - Aggregation properties of pollutant.

Terrestrial Ecosystem

This ecosystem includes soil formation, water content, porosity of soil media, and underground aquifers.The most important relation of the Terrestrial Ecosystem is with plants. This has a definite impact on the Food Chain from soil to animal and man. For such purpose, radionuclides in soil find their way to plants by root uptake. Soil-plant transfer coefficients have been calculated for several radionuclides and for several plants.In addition to root uptake, direct deposition on foliar surfaces occurs, in which case contaminants can be absorbed metabolically into the plant. More likely, may be transferred directly to animals as fodder.

RADIOACTIVITY RELEASED INTO ENVIRONMENT.

The behavior and fate of radionuclides released into the environment as a result of nuclear practices has developed into a discipline of science that deals with the physical and chemical nature of the radionuclides and the very complex properties of the environmental ecosystems. The problems of Environmental Radioactive Pollution are very extensive and complex.They primarily concern the behaviour and fate of the various radionuclides released into the ecosystems. The final outcome of this maltifactorial behaviour is the incorporation and subsequent translocation of the radionuclides in the Air - Water - Soil - Plant - Animal - Man pathways.

Factors Affecting Behaviour and Fate.

- Abundance of radionuclide release.
- Chemical properties of radionuclide.
- Critical pathways of radionuclides.
- Controlled Release Limits.
- Type and extent of radionuclides pollution.
- Nature and physical characteristics of the ecosystems.
- Protracted impact of radionuclide release into environment.
- The transfer of radionuclides from one ecosystem to the other.
- Potentials of each ecosystem to dilute or concentrate a radionuclide.
- The kinetics of uptake of radionuclides by plants.
- Digestion and excretion pathways in animals.
- The changing patterns of Air - Water - Soil - Plant - Animal -Man cycle.
- Food habits and Food consumption of resident populations.
- The population size exposed.

MODALITIES OF HUMAN RADIATION EXPOSURE.

Mankind is exposed from the natural and man-made sources of radiation by two exposure routes, namely External Exposure and Internal Exposure. From the stand point of basic radiobiology, it is the combined dose of radiation energy absorption from both External and Internal Exposures that is important. The biological effects incurred from both types of exposures are the same provided the absorbed dose and energy distribution is the same.

External Exposure

This involves the absorption of radiation energy emitted from a radiation source outside the body. The radiation energy is absorbed through the body surface to the underlying tissue volume in the field of exposure. In this case, there is a uniform process of energy distribution which is governed by the factors controlling the mechanisms of radiation energy absorption of the various types of radiation.

Internal Exposure.

This involves the entry of radioactive material into the body systems. The various radionuclides gain access into the body through three main routes of entry, namely, Inhalation, Ingestion and Entry through skin to the blood stream. Therefore, considerations of radionuclide transmission from the environment to man are through gaseous, food, and water intake. When radionuclides gain entry into body, they are adsorbed, metabolized, and distributed in body tissues according to the chemical properties of the element or compound which they represent.

In case of Internal Exposure, there is a non-uniform energy distribution, and several factors govern the ultimate effects. These effects tend to develop slowly due to the time required for the biokinetics of absorption, distribution and localization; the non-uniform radiation energy distribution within the cellular components of tissues and organs, and the time required for radioactive decay resulting in a protracted dose rather than an acute dose. The factors determining the ultimate Biological Effect of Internal Exposure are considered as physical and biological entities.

Physical Factors of Internal Exposure.

- Physical properties of radionuclide (half life).
- Type and Energy of radiation emitted.
- The Linear Energy Transfer (LET).
- Spatial distribution of Radiation Energy Absorption.
- Microdosimetric considerations.

Biological Factors of Internal Exposure.

- Chemical properties of radionuclide.
- Transportation of radionuclide through body.
- Translocation from one tissue to another
- Localization in target tissue or organ .
- Transit time in body organs .
- Excretion pathways outside the body.
- Biological Half life and Effective Half life.
- Radiation Response of Tissues.
- Other factors - Age, Sex, Pregnancy, Disease, etc.

These Physical and Biological factors are very essential in considering the pathways of radionuclides in human body, their transportation, translocation, retention, localization, modes of excretion and transit time within the body. These factors are used to calculate the Absorbed Dose to organs and tissues, and to construct mathematical models for the purpose of Internal Dose Assessment.

HEALTH EFFECTS OF RADIATION EXPOSURE

When the body is exposed to Ionizing Radiation, the radiation energy interacts with the tissues by transfer of the energy to the cellular and other constituents and results in ionization of their atoms. This phenomenon has been extensively studied in the critical genetic material DNA which controls celluair functions, and in other important biomlecules involved in the preservation of cellular and tissue integrity. If the radiation induced damage to DNA and other biomolecules is slight, and the rate of damage production is not rapid due to the low radiation dose and low dose rate exposure, the cells may be able to repair most of the damage. If the radiation induced damage is irreparable and severe due to the high radiation dose and high dose rate exposure, the induced damage will interfere with cellular function and integrity, and the cell will die either immediately or after several divisions. The cellualr response to radiation injury varies greatly according to the cell type involved. Highly proliferative and differentiating cells have the highest response.

At low doses, the cell injury is accomodated by the normal mechanisms that regulate molecular repair and cellular regeneration. However, this molecular repair may be defective and incmplete; in which case the future life of the cell is threatened by possible alteration of the normal cellular proliferation and differentiation processes to convert into the path of malignant transformation many years later. The incurred unrepaired defect in cells of the gonads may lead to hereditary effects in future generations.

Both Cancer Transformation and Hereditary Effects are called Delayed Stochastic Effects; they may occur with certain probability after exposure to ionizing radiation at low doses and low dose rates. The frequency, and not the severity of these effects is dose dependent. These effects are not radiation specific, and therefore cannot be directly attributed to a given radiation exposure. These effects are expected to appear as long term effects and would require meticulous epidemiological studies to establish proper dose response relationship.

At high dose and high dose rate exposure, repair and regeneration mechanisms are inadequate to meet the type and degree of cellular damage inflicted by the high dose. In this case, large number of cells are destroyed leading to impairment of tissue and organ function. This rapid uncompensatable cell death at high doses leads to early deleterious radiation effects which become clinically evident within days or few weks after exposure. These are known as Acute Deterministic Non-Stochastic Effects. These effects are radiation specific, and their severity is dose dependent. These deterministic effects can be lethal in a very short time if the radiation dose is sufficiently high.

Stochastic Effects

- Occur with both high and low doses.
- Conform with the Linear, Quadratic and Linear - Quadratic Dose Effect Relationship.
- No evidence of causative Threshold Dose.
- Chance of occurrance is purely Probabilistic
- Severity of Effect is not a function of magnitude of dose.
- Probability of occurrence is a function only of dose magnitude. It is not a function of dose rate or dose fractionation.Also, the number of persons exposed increases the probability of occurrence in the exposed population.
- Examples : Cancer transformation of tissues,Genetic Effects, Non specific aging,Other effects

Non - Stochastic Effects

- Occur only after relatively high doses.
- Have a threshold dose for each effect, below which the effect does not occur.
- Occur if dose is at or above the threshold dose for that effect.
- Occurrence and severity are highly dependent on dose rate and dose fractionation.
- Examples : Hemopoietic and Gastero - Intestinal Syndromes, Central Nervous System Syndrome, Acute Skin Lesions, All forms of Acute Radiation Injury, Depression of Immune Response, Psychosomatic Disturbances, Cataract and Infertility.

PATHWAY MODELS OF RADIONUCLIDES

These Pathway Models are designed by ICRP expert committees for the uptake of radionclides into the body. The models consider the various Metabolic Pathways, Transfer Compartments , Transloction and Retention processes and the final localization and deposition in critical organs. Such models were developed in accordance with the terms and parameters of the Reference Man. These models are used for computations of Internal Dose Assessment from radionuclides incorporated into the body.

The Lung Model This model comprises two components:

The Respiratory Deposition Model

This is governed by the Activity Median Aerodynamic Diameter (AMAD) or the Mass Median Aerodynamic Diameter (MMAD) of the aerosol. The Mass Median Aerodynamic Diameter is the particle size which determines the fraction by weight of the inhaled particles which will be deposited in each anatomical compartment of the lung. The Activity Median Aerodynamic Diameter (AMAD) is that diameter that determines the fraction of Inhaled Air Activity that is deposited in a particular compartment.

Retention Model.

This represents the various components of the retention process in the respiratory tract. This model also represents the three major closely related organ systems, namely the gastrointestinal tract, the systemic circulation, and the pulmonary lymph nodes. The dynamics of the retention model and its constituent pathways depend on the classification of elements by ICRP task group on Lung Dynamics. This falls into three categories; class Y Avid retention, slow clearance (years); Class W Moderate retention, intermediate clearance (weeks); and Class D Minimal retention, rapid clearance (days).

The Ingestion Model.

Any internal exposure by radionuclides whether by Inhalation or Ingestion leads ultimately to the entry of the radionuclides into the Gastrointestinal Tract. This Model describes the kinetics of radionucldes in the G.I. tract compartments : Stomach, Small Intestine, Upper Large Intestine, Lower Large Intestine, and the Body Fluids Compartments. The Mean Residence times in each compartment is considered. The translocation from one compartment to the next is assumed to be governed by first order kinetics. Any pathology delaying the transient times through the different compartments of the G.I. tract will affect the calculation of the internally absorbed radiation dose.

Uptake and Retention Model. (Translocation Model)

This model represents the intake of radionuclides by Inhalation and or Ingestion. In either case, there will be absorption of the radionuclide into the blood and the body fluids (The Transfer Compartment); and from there to the systemic organs, at rates depending on the metabolic processes and the chemical properties of the particular material. The radionuclides in the transfer compartment are removed by first order kinetics processes, with biological half life in the transfer Compartment ($T_{1/2}$) which differs from one radionuclides to the other).

The Iodine Model (Riggs - ICRP).

This is a three compartment model representing the Iodine Transfer Compartment, the Thyroid gland and the remaining body organs. Iodine deposited in the Transfer Compartment is removed with biological half life of 0.25 days. The thyroid gland takes 30%, and 70% is excreted via urine. Iodine is removed from Thyroid with biological half time of 120 days, and the iodine in organic form is deposited into the compartment representing other organs and tissues. Iodine is removed from the organs, 10% goes to fecal excretion, and 90% is returned to the Transfer Compartment with a biological half life of 12 days for both pathways.

HEALTH HAZARDS OF INTERNAL EXPOSURE.

Somatic Effects.

These effects appear after a latent period of time following exposure. They are considered as Delayed Probabilistic Stochastic Effects. These effects comform with all the features of stochastic effects and the underlying stochastic mechanisms and probabilities. The most common of these effects are :-

- Leukemia which affects the bone marrow cells. High incidence have been observed in populations receiving radiation doses to the bone marrow cells. It is caused from radionuclides deposited in Bone Marrow cells, or from those deposited in bone osteocytes.
- Bone cancer occurs from radiations emitted from radionuclides deposited in " Endosteal " bone cells or "Osteocytes" . Such malignancies have been observed mainly in Radium, Strontium, Plutonium bone depositions.
- Bone osteoporosis has been observed, also extensive bone necrosis, both of which are associated with spontaneous fractures.
- Lung cancer has been observed particularly in population groups exposed to high concentrations of radon gas. Extensive Dosimetric and Epidemiological studies have been performed and many are in progress.
- Aging effects which are non specific acceleration of the ageing process. However, data reported in literature indicates that there is no evidence of life shortening caused by Internal Exposure.

Hereditary Effects.

These may appear after radiation induced induction of mutation on the DNA molecule of human gonadal cell chromosomes. Most radiation induced mutations are recessive which do not express themselves in the offspring unless similar mutation is encountered in the chromosome of the mate. The probability of this increases after several generation. It is estimated that 4% of all individuals inherit characteristics that result from recessive mutations due to natural factors in environment. This percentage certainly increases in populations subject to high radioactive environmental pollution.

INTERNAL EXPOSURE AND LOW LEVEL RADIATION.

The mechanisms of radiation injury and the ecological relationship that exists in an environment contaminated by radioactive material have been extensively studied during the past fifty years. The greatest body of information comes from experimental animal studies and much was obtained from human experience. This data establishes much knowledge related to the Dose Response Mechanisms of Radiation Injury to Biological Systems.

The problems related to Internal Exposure are formidable because they deal with the behaviour of the radionuclide in the complex environment, its pathway in the human body, and the non-uniform mode of Radiation Energy Distribution emitted from the radionuclide inside body tissues.

All the studies performed and the pathway Models postulated are constructed according to the concept of the "Reference Man" . Internal Exposure is usually associated with low level radiations, and therefore, Internal Exposure does not usually lead to Acute Radiation Effects. However, Delayed Effects do occur governed by the probability of the Dose effect relationship that controls exposures to Low Level Radiation, and the factors involved in the probability.

Quantitative Aspects.

The dose response relationship for induction of hereditary effects, and also the dose response relationship for cancer induction are Linear without threshold, ie they are dependent on a Stochastic Response. This statement has been established on experimental evidence.This implies that:

- No threshold dose exists for both delayed somatic and hereditary effects.
- Both effects are inherently stochastic in nature.
- The frequency with which the effects occur depend on probabilistic mechanisms.
- The probability of induction of an effect is a continuous function of radiation dose.

A hypothesis that competes with the Linear dose response relationship in the Quadratic form in which the number of effects produced per unit dose increased progressively with increasing dose. Recently, both hypothesis are put together, the so-called "Linear-Quadratic" relationship, which has been favored by Radiobiologi st. In this relationship, the effects are linear at low doses, but become curvilinear at higher doses according to the relationship ($I = a D + b D2 + C$)

Where : I incidence.
C incidence at natural radiation background exposure.
D Exposure Dose at low levels.
a,b Constants determined empirically, which determine the slopes of the Linear and Quadratic portions of the curve respectively.

Exposure levels from environmental radioactivity (natural and man made) are considered low level radiations, and the effects are therefore assumed to be governed by the Linear portion of the Linear - Quadratic dose response relationship.

The fact that the dose - response relationship is assumed to be linear with absence of a threshold, has important implications for risk assessment and formulation of public policy. The absence of a threshold implies that there is no absolutely safe level of exposure. Every increment of dose however small above natural radiation background has an increment of risk (probability of an effect occurring); this risk becomes small as the dose diminishes.

A dilemma arises from the assumption of the linearity relationship and the absence of a threshold; that is Individual risk can be very small, but Collective risk can be very significant. The important question therefore arises whether the permissible dose levels should be defined on the bases of individual risk or collective risk. The question fails to be answered by the existing technical, moral and political concepts.

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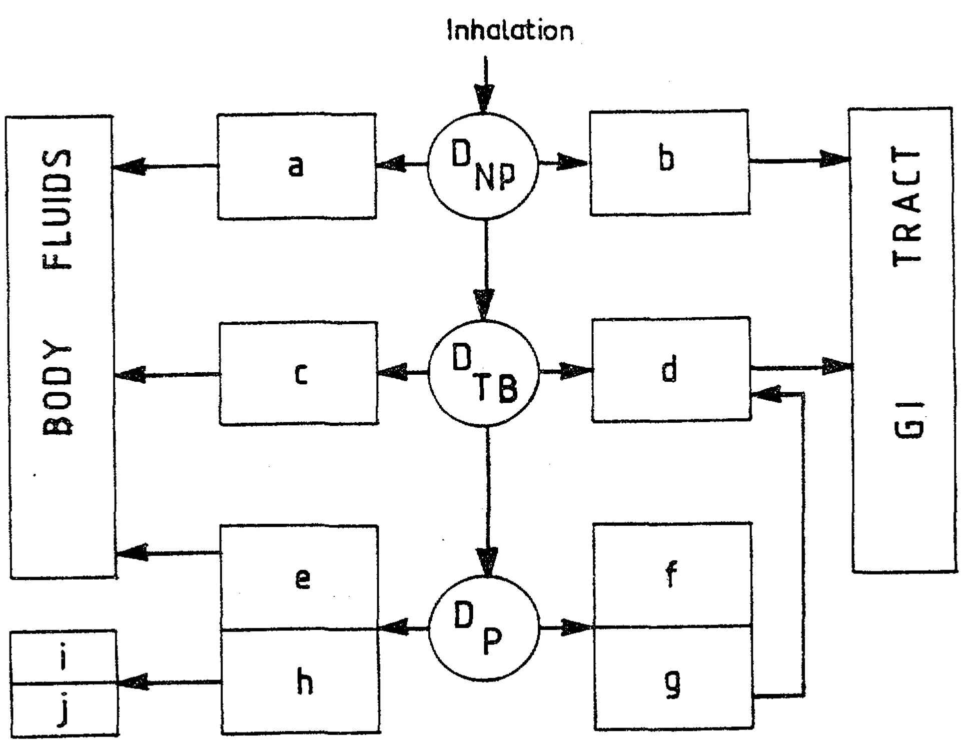
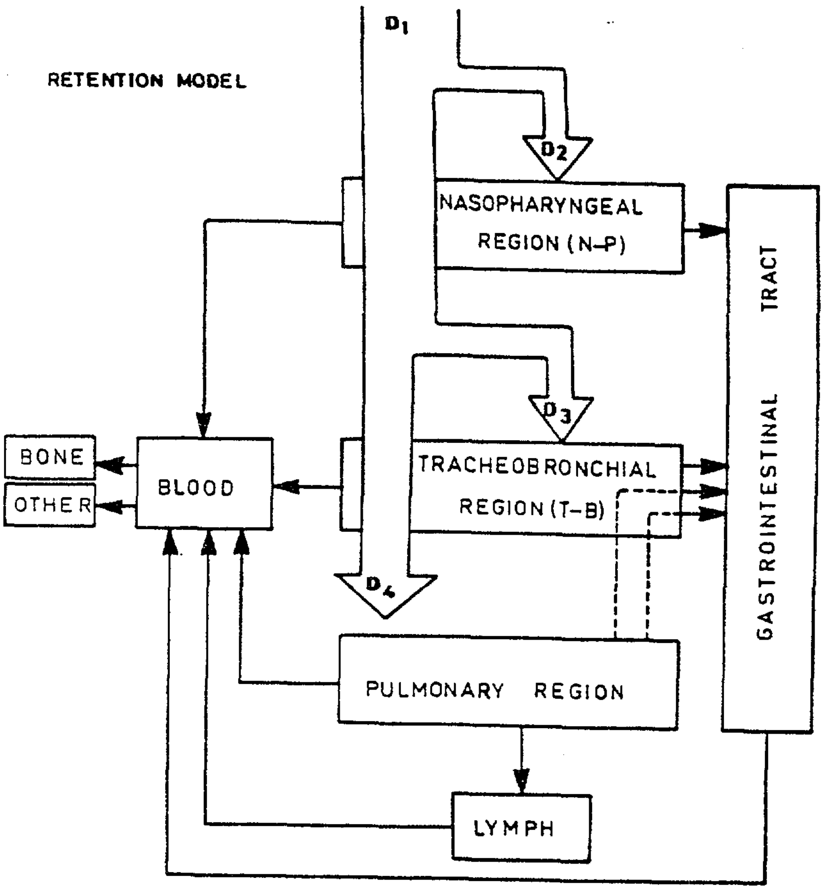
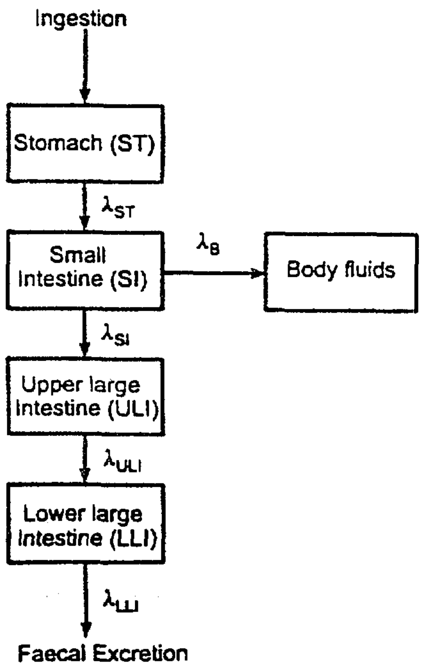
DESCRIPTION OF PATHWAYS

a) Rapid uptake from nasopharynx to blood circulation.
b) Rapid clearance from nasopharynx to G.I. tract by ciliary mucous transport.
c) Rapid absorption of dust from tracheobronchial region to blood.
d) Rapid ciliary clearance from tracheobronchial region to G.I. tract.
e) Direct translocation of dust from pulmonary region to blood.
f) Clearance of pulmonary region via tracheobronchial tree to G.I. tract by action of macrophages and ciliary mucous transport processes.
g) Secondary clearance process by ciliary mucous transport via tracheobronchial region to G.I. tract, at slower rate than (f).
h) Slow removal of dust from pulmonary compartment via lymhatic system transport.
i) Dust cleared by lymphatic system is introduced into systemic circulation. This depends on ability of cleared material to penetrate the lymphatic tissues.
j) Passage of material from G.I. tract to systemic circulation.

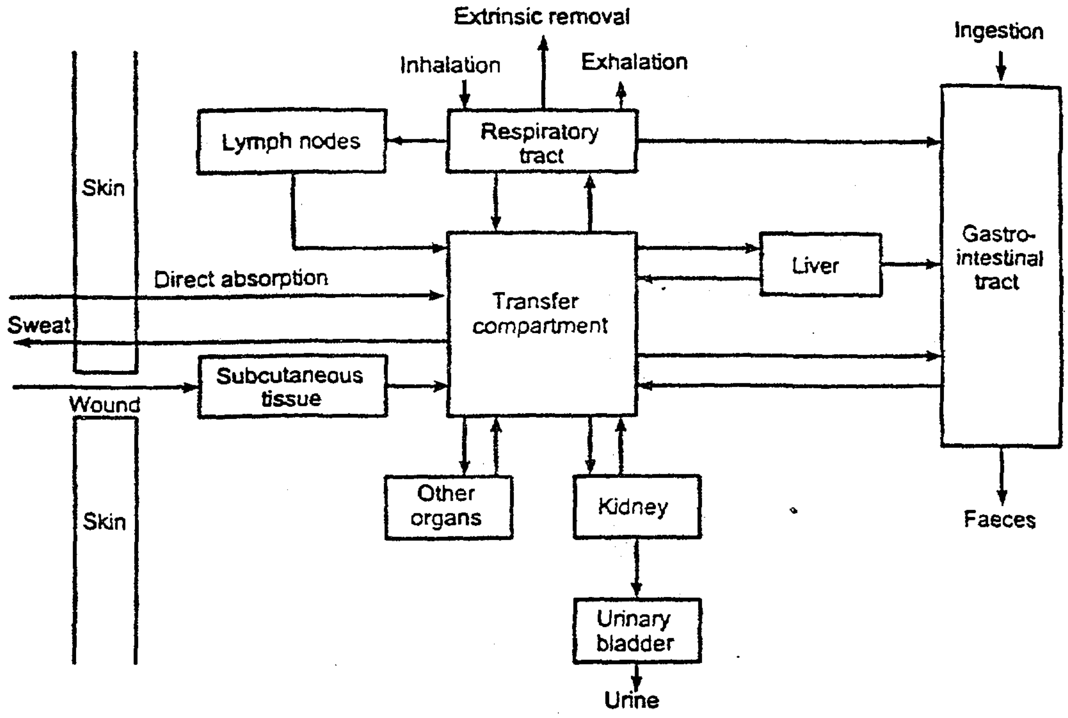


The ICRP lung model

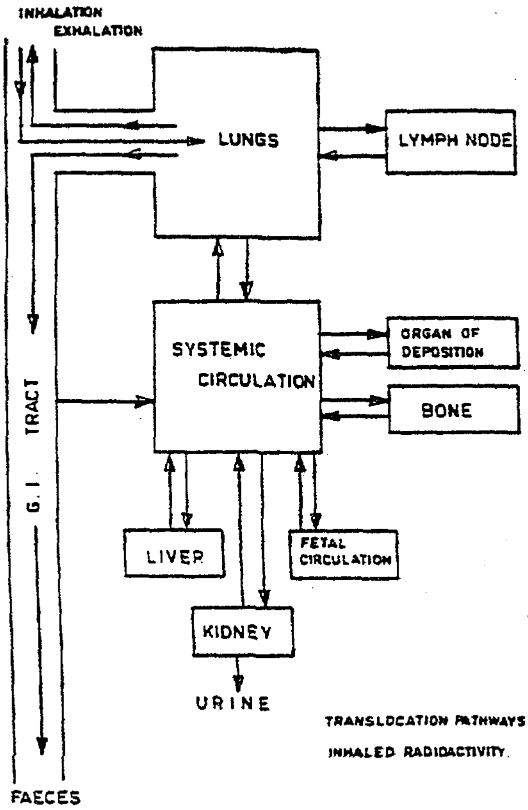




Mathematical model used to describe the kinetics of radionuclides in the gastrointestinal tract



. Routes of intake. transfers and excretion.



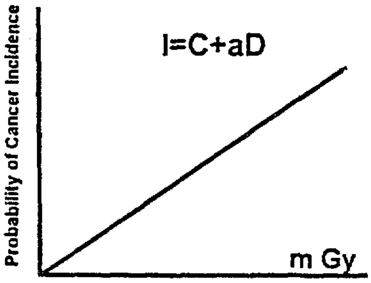
TRANSLOCATION PATHWAYS OF INHALED RADIOACTIVITY.

Dose Response Relationships

- Dose Response Relationship for these effects is very complicated. The most important models for this relation are that which conform with the No Threshold Concept. These are :

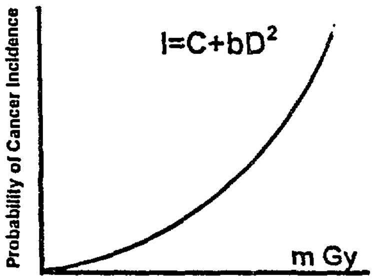
1- The Linear Proportionality

a- Coefficient that determines the slope of linear curve.
I - Total Incidence .
C- Spontaneous Incidence.
D- Radiation Dose.
(Low LET Radiation).



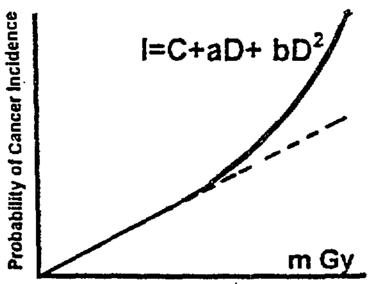
2- The Quadratic Relation

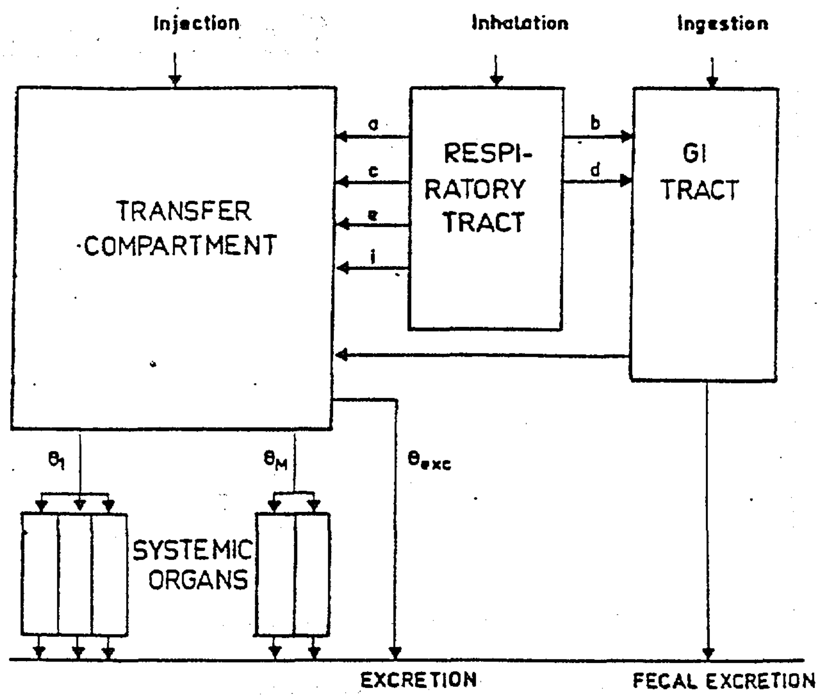
b- Coefficient that determines the slope of Quadratic Seg.
I - Total Incidence .
C- Spontaneous Incidence.
D- Radiation Dose.
(Low LET Radiation).



3- The Linear Quadratic Relation

a- Coefficient that determines the slope of Linear Seg.
b- Cofficient that determines the slope of Quadratic Seg.
I - Total Incidence .
C- Spontaneous Incidence.
D- Radiation Dose.
(Low LET Radiation).



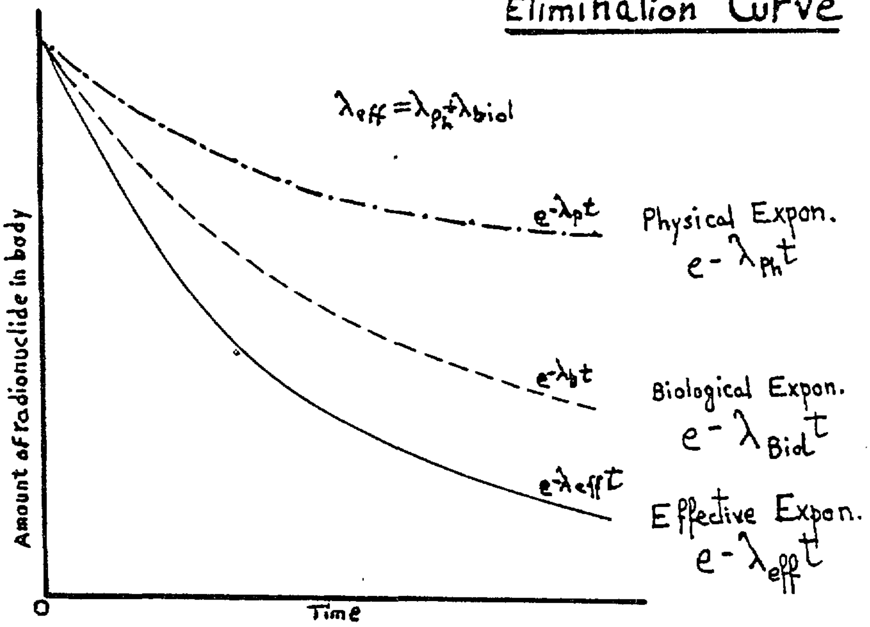


Uptake and retention of radionuclides in the body

- Final pool of Inhalation and Ingestion of radionuclide is the Transfer Compartment. (T.C.)
- Radionuclides are removed from T.C. by systemic Organs at rates that depend on :-
  - Organs metabolic processes.
  - Chemical properties of radionuclide.
  - Loss from T.C. by radioactive decay.
  - Formation and decay of radioactive daughters.
- Radionuclides in T.C. are removed by first order kinetics processes with biological half time for the T.C. (T_{Tc}) of about six hours (except for certain radionuclides).
- The systemic organs and direct urine excretion are arranged in parallel and compete with each other to remove the radionuclide from the T.C. with parameterized allocation by fractions $\theta, \ldots\ldots \theta_M$ and θ exc.

  where $\theta + \cdots\cdots + \theta_M + \theta$ exc.

Elimination Curve



Typical elimination Curve of a radionuclide in the body

where

λ_{ph} = radioactive decay constant.
λ_b = biological decay constant .

Since the decay constant is equal to $\log_e 2$ half-life, this equation becomes: —

$$\frac{1}{T_{eff}} = \frac{1}{T_{ph}} + \frac{1}{T_{biol}} \quad \text{i.e.} \quad \boxed{T_{eff} = \frac{T_{ph} \times T_{Biol}}{T_{ph} + T_{Biol}}}$$

where :

T_{eff} = effective half-life of a radioactive substance in the body.
T_{ph} = radioactive half-life of the substance.
T_b = biological half-life of the substance..