Australian Government
Department of Health

Australian clinical guidelines for radiological emergencies

September 2012

Australian Clinical Guidelines for Radiological Emergencies, September 2012

Contents

Preface

An incident involving even a single casualty from an incident involving radiological materials is likely to trigger widespread community concern. Significant numbers of individuals may seek assessment and reassurance about potential health effects, from hospitals and other clinical providers.

The nature of radiation is frequently poorly understood, and this may create anxiety even amongst health professionals. The principles of ionising radiation, its health effects and treatment should be included in clinical education to address knowledge deficits. Enhanced understanding is relevant, not just in preparedness for radiological incidents, but also to the concept of justification in the use of diagnostic radiology. Justification is the principle of minimising exposure to ionising radiation unless the benefit outweighs the risk of harm.

Organisationally, a structured approach to the management of radiological incidents is essential to ensure occupational safety of personnel, and appropriate allocation of resources. Preparedness for radiological events is a component of all hazards approach that ambulance and hospitals must address as part of emergency planning. Planning must consider both mass casualties and the hazardous nature of radioactive substances.

Procedures should be documented as part of emergency response plans, taught and exercised.

The Australian Health Protection Principal Committee (AHPPC) commissioned a comprehensive technical guide for clinicians and public health professionals to provide a reference for education and planning for the management of radiation incidents. The document also needed to provide specific therapeutic indications and protocols for the use of decorporation agents used to treat radiation injuries. The guidelines were developed to complement existing national guidelines on Anthrax, Smallpox and Chemical Agents.

The ARPANSA Technical Report Series number 131, Medical Management of Individuals Involved in Radiation Accidents, 2000 formed the starting point for development of the Australian Radiological Clinical Guidelines. At times, content in these guidelines is based on ICRP 60 rather than the updated ICRP 103, 2007 Recommendations of the International Commission on Radiological Protection. Whilst these are likely to be adopted within Australia in the near future, they have not been endorsed at the time of writing.

The guidelines aim to provide:

- A plain language, practical manual written for clinicians to address basic knowledge gaps
- Sufficient information to contribute to realistic risk assessment
- Technical content consistent with contemporary evidence-based clinical practice
- Health professionals with resources to facilitate the administration of clinical care in a mass casualty radiation event.

The guidelines do not include laboratory methodology, as this is beyond the scope of this document.

Contributors to this document include:

- Dr Stephen Solomon, ARPANSA
- Cmdr Alison McLaren, RAN
- Dr Andrew Pengilley, ACT Department of Health Jon Byrne, Ambulance Victoria

- Dr Jane Canestra, Victoria Department of Health

Special thanks go to Dr Lindsay Murray, University of WA, Sir Charles Gardiner Hospital, and Poisons Information Centres WA/NSW/Qld, and Mr Jeff Robinson, Victorian Poisons Information Centre for their assistance in reviewing the toxicological content of these guidelines.

Dr Jane Canestra

Chair of the Writing Group for National Clinical Guidelines for Radiological Emergencies

How to use these guidelines

The guidelines are intended as a resource for paramedics, hospital clinicians and public health officials to enable better understanding of radiation hazards and effects, and optimal management of radiation casualties and concerned communities.

The guidelines are arranged in three sections:

- Introduction to ionising radiation, its health effects, the system of radiation protection, and possible radiological scenarios that could result in casualties;

- Arrangements for ambulance, hospitals, public health advice, laboratories and obtaining specialist advice; and

- Clinical management of radiation dose assessment, contamination, injury and prenatal exposure.

Each section is written with the needs of health professionals in mind, and structured to provide detailed standard operating procedures, therapeutic information, management advice, and planning guidance as necessary. Where appropriate, very technical detail is contained within an appendix immediately following the relevant chapter.

References have been included in some sections to provide clinicians with the source material and further reading opportunities.

It is hoped that this document serves as a useful reference.

Acronyms and abbreviations

Terms	Definition
ACPSEM	Australian College of Physical Scientists and Engineers in Medicine
AFRRI	Armed Forces Radiobiology Research Institute
AHPPC	Australian Health Protection Principal Committee
AIR	Australian Institute of Radiography
ALARA	As Low as Reasonably Achievable
ALI	Annual Limit of Intake
Am	Americium
ANSTO	Australian Nuclear Science and Technology Organisation
ANZSNM	Australian and New Zealand Society of Nuclear Medicine
ANZSNMT	Australian and New Zealand Society of Nuclear Medicine Technologist
ARPANSA	Australian Radiation Protection and Nuclear Safety Agency
ARPS	Australian Radiation Protection Society
ARS	Acute radiation syndrome
BAT	Biodosimetry Assessment Tool
Bq	Becquerels
BSA	Body Surface Area
Ca	Calcium
CBMN	Cytokinesis Block Micronucleus
CBRN	Chemical, Biological, Radiological, and Nuclear
CCs	Collaborating Centres
CDC	United States Department of Health and Human Services Centers for Disease Control and Prevention
CEDE	Committed Effective Dose Equivalent
CNS	Central Nervous System
Co	Cobalt
CRI	Cutaneous Radiation Injury
CRS	Chronic Radiation Syndrome
Cs	Caesium
CSIRO	Commonwealth Scientific and Industrial Research Organisation CT Computed Tomography

Terms	Definition
DMPS	2,3-Dimercapto-1-propanesulfonic acid
DMSA	Dimercapto-succinic acid (Succimer)
DNA	Deoxyribonucleic Acid
DPM	Disintegrations per minute
DTPA	Diethylene Triamine Penta-acetic Acid
DVI	Disaster Victim Identification
ECG	Electrocardiogram
ED	Emergency Department
EPR	Electron Paramagnetic Resonance
ESO	Emergency Service Organisation
ESR	Electron Spin Resonance
FBE	Full Blood Examination
FISH	Fluorescent In Situ Hybridisation
G-CSF	Granulocyte Colony-Stimulating Factor
GM-CSF	Granulocyte Macrophage Colony-Stimulating Factor GvHD Graft versus Host Disease
Gy	Gray
HAZMAT	Hazardous Materials
HBV	Hepatitis B Virus
HCV	Hepatitis C Virus
HIV	Human Immunodeficiency Virus
HSANZ	Haematology Society of Australia and New Zealand
I	Iodine
IATA	International Air Transport Association

Glossary

Term	Definition
Absorbed dose	The quantity of energy imparted by ionising radiation to unit mass of matter. Unit gray (Gy). 1 Gy = 1 joule per kg
Activity	Attribute of the amount of a radionuclide. The rate at which a radionuclide transforms. Unit becquerel (Bq). 1 Bq = 1 disintegration per second
Alpha particle	A particle comprised of two protons and two neutrons emitted from a radionuclide
Annual limit of intake (ALI)	One ALI is the maximum permissible exposure each year for occupational exposure, without detectable health risk. One ALI corresponds to a committed effective dose equivalent of 0.05 Sv, or a committed effective dose equivalent of 0.5 Sv to any individual organ or tissue, whichever is the more limiting
Becquerel	The unit of activity. Symbol Bq
Beta particle	An electron emitted by the nucleus of a radionuclide
Biodosimetry	The measurement of radiation induced biological or physical effects within the body to assess the radiation dose to an individual
Biokinetics	The study of movement (of radionuclides) within organisms
Biological half-life	The time for half the amount of a substance to be eliminated from the body following absorption.
Chromosomes	Genetic material seen as rod-shaped bodies found in the nucleus of cells at metaphase. Humans have 23 pairs of chromosomes
Cloudshine	The external dose received from radioactive material that is still suspended in the atmosphere
Committed effective dose equivalent	The calculated dose over 50 years from internal contamination is the *committed effective dose equivalent* (CEDE)
Contamination	The deposition of radioactive material on skin, clothing, or in the body or environment.
Cosmic radiation	High energy ionising radiations from outer space
Curie	An older unit of activity. Symbol Ci. 1 Ci = 37 GBq (3.7 x 10^2 Bq)
Cytogenetics	The study of cell structure and functions, especially the chromosomes
Decay	The process of spontaneous transformation of a radionuclide. The decrease in the activity of a radioactive substance
Decorporation	Treatment to displace incorporated radionuclides from tissues

Term	Definition
Desquamation	Peeling of skin
Deterministic effects	Dose-related, acute health effects caused by exposure to high levels of radiation that cause large numbers of cells to die or lose their ability to replicate
Dicentrics	During repair of DNA strand breaks in cells affected by radiation, misrepair of two chromosomes and abnormal replication during cell division may result in the formation of a chromosome with two centromeres, a dicentric
Dirty bomb	Conventional explosive material combined with a radioactive substance
DNA	Deoxyribonucleic acid, genetic material
Dose	A general term for quantity of ionising radiation. See *absorbed dose, equivalent dose, effective dose* and *collective dose*. Frequently used for effective dose
Effective dose	The quantity obtained by multiplying the equivalent dose to various tissues by a weighting factor appropriate to each and summing the products. Unit sievert (Sv). Frequently abbreviated to dose
Effective half-life	The time taken for the radiological effect of the substance absorbed into the body to be reduced by half by biological elimination and radioactive decay.
Electron	An elementary particle with low mass, 1/1836 that of a proton, and unit negative charge
Electron volt	An electron volt is a unit of energy equal to the energy gained by an electron in passing through a potential difference of 1 volt. Symbol eV. 1 eV = 1.6×10^{-19} joule approximately
Epilation	Hair loss
Equivalent dose	The quantity obtained by multiplying the absorbed dose by a factor to allow for the different effectiveness of the various ionising radiations in causing harm to tissue. Unit sievert (Sv)
Fission	A process in which the nucleus splits into two or more nuclei and energy is released
Fractionated dose	(Radiation) administered in divided doses
Free radical	A grouping of atoms that normally exists in combination with other atoms but can sometimes exist independently. Generally, very reactive in a chemical sense
Gamma ray	A discrete quantity of electromagnetic energy without mass or charge. Emitted by a radionuclide.

Term	Definition
Germ cell	The gametes of any organism that reproduces sexually, i.e. ova and sperm
Germinal layer	The basal layer of skin, composed of proliferating and non-proliferating cells
Gray	The unit of quantity of energy imparted by ionising radiation to unit mass of matter. 1 Gy = 1 joule per kg
Groundshine	The external dose received from radioactive material deposited on the ground
Half-life	The time taken for the activity of a radionuclide to lose half its value by decay
Hospital health physicist	A hospital-based, non-medical, health professional working in the areas of radiology, nuclear medicine, or radiotherapy • qualified in the application of physics of therapeutic or diagnostic uses of ionising radiation, • able to perform the dosimetric calculations, radiation measurements and monitoring relevant to their area of expertise
Incorporation	Uptake of radioactive material by cells, tissues and target organs
Internal contamination	Intake of radioactive material via breathing, ingestion or through contamination of wounds
Ionisation	The process by which a neutral atom or molecule acquires or loses an electric charge. The production of ions
Ionising radiation	Radiation that produces ionisation in matter. Examples are alpha particles, beta particles, gamma rays, X-rays and neutrons. When these radiations pass through the tissues of the body, they have sufficient energy to damage DNA
Irradiation	Exposure to penetrating radiation from an external source. It does not make the irradiated person radioactive
Isotope	Nuclides with the same number of protons but different numbers of neutrons
Justification	A radiation protection principle which states that human activities that cause exposure to radiation may be permitted only if they do more good than harm
keV	Equal to 1000 eV
Linear energy transfer	The measure of energy transferred to tissues as a result of ionising radiation passing through it

Term	Definition
Medical health physicist	A non-medical, health professional working in the areas of radiology, nuclear medicine, or radiotherapy • qualified in the application of physics of therapeutic or diagnostic uses of ionising radiation, • able to perform the dosimetric calculations, radiation measurements and monitoring relevant to their area of expertise
Myelosuppression	Bone marrow suppression
Neutron	An elementary particle with unit atomic mass approximately and no electric charge
Nuclear medicine physician	A registered medical practitioner with specialist qualifications in nuclear medicine
Nuclear reactor	A device in which nuclear fission can be sustained in a self-supporting chain reaction involving neutrons.
Nucleus	The core of an atom, occupying little of the volume, containing most of the mass, and bearing a positive charge
Nucleus of a cell	The controlling centre of the basic unit of tissues. Contains DNA
Nuclide	A species of atom characterised by the number of protons and neutrons
Optimisation	A radiation protection principle which states that exposure to radiation from justified activities should be kept as low as reasonably achievable, social and economic factors being taken into account
Penetrating radiation	Refers to the properties of different types of ionising radiation to travel through tissue. For example, alpha particles are generally considered unable to penetrate intact skin, but gamma radiation travels many centimetres through tissues
Photon	Quantity of electromagnetic radiation
Physical half-life	The time for half the amount of a substance to undergo radioactive decay.
Probability	The mathematical chance that a given event will occur
Proton	An elementary particle with unit atomic mass and unit positive charge
Pulmonary lavage	Bronchopulmonary lavage is a procedure for washing out the lungs
Radiation	The process of emitting energy as waves or particles. Frequently used to mean ionising radiation, except when it is necessary to avoid confusion with non-ionising radiation

Term	Definition
Radiation oncologist	A registered medical practitioner with specialist qualifications in the therapeutic use of radiation in cancer treatment
Radiation safety officer	A member of the diagnostic radiology department or occupational health and safety unit responsible for safe operations in everyday use of radiation and, in a radiological emergency, assisting staff to ensure their doses are as low as reasonably achievable, and providing technical support and documentation
Radioactive	Possessing the property of radioactivity
Radioactivity	The property of radionuclides spontaneously emitting ionising radiation
Radiological protection	The science and practice of limiting harm to human beings from radiation
Radiologist	A registered medical practitioner with specialist qualifications in diagnostic and/or interventional radiology
Radiomimetic effect	Inducing effects comparable to the biological effects of ionising radiation
Radionuclide	An unstable nuclide that emits ionising radiation
Radiotherapy	The use of radiation beams for treating disease
Risk	The probability of injury, harm or disease
Risk factor	The probability of cancer, leukaemia or hereditary damage per unit equivalent dose. Usually refers to fatal malignant diseases and serious hereditary damage. Unit Sv^{-1}
Sievert	The unit defined by the quantity obtained by multiplying the equivalent dose to various tissues by a weighting factor appropriate to each and summing the products. Symbol Sv
Stochastic effects	Doses below the thresholds for deterministic effects may cause cellular damage, with effects that are probabilistic (occurring by chance) or 'stochastic' in nature. Stochastic effects are believed to result from damaged cells not dying but surviving in a modified form. These effects usually appear many years after the exposure, although they do not occur in every exposed individual, the likelihood of a cancer or hereditary effect occurring after exposure is assumed to be proportional to the level of exposure
Stratum corneum	The outermost layer of the skin, comprising dead cells
Total effective dose equivalent	The sum of the committed effective dose equivalent and any external dose received is the *total effective dose equivalent* (TEDE)
Tritiated water	Water molecules incorporating tritium (^{3}H)

Term	Definition
Unstable	An isotope or nuclide is considered to be unstable if it has a half-life less than the age of the universe i.e., less than about 13.7 billion years
X-ray	A discrete quantity of electromagnetic energy without mass or charge. Emitted by an X-ray machine

Reference: ARPANSA. Radiation basics – glossary of terms. Available from
http://www.arpansa.gov.au/radiationprotection/basics/glossary.cfm

Introduction

Ionising radiation and human health

Introduction

Radiation is energy that comes from a source and travels through some material or through space. Ionising radiation is produced by unstable atoms. Unstable atoms differ from stable atoms because they have an excess of energy or mass or both. Unstable atoms are said to be radioactive. In order to reach stability, these atoms give off, or emit, the excess energy or mass. These emissions are called radiation. When the radiation interacts with other atoms, it ionises the atoms altering their chemical properties, hence ionising radiation.

The kinds of radiation are electromagnetic (like light) and particulate (mass given off with the energy of motion). Gamma radiation and X-rays are examples of electromagnetic radiation. Beta and alpha radiation are examples of particulate radiation. Ionising radiation can also be produced by devices such as X-ray machines. There is also natural background radiation exposure. It comes from cosmic rays and from naturally occurring radioactive materials contained in the earth and in living things.

Ionising radiation comprises four basic types:

- Gamma rays and X-rays
- Beta particles
- Alpha particles
- Neutrons

These have different physical characteristics and biological effectiveness in causing tissue damage.

Gamma radiation

Gamma radiation and X-rays are electromagnetic radiation like visible light, radio waves, and ultraviolet light. These electromagnetic radiations differ only in the amount of energy they have. Gamma radiation is able to travel many metres in air and many centimetres in human tissue. It readily penetrates most materials and is sometimes called 'penetrating radiation.' Radioactive materials that emit gamma radiation and X-rays constitute both an external and internal hazard to humans. Dense materials are needed for shielding from gamma radiation. Clothing and turnout gear provide little shielding from penetrating radiation but will prevent contamination of the skin by radioactive materials.

Beta radiation

Beta radiation consists of subatomic particles (electrons) ejected from a radioactive atom. Beta radiation may travel metres in air and is moderately penetrating. Beta radiation can penetrate human skin to the 'germinal layer,' where new skin cells are produced. If beta-emitting contaminants are allowed to remain on the skin for a prolonged period of time, they may cause skin injury. Beta-emitting contaminants may be harmful if deposited internally and clothing and turnout gear provide some protection against most beta radiation. Turnout gear and dry clothing can keep beta emitters off of the skin.

Alpha radiation

Alpha radiation consists of specific particles ejected from some radioactive atom. Alpha particles are essentially helium nuclei. They have low penetrating power and short range. Alpha radiation is not able to penetrate skin, but they can be harmful to humans if the materials are inhaled, swallowed, or absorbed through open wounds. Alpha radiation is not able to penetrate turnout gear, clothing, or a cover on a probe.

Neutrons

Neutrons are uncharged subatomic particles produced by the fission of radioactive atoms. Within tissue, neutrons predominantly lose energy in collisions with protons in the nuclei of hydrogen atoms, in body water. The interaction results in ionisation within the tissue atoms so irradiated. Except at lethal levels the neutron flux is not sufficiently high to cause the tissue to become radioactive.

Table 1.1 Summary of types of ionising radiation

Radiation	Range in air	Range in tissue	Hazard
Alpha	Few cm	50 micron	Internal
Beta	Few metres	Few mm	External and internal
Gamma	Many metres	Many cm	Mainly external
X-ray	Many metres	Many cm	Mainly external
Neutron	Many metres	Many cm	Mainly external

Radiation quantities

Radioactivity (and contamination by radioactive material) is measured in becquerels (1 Bq = 1 disintegration per second). The **absorbed dose** of radiation (the amount of energy absorbed by per unit mass of tissue) is measured in gray (Gy), where 1 Gy = 1 joule/kg of tissue.

Different types of radiation have different effects on human tissue (gray for gray, alpha particles and neutrons are more damaging than beta particles, gamma rays or X-rays in terms of the risks of cancer or of heritable genetic defects), so the absorbed dose in tissue is multiplied by a radiation weighting factor to account for this. This gives the **equivalent dose** (to an organ or tissue), measured in sievert (Sv). For X-rays, gamma rays, and beta particles, the weighting factor = 1.

The amount of damage caused by exposure to radiation depends on the efficiency with which it transfers energy into body tissues. Radiation comprised of particles with relatively high mass delivers a greater proportion of their energy into tissues than do electromagnetic radiation, such as X-rays and gamma-rays, which may pass through the body. Doses of different types of radiation are, therefore, converted into 'equivalent dose.

Table 1.2 Weighting factors for ionising radiation

Radiation	Energy transfer	Weighting factor
Alpha particle	High	20
Neutron	High	5 - 20
Beta particle, electrons	Low	1
Gamma ray, X-ray	Low	1

Reference: Recommendations for limiting exposure to ionizing radiation (1995) and national standard for limiting occupational exposure to ionizing radiation (republished 2002); Radiation Protection Series No. 1; ARPANSA.

Equivalent doses are measured in sieverts (Sv), which is equal to the absorbed dose in grays multiplied by the weighting factor. A dose of 1/100 gray delivered entirely as alpha particles would, for example, equal 20/100 sieverts.

Tissues differ in their susceptibility to radiation for a given absorbed dose. Some organs are more radiosensitive than others (e.g. bone marrow is more sensitive than thyroid), and exposures are rarely uniform. Weighting the equivalent doses received by different organs and tissues during an exposure to allow for each organ's radiosensitivity, and then summing the results, gives the **effective dose**. The 'effective dose' is calculated by multiplying the absorbed dose by a tissue weighting factor which represents the sensitivity of each tissue to radiation.

Table 1.3 Tissue weighting factors by organ

Organ	Tissue weighting factor $_T$
Gonads	0.20
Colon	0.12
Bone marrow (red)	0.12
Lung	0.12
Stomach	0.12
Bladder	0.05
Chest	0.05
Liver	0.05
Thyroid gland	0.05
Oesophagus	0.05
Skin	0.01
Bone surface	0.01
Adrenals, brain, small intestine, kidney, muscle, pancreas, spleen, thymus, uterus	the weighting factor 0.05 is applied to the average dose of these organs

Radiation exposure

Regardless of where or how an incident involving radiation happens, three types of radiation-induced injury can occur: external irradiation, contamination with radioactive materials, and incorporation of radioactive material into body cells, tissues, or organs.

External irradiation

External irradiation is exposure to penetrating radiation from a radiation source. People exposed to a source of radiation can suffer radiation illness if their dose is high enough, but they do not become radioactive. For example, an X-ray machine is a source of radiation exposure. A person does not become radioactive or pose a risk to others following a chest X-ray. Irradiation occurs when all or part of the body is exposed to radiation from an unshielded source. External irradiation does not make a person radioactive.

Radioactive contamination

Radioactive contamination occurs when material that contains radioactive atoms is deposited on skin, clothing, or any place where it is not desired. If is important to remember that radiation does not spread or get 'on' or 'in' people; rather it is radioactive contamination that can spread. A person contaminated with radioactive materials will be irradiated until the source of radiation (the radioactive material) is removed.

- A person is externally contaminated if radioactive material is on skin or clothing
- A person is internally contaminated if radioactive material is breathed in, swallowed, or absorbed through wounds
- The environment is contaminated if radioactive material is spread about or uncontained

The third type of radiation injury that can occur is **incorporation** of radioactive material. Incorporation refers to the uptake of radioactive materials by body cells, tissues, and target organs such as bone, liver, thyroid, or kidney. In general, radioactive materials are distributed throughout the body based upon their chemical properties. Incorporation cannot occur unless contamination has occurred. These three types of exposures can happen in combination and can be complicated by physical injury or illness. In such a case, serious medical problems always have priority over concerns about radiation, such as radiation monitoring, contamination control, and decontamination.

Table 1.4 Radiation exposure from common radionuclides

Radionuclide half-life	Radionuclide half-life	Decay energy [keV]	Practice or application	Typical activity	Dose rate at 1m	Time at 1m to exceed 1mSv
^{137}Cs	30 y	γ (662) β (max.: 512) e (624)	Sterilization and food preservation	0.1–400 PBq	24,000 Sv/h	< 1 s
			Whole blood irradiation	2–100 TBq	6 Sv/h	1 s
			Moisture/density detector	400 MBq	20 uSv/h	2 d
^{60}Co	5.3 y	γ (1173; 1333) β (max.: 318)	Sterilization and food preservation	0.1–400 PBq	120,000 Sv/h	< 1 s
^{192}Ir	74 d	γ (317) β (max.: 675) e (303)	Industrial Radiraphy	0.1–5 TBq	0.4 Sv/h	9 s
			Well logging	1–800 GBq	2 mSv/h	20 m
^{241}Am	432.2 y	γ (60) α (5486) neutrons	Moisture/density d (Am-241/Be)	0.1–2 GBq	6 uSv/h	7 d
			Smoke detectors	0.02–3 MBq 9 nSv/h 10 y	9 nSv/h	10 y

Radiation health effects

Adverse health effects from exposure to radiation may be deterministic, occurring soon after exposure, or stochastic, occurring some time, often many years, after exposure.

Deterministic effects

Deterministic effects are dose-related, acute health effects caused by exposure to high levels of radiation that cause large numbers of cells to die or lose their ability to replicate. Organs containing these cells then fail to function correctly. Such effects include nausea (radiation syndrome), reddening of the skin, cataracts, sterility and bone marrow failure. Each effect becomes apparent only above a threshold level and the severity of the effect depends on the level of exposure above

its threshold. Below the threshold, the body can cope with the level of cell death by repair and replacement, when no explicit damage is seen.

Extreme doses of radiation to the whole body (around 10 sievert and above), received in a short period, cause so much damage to internal organs and tissues of the body that vital systems cease to function, and death may result within days or weeks. Very high doses (between about 1 sievert and 10 sievert), received in a short period, kill large numbers of cells, which can impair the function of vital organs and systems. Acute health effects, such as nausea, vomiting, skin and deep tissue burns, and impairment of the body's ability to fight infection may result within hours, days or weeks. The extent of the damage increases with dose. However, 'deterministic' effects such as these are not observed at doses below certain thresholds. By limiting doses to levels below the thresholds, deterministic effects can be prevented entirely.

Table 1.5 Biological effects of acute, total body irradiation

Amount of Exposure	Effect
50 mSv	No detectable injury or symptoms
1 Sv	May cause nausea and vomiting for 1–2 days and temporary drop in production of new blood cells
3.5 Sv	Nausea and vomiting initially, followed by a period of apparent wellness. At 3–4 weeks, there is a potential for deficiency of white blood cells and platelets. Medical care is required.

Higher levels of exposure can be fatal. Medical care is required.

Reference: ARPANSA Technical Report Series No. 131; Medical management of individuals involved in radiation accident. 2000

Doses below the thresholds for deterministic effects may cause cellular damage, but this does not necessarily lead to harm to the individual: the effects are probabilistic (occurring by chance) or 'stochastic' in nature. **Stochastic effects** are believed to result from damaged cells not dying but surviving in a modified form. These modified cells may, after a prolonged process, develop into a cancer. These stochastic effects usually appear many years after the exposure and, although they do not occur in every exposed individual, for radiation protection purposes it is assumed that there is no threshold below which they will not occur. Rather, the likelihood of a cancer or hereditary effect occurring after exposure is assumed to be proportional to the level of exposure.

If the modified cell is a germ cell, then the damage may be passed on to that person's future descendants. Then, hereditary effects may be observed in these descendants. However, as the risk of serious stochastic effects to the individual is higher than that of hereditary effects to the individual descendants, if the individual is suitably protected the risk to the descendants will be minimised.

It is known that doses above about 100 millisievert, received in a short period, lead to an increased risk of developing cancer later in life. There is good epidemiological evidence – especially from studies of the survivors of the atomic bombings -that, for several types of cancer, the risk increases roughly linearly with dose, and that the risk factor averaged over all ages and cancer types is about 1 in 100 for every 100 millisievert of dose (i.e., 1 in 10,000 per millisievert).

At doses below about 100 millisievert, the evidence of harm is not clear-cut. While some studies indicate evidence of radiation-induced effects, epidemiological research has been unable to establish unequivocally that there are effects of statistical significance at doses below a few tens of millisieverts. Nevertheless, given that no threshold for stochastic effects has been demonstrated, and in order to be cautious in establishing health standards, the proportionality between risk and dose observed at higher doses is presumed to continue through all lower levels of dose to zero. This is called the linear, no-threshold (LNT) hypothesis and it is made for radiation protection purposes only.

There is evidence that a dose accumulated over a long period carries less risk than the same dose received over a short period. Except for accidents and medical exposures, doses are not normally received over short periods, so that it is appropriate in determining standards for the control of exposure to use a risk factor that takes this into account. While not well quantified, a reduction of the high-dose risk factor by a factor of two has been adopted internationally, so that for radiation protection purposes the risk of radiation-induced fatal cancer (the risk factor) is taken to be about 1 in 20,000 per millisievert of dose for the population as a whole.

Radiation protection

Introduction

Radiation protection standards recognize that it is not possible to eliminate all radiation exposure, but they do provide for a system of control to avoid unnecessary exposure and to keep doses as low as reasonably achievable. Measures for control of exposure for stochastic (latent, probabilistic) effects seek to minimise all reasonably avoidable risk. This is called optimising protection. However, risk in this sense may often be assessed in terms of risk to a population and may not ensure sufficient protection of the individual. Consequently, the optimisation approach is underpinned by applying dose limits that restrict the risk to individuals to an acceptable level.

The fundamental regulatory philosophy is expressed in three principles, based on the recommendations of the International Commission on Radiological Protection (ICRP), which may be summarised as follows:

Justification: human activities that cause exposure to radiation may be permitted only if they do more good than harm;

Optimisation of protection: exposure to radiation from justified activities should be kept as low as reasonably achievable, social and economic factors being taken into account; and

Limitation of individual dose: doses must not exceed the prescribed dose limits.

The Australian radiation protection framework in ARPANSA Radiation Protection Series 1, *Recommendations for limiting exposure to ionising radiation (2002)* is consistent with that recommended by the ICRP and endorsed by the International Atomic Energy Agency, the World Health Organization, and the International Labour Organisation. The recommended dose limits are summarised as follows:

Table 2.1 Recommendations for limiting exposure to ionising radiation

Application	Dose limits	
	Occupational	**Public**
Effective dose	20 mSv per year, averaged over a period of 5 consecutive calendar years	1 mSv in a year
Annual equivalent dose in:		
the lens of the eye	150 mSv	15 mSv
the skin	500 mSv	50 mSv
the hands and feet	500 mSv	–

Reference: Recommendations for limiting exposure to ionizing radiation (1995) and national standard for limiting occupational exposure to ionizing radiation (republished 2002); Radiation Protection Series No. 1; ARPANSA.

In most situations, the requirements for limiting individual risk ensure that doses are below deterministic thresholds.

In an emergency, where there may be a need for emergency personnel to take action to save lives or to bring an accident under control, these radiation dose limits may no longer be appropriate. In emergency situations where compliance with the dose limits is not possible, every effort should be made to keep the doses to emergency personnel below those specified in the Table below (from *Intervention in Emergency Situations Involving Radiation Exposure, ARPANSA Radiation Protection Series Publication No. 7, (2004)*). Radiation doses to response personnel for all actions, including life-saving action, must be kept well below those at which serious deterministic health effects may occur.

Table 2.2 Total effective dose guidance for emergency situations

Tasks	Total effective dose guidance [mSv]
Type 1: Life-saving actions	<500
Type 2: Prevent serious injury Avert a large collection dose Prevent the development of catastrophic conditions	<100
Type 3: Short term recovery operations Implement urgent protective actions Monitoring and sampling	<50
Type 4: Longer term recovery operations Work not directly connected with an accident	<20

Reference: Recommendations for intervention in emergency situations involving radiation exposure (2004); Radiation Protection Series No. 7; ARPANSA.

Personnel undertaking a Type 1 task must be fully aware of radiation hazards and the consequences of radiation exposure. The benefits to others must clearly outweigh the risks to the emergency personnel. The individual should be trained in radiation protection and they must be instructed on the potential consequences of exposure. They should be in good health and be well trained for the necessary emergency task. They must wear personal monitors that provide estimates of personal radiation dose. Breathing protection, protection of the skin against beta radiation and contamination and other protective devices must be provided and used when necessary. All personnel will need to be closely monitored by a Radiation Safety Officer (RSO) to ensure that exposure to external radiation does not exceed the relevant radiation dose limits specified above.

Radiation measurement

Radiation cannot be detected by the human senses. A radiological survey conducted with specialized equipment is the only way to confirm the presence of radiation. In the response to a radiation emergency there are three types of radiation monitors; survey meters, contamination monitors and personal dosimeters.

Typically, gamma radiation is detected with radiation survey meters that are calibrated to read out in units of effective dose rate. Survey meters for use at low levels of radiation have Geiger-Müller

detectors or a scintillation detector such as sodium-iodide (NaI) for increased sensitivity. High levels can be measured with a high range Geiger-Müller detector or an ionization chamber. Survey meters are available to measure from lethal dose rates of Sv/h down to background radiation levels below a few microsievert per hour.

Most beta emitters can be detected with a survey instrument (provided the metal probe cover is open). Some beta emitters, however, produce very low energy, poorly penetrating radiation that may be difficult or impossible to detect. Examples of these are carbon-14, tritium, and sulfur-35.

Contamination monitors use a radiation detector with a thin window pancake probe for increased sensitivity to alpha and beta radiation. Thin window Geiger-Müller probes will detect alpha, beta and gamma radiation. Scintillation probes can be selected for detection of alpha or beta radiation. Contamination monitors are calibrated to display in units of count rate or activity (Bq). Contamination probes need to be positioned close to the radiation source, but they cannot detect alpha radiation through even a thin layer of water, blood, dust, paper, or other material, because alpha radiation is not penetrating. Special training in use of these instruments is essential for making accurate measurements.

Pocket chamber (pencil) dosimeters, film badges, thermoluminescent, and other types of electronic integrating dosimeters can be used to measure accumulated exposure to gamma radiation.

Airborne particulate radiation is a potential respiratory hazard. It is measured using a pump which draws the contaminated air across a filter for a fixed period of time. The amount of radioactivity deposited on the filter can be measured using the appropriate survey or contamination meter.

Minimising radiation effects

The cornerstones of personal safety are:

- radiation hazards decrease with distance from the source, in inverse proportion to the square of the distance
- minimising time in the vicinity of the source
- using shielding where available
- avoidance of internal contamination by appropriate use of protective equipment and personal hygiene
- source intensity
- strict adherence to instructions given by the radiation safety officer (RSO).

In the event of a radiation emergency and other emergencies involving radiation exposure, the initial safe distances in the Table below should be used in minimising the dose to emergency personnel. The actual boundaries of the safety and security perimeters should be defined in the way that they are easily recognizable (e.g. roads) and secured. However, the safety perimeter should be established at least as far from the source as indicated in the Table below, until the situation has been assessed.

Table 2.3 Initial safe distances in radiological emergencies

Situation	Initial inner cordoned area (Safety perimeter)
Initial determination – Outside	
Unshielded or damaged potentially dangerous source	30 m around or at readings of 100 □Sv/h
Major spill from a potentially dangerous source	100 m around or at readings of 100 □Sv/h
Fire, explosion or fumes involving a potentially dangerous source	300 m radius or at readings of 100 □Sv/h
Suspected bomb (potential RDD) exploded or unexploded	400 m radius or more to protect against an explosion
Initial determination – Inside a building	
Damage, loss of shielding or spill involving a potentially dangerous source	Affected and adjacent areas, floors above and below
Fires or other event involving a potentially dangerous source that can spread materials throughout the building (e.g. through the ventilation system)	Entire building and appropriate outside distance indicated above
Expansion based on radiological monitoring	
Dose rate of 100 uSv/h	Wherever these levels are measured

Reference: Recommendations for intervention in emergency situations involving radiation exposure (2004); Radiation Protection Series No. 7; ARPANSA.

Radiation emergencies

Introduction

Emergencies happen when there is a failure of the radiation safety controls in place (e.g. an industrial gamma radiography source left outside its shielded enclosure, or a radioactive package found in a public place). The greatest potential for serious injury arising from these sources comes principally from an unshielded high activity source. Consequences can be very serious, in some cases death, especially if the source is handled by persons who are not familiar with the hazard of radiation, or who do not know that the source is radioactive.

In addition to external irradiation hazard damaged sources of any nature and size can result in contamination of people and/or the environment. As a result of a fire or dispersion by wind or ventilation, contamination can also become airborne. The consequences could include serious skin burns from beta radiation and internal contamination potentially leading to serious health consequences. The situation can be made worse if the accident is not discovered in time and dealt with properly.

Radiological emergencies

Australia does not have a nuclear power industry. Radiation emergency planning for Australia is directed towards low probability incidents that will have less radiological impact than a major nuclear reactor accident. In Australia, radioactive sources used for radiotherapy and for industrial radiography are tightly controlled and regulated. Radioactive materials in the form of sources are used for a wide variety of purposes in industry, medicine, research and teaching as well as in a number of consumer products on sale to the general public. They are used for radiography, sterilisation units, radiotherapy and nuclear medicine, well logging, level-thickness-, density-, and moisture gauges, anti-static devices and lightning rods and consumer products such as smoke detectors. These sources vary enormously in the magnitude of their activity.

Reactor emergencies

These emergencies may occur when breach of irradiated fuel elements occurs due to loss of coolant. If sufficient venting or failure of containment occurs, high doses may be received by on-site workers or members of the general public in the vicinity of the reactor. Widespread environmental contamination may occur and lead to external exposure of the general public from cloud or ground shine or to internal exposure from inhalation/ingestion of released radionuclides. Reactor emergencies may also result in widespread non-radiological consequences including long lasting psychological effects.

Criticality emergencies

These emergencies may occur when sufficient quantities of special nuclear material are inadvertently allowed to undergo fission. Prompt, high level exposure is generally associated with the emergency, and persons in close proximity can receive very high doses. Workers more than about 10 metres from the assembly receive lower doses (it depends on circumstances, such as physical barriers or shielding). Members of the general public may also receive low doses due to neutron radiation.

Lost or stolen dangerous source

A lost or stolen source is a special case of emergency involving radioactive material. The risk to the public will depend mainly on the total activity involved and the length of time that people may be exposed to the source. It must be assumed that the source may be in possession of persons who do not know its nature and hazard, who may handle or break it resulting in contamination. Such emergencies can result in high doses to the whole body (WB) or localized body areas, and internal or external contamination. Serious injury or death may be a consequence of these emergencies.

Misuse of dangerous industrial sources

These emergencies may occur when proper industrial radiography procedures are not followed. Failure to use exposure control may lead to inadvertent overexposure to workers in the immediate work area. Touching the source for any reason often leads to serious injury to the hands. Whole body exposure in high doses may lead to death.

Emergencies at industrial irradiation facilities most often lead to whole body exposure at high doses. Emergencies involving mobile industrial radiography sources mostly lead to local radiation exposure.

Accidental medical overexposure

Accidental medical overexposure may occur because of miscalculation of the activity of a therapy source, improper function of an X-ray device or accelerator, or when higher activities than intended are inadvertently administered during diagnosis and therapy. When a patient receives a lower dose than that prescribed by the physician this can lead to a serious medical problem. However, this is not considered a radiation emergency, and such a situation is not considered in the manual.

Transport and laboratory emergencies

Many thousands of transport operations occur daily with the use of radiation and radioactive material. Transport can include road, rail, air, or sea. The spectrum of items transported varies greatly and includes nuclear industry products, radiography sources for industrial and medical use, gauges, and consumer products. The largest fraction of transport operations is associated with radiopharmaceuticals for medical use. The main problem with planning for transport emergencies is that they can occur anywhere and potentially affect the general public. Nevertheless, radioactive transport emergencies are, compared to all other categories, extremely rare. Moreover, transport packages are designed to resist different types of emergency situations (fire, pressure, etc). Therefore, even in an emergency, radioactive material will be intact if properly packed in accordance with the appropriate procedure.

Emergencies in laboratories (research or hospital) could have a potential for severe exposure to personnel due to external exposure and/or intake.

Contamination of air, food products and water supplies

Contamination of air, food products and water supplies could result from accidents (e.g. reactor emergency with outside release, damaged and dispersed lost or stolen dangerous source) or intentionally (malicious acts involving radioactive material (e.g. deliberate addition of radioactive material in food/water supply).

As a result of a reactor emergency, the contamination of food/products could lead to the low level exposure of a large number of people. Widespread public health action to restrict contaminated food consumption could be necessary. In the event of intentional contamination of food/products, significant exposure of large numbers of the public is very unlikely. However, there is a potential for significant exposure to small numbers (e.g. contamination of products on store shelves) and to those working with or transporting the products/food. Contamination in excess of national and international trading standards for commodities is possible. Allowing contaminated or potentially contaminated products into the local, national, regional or international distribution system could have massive economic consequences.

Malicious use of radioactive material

There is the possibility that terrorists may commit a malevolent act that involves the use of radioactive materials that could have widespread radiological consequences. These scenarios include:

- A threat to commit a malevolent act involving the use of radioactive materials
- A deliberate act to irradiate persons
- A deliberate act to contaminate food or water supplies with radioactive materials
- the use of conventional explosives or other mechanisms to disperse radioactive materials, such as a radiation dispersal device (RDD)
- A deliberate act to contaminate a site or the environment with radioactive materials
- A sabotage attack upon a nuclear facility aimed at causing an uncontrolled release of radioactive materials.

The suitability of a radioactive source for malevolent use will depend on the size of the source, the type of radiation emitted by the source (alpha emitters are problematic if inhaled or ingested), the half-life of the source, the ease of accessibility to the radioactive material in the source, the portability of the source and the physical and chemical properties of the source (e.g., powdered sources allow for ease of dispersion). For convenience and clarity, radiological dispersal incidents are divided into two broad categories: those involving small and generally highly localized sources and those involving the dispersal of large amounts of radioactive materials over large areas.

Localized sources

A single or a few, small low-level (containing small amounts of radioactive material) sources may be used with the principal objective of causing fear within a population and ultimately of disrupting the social order. The radioactive material could be packaged in a small container such as an ampoule, shoe box, or even a suit-case sized container. If in liquid form, the material could be dumped into a water reservoir or spilled over some small area; or, to create mayhem over a larger area, it could be released in small amounts from a bicycle, motor vehicle, or even an aircraft. Because the amount of radioactivity is small, the exposure to individuals would also be expected to be low. Thus, the harm from this kind of source is primarily psychosocial, and whatever low external or internal dose is received should produce no immediate adverse health effects and only a small probability of long-term health effects.

Widely dispersed sources

Of greater concern are events that result in the dispersal of radioactive materials over large areas through the use of explosives coupled with large amounts of radioactive material. If the target area is populated, individuals injured by the explosion are likely to be contaminated with radioactivity. Greater amounts of radioactive materials would likely be used in such devices and radiation casualties may include individuals who could have received life-threatening levels of exposure. The objective of such a device is similar to that of a smaller source but is intended to affect an extended area or population. The most likely scenarios involve:

- use of a solid radioactive material that would be of low enough activity that the construction and delivery of the RDD will not seriously inhibit the terrorist from carrying out the attack
- radioactive material in some kind of solution, or even a gas.

Large sources of penetrating radiation are difficult to handle safely and without detection by authorities. Shielding materials that are adequate to protect both the individuals who construct these devices, and those who are to deploy them, complicate the design and fabrication of effective weapons.

Nuclear reactors, adjacent spent fuel storage depots, transport vehicles, or any high-level waste site are potential targets for the use of high explosives to disperse into the atmosphere the very high levels of radioactivity associated with materials at these facilities. Australia has no nuclear power reactors and the ANSTO Research Reactor has security measures in place to protect the facilities.

The main radiological consequences of such a malevolent act are likely to be:

- Fatalities or casualties suffering from the effects of exposure to ionising radiation
- Radioactive contamination of the location where the radioactive materials were concealed
- Generation of public fear leading to economic, transport, and medical infrastructure disruption.

Radioactive material can also be hazardous if it gets into a person's body, via inhalation, ingestion or through the open wounds. Inhalation of radioactive material within about 100 metres of a fire or an explosion involving a very large, dangerous source could potentially cause severe deterministic health effects. However, this is probably only possible if the person does not have respiratory protection and stands in the smoke for most of the release duration. Inadvertent ingestion of contamination (e.g. resulting from eating with contaminated hands) could also cause severe deterministic health effects. However this is probably only possible if the person is in direct contact with material that is spilled or leaked from a source.

On the basis of types of high activity radioactive sources in use in Australia, the following scenarios have been used for planning for the medical response:

- Radiation Exposure Devices (RED) involving the use of Category 1 or 2 ^{60}Co, ^{137}Cs, or ^{192}Ir sources.
- Radiation Dispersal Device (RDD) involving the use of Category 1 or 2 ^{137}Cs or ^{241}Am (including Am/Be neutron sources).
- Radiation poisoning involving the use of ^{210}Po in food or water.

Emergencies involving nuclear devices

A second category of terrorist incidents is the use of nuclear weapons. These weapons might be constructed from nuclear material and conventional explosives or they might be stolen from military stockpiles. The detonation of a weapon with even a small nuclear yield will cause significant radiological consequences in addition to substantial damage to infrastructure. These consequences result from both the initial ionising radiation at the time of detonation and from radioactive fallout that will occur for a considerable time after the initial event.

The probability of a terrorist incident within Australia involving a nuclear device in considered to be negligible. The most likely terrorist nuclear weapons scenario involves the use of a single, low-yield device. There are a number of significant effects that need to be considered in responding to such a catastrophic event. These effects include air blast, ground shock, thermal radiation, the initial nuclear radiation and the residual nuclear radiation. For a 0.01 kT nuclear detonation the range for an initial radiation dose of 4 Gy is of the order 250m. For the same detonation, the range for a radiation dose of 4 Gy in the first hour extends out to 1250 m. (NCRP 138).

The characteristics of possible health consequences arising from these different types of radiation emergencies in Australia are summarised in Table 3.1.

Table 3.1 Characteristics of possible health consequences for different types of radiation emergencies

Type of radiation emergency	Effects related to radiation				contaminated persons	Effects related to emergency			Combined trauma	No. of people	
	deterministic		stochastic			conventional trauma	affected area			limited	large
	deterministic ARS	burns	detectable	protective measures			limited	widespread			
Nuclear detonation	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes	No	Yes
Reactor (OPAL, NPW)	Maybe	Maybe	Maybe	Maybe	Maybe	Maybe	No	Yes	Maybe	Yes	Maybe
Criticality	Maybe	Maybe	No	Maybe	Maybe	Maybe	Yes	Maybe	Maybe	Yes	No
Lost dangerous source	Maybe	Maybe	No	No	Maybe	No	Yes	Maybe	No	Yes	Maybe
Misuse of industrial dangerous source	Maybe	Maybe	No	Maybe	Maybe	No	Yes	Maybe	No	Yes	Maybe
Transport/Laboratory	No	No	No	Maybe	Maybe	Maybe	Yes	No	Maybe	Yes	No
Malicious use of radioactive material	Maybe	Maybe	No	Yes	Maybe	Maybe	No	Yes	Maybe	No	Yes
Radioactive contamination air, food, water	No	No	No	Yes	Yes	No	No	Yes	No	No	Yes

Medical implications

In a nuclear or radiological emergency, the practical goals of emergency response are to:

- regain control of the situation
- prevent or mitigate consequences at the scene
- prevent the occurrence of deterministic health effects in workers and the public
- render first aid and manage the treatment of radiation injuries
- prevent, to the extent practicable, the occurrence of stochastic health effects in the population
- prevent, to the extent practicable, the occurrence of adverse non-radiological effects on individuals and among the population
- protect, to the extent practicable, the environment and property
- prepare, to the extent practicable, for the resumption of normal social and economic activity.

Most of the goals are directly related to human health. Therefore, every medical and technical specialist participating in emergency response has to know and understand the meaning of the terms and the relation between radiation medicine, emergency medicine, physics and radiation protection. Medical response actions need to be in line with the goals of emergency response.

The goals of medical response to nuclear or radiological emergency are to:

- save lives and perform required emergency medical procedures
- treat radiation and other injuries
- provide public advice, counselling and long-term medical follow-up.

In general, the clinical management of radiation casualties is the same whether for single or for mass casualty nuclear or radiological emergencies However, the consequences of malicious acts involving radioactive material, resulting in potentially large numbers of casualties, rapid depletion of medical resources, and limited personnel, dictate a different overall medical management strategy for emergency response.

Sealed sources spread in the environment do not present a contamination hazard. As long as these sources are intact, contamination is not possible. Sealed sources can result in low level exposures to persons who come near an individual source. However, persons who handle these sources may suffer significant local radiation injury to the skin and underlying tissues. Mass casualties are not expected when sealed sources are considered.

Radiological dispersal devices (RDDs) are likely to affect relatively small areas compared to a nuclear detonation. The immediate environment, and persons in the area, will become contaminated as the radioactive material is deposited on surfaces. The most effective protection is to leave the affected area. It is highly unlikely that persons in the contaminated area will have medically significant levels of contamination, either external or internal, but fear and concern regarding personal safety will lead to psychological stress.

The medical response required is essentially the same as that required for dealing with a conventional radiation emergency. The differences are:

- potentially large number of casualties
- potentially significant conventional medical impact of the blast, and
- the need to preserve criminal evidence.

This means that the medical response may need to be centrally coordinated, use a network of facilities and establish a triage system, in coordination with radiation specialists, to optimize the use of the medical infrastructure. Conventional trauma victims may be sent to non-radiological specialized facilities, while contaminated severe injuries will have to be treated by facilities with some basic knowledge in the treatment of contaminated casualties. Depending on the number of victims, it may be required to setup a triage and first aid centre near the scene of the terrorist act. All items removed from the casualties need to be preserved for the ensuing criminal investigation.

A nuclear detonation, with the resultant radiation, blast, and thermal injuries, would be catastrophic in comparison to the malicious acts involving conventional explosive or other means of dispersion. In addition to numerous prompt fatalities from conventional trauma, the nuclear fallout and associated damage to structures will severely disrupt civil authority and infrastructure, thereby complicating the delivery of medical care in the affected area. The detonation of a nuclear weapon will result in significant impact on medical response at both pre-hospital and hospital levels. Hundreds to thousands of prompt fatalities are expected in the detonation zone, with an even greater number of persons with blast and burn injuries as one moves away from the detonation zone. The size of the area will be related to the actual yield of the weapon. Triage and initial treatment will affect overall delivery of medical care and stress pre-hospital and hospital resources to their limits. Fallout from these weapon detonations may lead to an even greater number of persons with significant levels of radiation exposure having an even greater impact on the delivery of medical care. Medical resources will be quickly overwhelmed as most survivors will have significant traumatic injuries and thermal burns. The impact of radiation exposure will be secondary to medical management of conventional trauma.

All malicious acts involving radioactive material must be considered as criminal acts and evidence must be retained for investigation by the proper authorities. Emergency medical response plans need to be vigilant for potential malicious acts involving radioactive material. Reporting to appropriate authorities of even a single radiation exposure case can contribute to the initial identification of a malicious act involving radioactive material. Such acts can also involve few seriously injured casualties but can evoke public hysteria and panic.

Table 3.2 Medical/Public health characteristics of radiation emergencies resulting from malicious acts

Type of event	Relative casualty-type distribution			
	Lethal		Non-lethal	
	Initial injuries	Delayed injuries	Exposed individuals	Non-exposed and/or psychologically affected individuals
Nuclear weapon	High	High	High	High
Sealed source dispersal	Low	Intermediate	High	High
Radiological dispersal device	Low	Low	Intermediate	High

Principles of nuclear and radiological medical responses

- Medical emergencies have priority over external or internal radiological risk, which is characterized by delayed occurrence of injuries.

- Treatment of internal contamination, enabling decrease in the binding of radionuclides to target organs, is an urgent task and must be planned in the logistical support.

- External contamination needs to be handled properly at the earliest stage in order to avoid the secondary dispersion of radionuclides in the environment, the contamination of rescuers and the subsequent contamination of casualties. If there is no time or no equipment for control of external contamination, a systematic undressing and showering of uninjured persons must be planned using any available resources of the rescuers and on-scene responders. All procedures and rescue behaviour must avoid internalizing external contamination at the level of the face.

- Emergency service personnel need to receive training and adequate equipment to protect themselves from radioactivity, chemical and biological hazards. In view of the probability of malicious acts resulting in mass casualties, training must be extended to a large number of personnel.

- Hospital staff need to receive sufficient training in order to avoid panic behaviour or refusal to give treatment when receiving casualties of CBRN events.

Arrangements

Paramedic response to a radiation dissemination device

The aim of this chapter is to provide a general overview of the recommended paramedic response to a radiological mass casualty incident. The most likely scenario to challenge paramedics in Australia is the dissemination of radiological material or a radiological 'dirty bomb' with multiple contaminated casualties. Events that irradiate casualties without associated contamination do not require special precautions, as there is no residual hazard once the source is rendered safe. The recommended operating procedures included in this chapter represent world's 'best practice' for the management of contaminated casualties. Specific information on local arrangements should be sought from the appropriate authorities in the State or Territory in question.

The importance of timely management of trauma victims to avert preventable deaths is well understood. By following the procedures within this chapter, paramedics will be able to mitigate the radiological contamination hazard whilst providing clinical care to trauma victims.

Role

The role of the paramedic in Australia varies slightly between jurisdictions, but it can be generally summarized as the following:

- Provide initial assessment and pre-hospital treatment of illness and injury
- Provide transport to an appropriate care facility, where required
- Paramedics are trained to different skill levels and have access to a variety of equipment and pharmacological regimes, but the basic goal of assess, treat and transport is a constant throughout the country.

History

Fortunately, ambulance services in Australia have never been exposed to a mass casualty incident as a result of a 'dirty bomb'. The type of event paramedics have been exposed to has generally been single patients who have been contaminated or potentially irradiated as a result of a manual handling incident or traffic accident.

International and domestic police and military intelligence agencies are on alert for possible terrorist incidents occurring on Australian soil. Whilst there has yet to be any attacks of this nature in this country this century, the current global environment we endure suggests that we must remain vigilant. Preparedness to respond to mass casualty incidents is high on the agenda of all levels of government and all response agencies across the country. It is therefore paramount for jurisdictions to prepare a response for all conceivable types of terrorism. Authorities around Australia have developed sophisticated procedures for responding to an accidental or deliberate chemical release. There are also detailed and well-rehearsed plans for managing the consequences of an incendiary explosion. In recent times a significant focus has centred on influenza pandemic planning. These plans may possibly be adapted to other biological hazards.

Planning for a response to mass casualties contaminated from a radiological 'dirty' bomb may require further development; this is possibly due to a variety of reasons:

- Widespread community misconceptions regarding radiological contamination/irradiation and its health effects
- Lack of experience with radiological incidents
- The pre-hospital environment largely reflects the views of the wider community. Subject awareness saturation will be the most effective tool in combating the misconceptions prevalent in the emergency services community.

Response

Ambulance response to a radiological incident will be as a support to a control agency, however paramedics may be the first emergency responders to arrive. As with any incident, paramedics should consider and be aware of any potential dangers present before entering the scene. If other emergency services are present, a situation report should be sought from the incident controller. If ambulance is first on scene, a thorough scene assessment should be undertaken and reported to the communications centre. Key fire service responders, who may carry portable radiation monitors, should be requested to attend the scene urgently.

Radiation risks

A credible 'worst case' scenario would involve an intact industrial radiography source. Based on the (gamma) dose rate at 3 metres from an unshielded 1.85 TBq iridium-192 source, it would take about 5 minutes to receive a radiation dose equal to the annual natural background dose received by individuals living in an Australian capital city (2mSv)[1]. It would take about 50 minutes to receive a dose equal to the annual limit for persons occupationally exposed to radiation.

In a credible scenario involving dispersal of radioactive contamination from a dirty bomb with contaminated casualties, the radiation dose received in one hour in close proximity to a highly contaminated casualty would be about 15% of total annual background radiation[2] and the dose in one hour at 1 metre would be about 0.15%[3]. Injured people at the scene of the emergency are only likely to have very small amounts of radioactive contamination on their clothing and bodies.

As can be seen from the above figures, the hazard to attending ambulance paramedics would be minimal, so that first aid can be administered safely to casualties.

Standard operating procedures for ambulance service paramedics for suspected radiation emergencies

- Consider all potential scene hazards
- When attending an event that seems out of the ordinary or suspicious for any reason, approach from upwind with caution

---

[1] Based on the (gamma) dose rate at 3 metres from an unshielded 1.85 TBq (50 Ci) iridium-192 source.
[2] Based on the (gamma) dose rate at 10 centimetres from an unshielded 37 MBq (1 mCi) caesium-137 source.
[3] Based on the (gamma) dose rate at 1 metre from an unshielded 37 MBq caesium-137 source.

- If the emergency involves an explosive device, consider the possibility of a secondary device and approach with caution, noting any nearby vehicles or objects that could contain a secondary device

- If hot/warm/cold zones have been established by other Emergency Services at the incident, pregnant or potentially pregnant paramedics must remain in the cold zone

- Avoid inadvertent internal contamination by using PPE and avoiding hand-to-mouth activities such as eating, drinking and smoking until personally decontaminated and in the cold zone. PPE required to enter the scene of a radiological incident is disposable gown or overalls, shoe covers, standard clinical use gloves, safety glasses and P2 (N95 equivalent) mask

- The medical stabilisation of casualties has first priority and takes precedence over any radiological consideration

- Request appropriate support resources from other ESOs e.g. portable radiation monitors, decontamination facilities, etc.

- Request appropriate resources from your own organisation, including a management structure

- If there are injured persons in the affected area requiring urgent medical care, administer treatment and evacuate as quickly as possible in order to keep exposure time as short as possible

- Prior to re-entering ambulance vehicle, remove disposable gown or overalls, shoe covers, gloves and mask; don fresh gloves. Double bag used garments and leave for monitoring by the Control Agency

- Record the time spent in the hot zone

- Transport to hospital, advising en route details of patient with possible radioactive contamination and appropriate vital signs

- Prior to being re-dispatched for duty, paramedics are to ensure that they and their vehicle and equipment are checked by a hospital health physicist or radiation safety officer (RSO) for any possible contamination

- If contaminated, shower and get checked for any residual contamination

- Don fresh clothing when satisfactorily decontaminated

Decontamination at the incident scene

Emergency decontamination of persons with actual or suspected contamination should be considered.

- The medical stabilisation of casualties has first priority and takes precedence over any radiological consideration

- If the patient has life threatening injuries, he/she should be transported directly to hospital by ambulance without decontamination

- If possible, remove the patient's clothing and double bag and tag. This will remove 75 to 90 % of the contamination. This should be performed in the warm zone as for all decontamination procedures

- Place non-absorbent material, e.g. polythene sheet, on the ambulance stretcher prior to placing patient on stretcher

- Place the patient on top of cotton sheet on ambulance stretcher and wrap sheet around the patient so that a cocoon is formed. This will contain any residual radioactive material on the casualty, minimising transfer of the material to ambulance personnel and the vehicle
- Advise hospital that patient will have to be monitored by a hospital health physicist or RSO to determine need for decontamination post stabilisation
- Patients without life threatening injuries may be decontaminated at the scene if this will not cause deterioration in the condition of the patient
- Decontaminate PPE as per standard CBR/HAZMAT processes

Note: Personal property such as wallets and purses may be placed in plastic bags and taken with the casualty.

Hospital response to radiological events

Introduction

An incident involving even a single casualty from an incident involving radiological materials is likely to trigger concern amongst other casualties, bystanders, emergency responders, treating staff and potentially the broader community. Significant numbers of individuals may seek assessment and reassurance about potential health effects, from hospitals and other clinical providers.

The nature of radiation is frequently poorly understood, and this may create anxiety even amongst health professionals. The principles of ionising radiation, its health effects and treatment should be included in clinical education to address knowledge deficits. Enhanced understanding is relevant, not just in preparedness for radiological incidents, but also to the concept of justification in the use of diagnostic radiology. Justification is the principle of minimising exposure to ionising radiation unless the benefit outweighs the risk of harm.

Organisationally, a structured approach to the management of radiological incidents is essential to ensure occupational safety of personnel, and appropriate allocation of resources. Preparedness for radiological events is a component of the all hazards approach that hospitals must address as part of emergency planning. Planning must consider both mass casualties and the hazardous nature of radioactive substances. Procedures should be documented as part of emergency response plans, taught and exercised.

Basic principles

An all hazards response should be implemented initially.

Until it is confirmed that radiation is the only hazard, it must be assumed that potential hazards include chemical, biological and radiological agents, as well as explosives and attackers. Hospital responders should implement their chemical procedures, including wearing Level C personal protective equipment for reception and initial triage of casualties, prior to their decontamination. Procedures should be down-graded, and appropriate personal protective equipment worn, when information is received that radiation is the only hazard.

In a radiological incident, the medical stabilisation of casualties has first priority and takes precedence over any radiological consideration.

Radiation does not cause immediate death, burns or wounds. Only in extremely high dose, does exposure to radiation cause incapacitation. Irradiation or contamination alone are not medical emergencies. Irradiation may not cause manifest illness for hours, days or weeks and does not make casualties radioactive. Efforts to control and contain external contamination are chiefly directed at avoidance or minimisation of internal contamination. However, traumatic injuries associated with an explosive radiation dispersal device may be life-threatening and require immediate intervention to stabilise. Concern about radiological contamination should not delay these interventions, as delay may result in preventable deaths due to trauma.

In the event of a mass casualty explosion of unknown or suspicious origin, it is advisable to screen casualties for possible radiological contamination.

Basic radiation detection equipment is simple to operate and maintain. Where radioactive materials are known to be involved in the incident, it is important to monitor casualties for contamination (after stabilising life-threatening medical conditions) to ensure that radiation doses to both casualties and medical staff are kept as low as reasonably achievable. This is the ALARA principle.

Radiological contamination on casualties can be controlled and contained.

'The only survivors of a radiation accident who have been so badly contaminated as to be a threat to those involved in treating them were some of those involved in the accident at Chernobyl. No other accident victims, including those at Goiânia, Brazil, where gross contamination of the victims occurred, have presented ANY threat to responders, due to the precautions and procedures they followed in managing those victims.' (Medical Management of Individuals Involved in Radiation Accidents. ARPANSA; 2000.) Simple measures such as the establishment of control lines, use of personal dosimeters, rotation of treating personnel, appropriate personal protective equipment, and casualty decontamination will minimise risk to healthcare workers from radiological contaminants.

Reduction of radiation levels to background is not always possible.

Decontamination should be as thorough as practical. However, radionuclides may chemically incorporate into the stratum corneum, leaving detectable residual superficial contamination. Additionally, if there has been internal contamination via inhalation, ingestion or via wounds, the incorporated radionuclide will be detectable externally if it emits gamma, X-ray or energetic beta radiation. Vigorous decontamination of the skin may cause abrasions, resulting in increased absorption of superficial radionuclides, potentially up to one hundredfold.

Provide psychological support for casualties throughout their care.

In addition to distress from the circumstances of their exposure, casualties are likely to experience fears regarding potential radiation exposure and its perceived health effects, and stress due to uncertainty. Good risk communication will help to alleviate this by the timely provision of accurate information and straightforward explanation of procedures.

Hospitals are likely to see large numbers of people who have concerns about their exposure to radiation as a result of a radiological incident.

This is not panic, but an over-response to a perceived health threat. They may exhibit a range of symptoms as part of a physiological response to stress. This somatisation may present a diagnostic challenge in the context of the non-specific symptoms of prodromal radiation sickness. Such people will request assessment of physical concerns, information and reassurance, perhaps in overwhelming numbers. Hospitals must plan for this surge in concerned individuals. These persons deserve someone to respectfully listen to their concerns, evaluate whether there is any evidence of toxic effect, provide information and reassurance, as well as offer information on possible psychological reactions to an incident of this nature. A duty of care is owed to them, even if resources must be carefully husbanded to meet the needs of all presenters. Failure to address their

concerns empathetically is likely to increase their perceived sense of injury and aggravate later psychological disturbance.

Radiation monitors for the Emergency Department

Basic radiation safety equipment will include personal dosimeters to monitor staff exposure and assist with appropriate staff rotation planning if required. It is preferable to have electronic dosimeters that provide immediate readings of dose-rate and cumulative dose. Film badges and thermo-luminescent dosimeters are not able to be read without processing and will not assist with management of staff safety during the event.

Portable contamination monitors, such as Geiger-Müller counters, are used in the evaluation of external radiological contamination. (See Contamination Monitoring Procedure.) Frequently, these can be located in the nuclear medicine department, and occasionally in the pathology department.

Area radiation monitors are wall or ceiling mounted units designed to alarm on detecting a significant amount of radioactivity in the vicinity of the monitor. The detector or probe of the area monitors is attached to the body of the monitor via an extendable cord. The probe may be used to measure levels of contamination on persons involved in radiation incidents. As such, it is an adjunct to the contamination monitor used by the health physicist or radiation safety officer of the hospital. (See Obtaining Specialist Advice.)

Portal radiation monitors are designed to resemble doorways with radiation detectors usually at 1.2 to 1.5 metres above floor level. The area and portal monitors will probably not passively detect casualties with lower levels of radioactive contamination, except where the probe of the area monitor is used and will not alarm in this situation. However, these monitors are likely to detect patients who have recently had nuclear medicine investigations, so they are fairly sensitive.

In this situation, the only way that ED staff will know that casualties have been involved in a radiation incident is if they have been so advised by either emergency response agencies or those responsible for the incident. ED staff should have a high index of suspicion in assessing victims of any blast and include assessment for possible radiological contamination.

The following section describes:

- The set up for receiving contaminated patients
- Personal protective equipment
- Triage of casualties involved in a radiation incident
- Casualty follow up and counselling
- Contamination monitoring procedure
- Area radiation monitor/portal monitor procedure
- Decontamination procedures
- Waste management
- Obtaining specialist advice

- Role statements:
  - Radiation safety officer
  - Medical health physicist
  - Haematologist/oncologist

Set up for receiving contaminated patients

Two areas should be established to receive patients: a treatment area for potentially contaminated patients requiring resuscitation or immediate care, and an assembly area for screening ambulatory casualties for radiological contamination.

Triage post

Establish conventional triage at the initial contact point external to the hospital to ensure patients in need of resuscitation are promptly identified and only stable patients are allocated to the assembly area. Also, set up for quick radiological triage, to scan briefly for any high activity shrapnel fragments that may pose greater risk for staff.

Arrange for the hospital entrances other than the emergency department entrance(s) to be secured.

Treatment area

- Set up a controlled area large enough to hold the anticipated number of victims
- Establish control lines and prevent the spread of contamination
- Temporary barriers should be erected to exclude others entering the designated corridor and treatment area
- Floor of corridor to treatment area, and treatment area itself, should be covered with heavy-duty paper or plastic to minimise spread of radioactive material. The covering materials should be secured to the floor with tape
- Large bins lined with disposable plastic bags are to be provided for the disposal of contaminated waste such as clothing, linens, dressings, etc. Bags to be sealed and tagged for subsequent monitoring by hospital health physicist or radiation safety officer (RSO)
- Non-essential equipment should be covered or removed from the controlled area
- There is no need to control air ventilation of areas receiving contaminated casualties as there is minimal aerosolisation of radioactive material
- A decontamination table or trolley with a waterproof cover, or a burn trolley provides a suitable treatment surface
- Small lead-lined storage containers (pigs) for holding any radioactive foreign bodies removed from wounds
- Swabs for sample collection and 'radioactive' labels for specimens
- Patient chart with outline of body (front, back and sides) for recording areas of contamination and wounds

- Decontamination materials
  - Soap, shampoo
  - Soft scrubbing brushes, sponges
  - Sterile water/saline for irrigation of wounds and mucosal surfaces

Notes: Special floor covering is not necessary for treatment of casualties contaminated with radioactive material. The sole purpose of placing floor covering down is to make clean-up of contamination easier afterwards. Medical treatment must not be delayed because there is no floor covering in place.

External assembly point

An assembly point for the purpose of monitoring of ambulatory casualties for radiological contamination (radiation monitoring point) should also be set up external to the hospital, with access to the decontamination facilities.

Personal protective equipment (PPE)

Normal clothing used in operating suites will provide sufficient protection for personnel treating patients who are contaminated with radioactive material:

- Dress in normal surgical scrubs, reserving normal work attire to be worn later.
- A gown with a waterproof apron.
- Cover all hair with a theatre cap.
- Waterproof shoe covers.
- Two pairs of surgical gloves. Single-use nitrile gloves are worn as the inner layer, with the cuffs under the gown sleeves. Tape the gown sleeves to the inner gloves. An outer pair of gloves is then donned, with the cuffs over the gown sleeves. The outer gloves can be changed as necessary during patient care.
- Surgical mask.
- Eye protection/goggles.

Lead aprons are ineffective against gamma radiation as the thickness of lead in the apron does not provide sufficient shielding against ionising radiation of this energy level. They should only be worn as needed to protect against (lower energy) X-rays, during diagnostic radiology procedures required to stabilise the patient. Unnecessary use of lead aprons is likely to increase fatigue.

Personal radiation dosimeters are to be worn outside clothing, by key treating personnel in closest proximity to casualties. Ensure the dosimeter is correctly oriented. It is suggested that dosimeters with alarm functions be set to alarm at 100 µSv/hour, which would permit up to 20 hours exposure at that dose rate before exceeding the average annual background exposure level. If personal dosimeters alarm, rotate staff to keep doses to a minimum and seek advice from the hospital health physicist or radiation safety officer. The health department radiation adviser is able to provide advice also.

Removal of PPE

- Remove protective garments and gloves standing adjacent to the control line, on the contaminated side. Bag and tag collected waste.

- Remove outer gloves, turning them inside out, and deposit into a lined bin.

- Remove the dosimeter and deposit into a bag held by another staff member, avoiding contaminating the outside of the bag.

- Remove all tape and deposit into a lined bin.

- Remove the gown, turning it inside out. Minimise shaking of the gown. Deposit into a lined bin.

- Remove cap, mask and goggles. Deposit into a lined bin.

- Stand or sit adjacent to the control line on the contaminated side. Remove one shoe cover and deposit into lined bin. The sole of the inner shoe should be scanned for contamination before placing on the floor/ground on the clean side of the control line. Repeat for the other side.

- Remove inner gloves and deposit into lined bin.

- The staff member should be scanned for contamination prior to showering. Staff members should be instructed not to eat, drink or smoke until after they have been surveyed and showered.

Triage of casualties involved in a radiation incident

Please see the algorithm on the next page.

- Provide triage outside the ED entrance and direct:
  - casualties with life threatening conditions to the prepared treatment area; and
  - other casualties to the radiation monitoring point.

- Scan briefly to identify any high activity shrapnel fragments that may pose greater risk for staff. Utilise time, distance and shielding to minimise staff exposure to high activity fragments during resuscitation.

- Stabilise life-threatening medical conditions of casualties.

- Ambulatory casualties who have recently entered the hospital, and have been at the site of the incident, should be advised to assemble at the radiation monitoring point for radiation monitoring by the hospital health physicist or RSO. (See Contamination Monitoring Procedure.)

- Decontaminate contaminated individuals as appropriate.

- Implement definitive medical treatment.

Casualty follow up and counselling

- Order **IMMEDIATE** full blood examination (FBE) and differential and follow with absolute lymphocyte counts every 6 hours for 48 hours when history indicates possibility of total-body irradiation.

- Identify casualties with potential internal contamination:
  - contamination of the face and nares is suggestive of inhalational exposure
  - contaminated wounds

- Conduct bioassays and whole body or lung scans as appropriate to assess internal contamination.

- Consider decorporation treatments early. (See the section on [Internal Contamination](#).)

- Casualties who have been involved in radiation incidents should be followed up for a week, with particular reference to the development of nausea and vomiting, areas of otherwise unexplained erythema, conjunctival redness, epilation, and changes in full blood and lymphocyte count.

- Casualties who have been or think they have been exposed to radiation may need psychological support to help alleviate any anxiety.

Radiation Accident With Trauma Or Illness

```
                        Radiation Accident With Trauma Or Illness
                                          |
                                          v
                                    ┌──────────┐
                         yes        │   Life   │
                      ┌─────────────│threatening│
                      │             └──────────┘
                      v                   │ no
                ┌──────────┐              │
                │ Stabilise │             v
                └──────────┘        ┌──────────────┐
                      │        yes  │  Externally  │  no
                      └────────────▶│ contaminated │────────┐
                                    └──────────────┘        │
                         ┌──────────┘                       v
                         v                          ┌────────────────┐
                  ┌──────────────┐                  │ Admit to emergency│
                  │   Admit to   │                  │  dept and treat  │
                  │controlled area│                 └────────────────┘
                  └──────────────┘                          │
                         │                                  v
                         v                          ┌────────────────┐
                  ┌──────────────┐                  │ Possible radiation│
                  │Remove clothing│                 │    exposure?    │
                  └──────────────┘                  └────────────────┘
                         │                          yes │        │ no
                         v                              v        v
                  ┌──────────────┐          ┌────────────────┐ ┌─────────┐
                  │  Survey and  │          │Evaluate history and│ │  Usual  │
                  │  document    │          │symptoms. Obtain baseline│ │treatment│
                  └──────────────┘          │ FBE, differential │ └─────────┘
                         │                  └────────────────┘
                         v       no                 │
                  ┌──────────────┐                  v
                  │    Stable    │────┐     ┌────────────────┐
                  └──────────────┘    │     │Nausea/vomiting or│
                      yes │           │     │   erythema?    │
                          │           v     └────────────────┘
                          │    ┌──────────┐  yes │        │ no
                          │    │ Stabilise │      │        v
                          │    └──────────┘      │  ┌──────────────┐
                  ┌──────────────┐◀──────────────┘  │Repeat FBE and│
                  │ Decontaminate │                 │differential 6│
                  └──────────────┘                  │    hourly    │
                                                    └──────────────┘
```

Acknowledgement to the diagram, upon which this is based, contained within *Medical Management of Individuals Involved in Radiation Accidents,* Technical Report Series No. 131 by Australian Radiation Protection and Nuclear Safety Agency

Contamination monitoring procedure

Portable contamination monitors are usually located in nuclear medicine departments of major hospitals for management of spills. However, it is recommended that emergency departments should acquire at least one Geiger-Müller counter in order to ensure ready access to this equipment at all times.

Skin and clothing

- Cover the probe, with a surgical glove or plastic bag to prevent inadvertent contamination of the probe. The glove can be changed if contamination occurs.
- Ensure that the instrument is used in fast response mode, where this is possible.
- Set the instrument selector switch to the most sensitive range of the instrument.
- Measure background radiation prior to commencing survey of the patient.
- Holding the probe approximately 1 to 2 cm from the person's skin and systematically survey the entire body from head to toe on all sides.
- Move the probe slowly (a few cm per second).
- Do not let the probe touch anything.
- Try to maintain a constant distance.
- Pay particular attention to body orifices, skin folds, hands, face and feet.
- An increase in count rate or dose rate above background indicates the presence of radiation.
- Document areas of contamination on a body map together with monitor details, monitor readings for the various body areas that are contaminated, and details of the casualty.
- When necessary, adjust the range of the instrument

Note that some instruments cannot detect alpha radiation and some low-energy beta radiation. Because alpha radiation is non-penetrating, it cannot be detected through even a thin film of water, blood, dirt, clothing, or through the probe cover.

Body orifices and wounds

- Nasal and oral swabs should be collected using moist, clean cotton tipped applicators.
- Any sputum, vomitus, or tissues from nose blows should be collected.
- Any initial wound dressings should be collected
- Swabs, dressings, etc. should be placed in separate plastic bags and labelled with patient details, site, and time for later analysis.
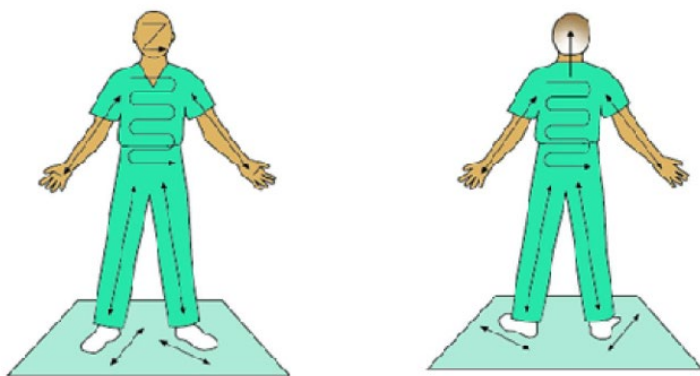
Source of graphic: Radiation Emergency Assistance Center/Training Site (REAC/TS); [Guidance for Radiation Accident Management](#).

Area radiation monitor/portal monitor procedure

Selected hospitals may be equipped with area radiation monitors or portal monitors positioned at the ambulance and ambulatory entry points to the emergency departments. They have adjustable alarm settings to allow for different doorway configurations. In general, these monitors may be set to alarm at a threshold of 20 microsieverts per hour (µSv/h).

They are designed to detect significant amounts of radiation, such as that from a part of a radiological source contained in a casualty as a shrapnel fragment and will NOT detect low-level radiation from diffuse superficial contamination from a radiological dispersion device ('dirty bomb'). The threshold is sensitive enough to detect some nuclear medicine patients, however.

If alarm of area radiation monitor sounds

- Turn alarm off by pressing 'HIGH ALARM' button.
- If unsure as to who set the alarm off, detach probe at right side of the area monitor and use this to determine who set the alarm off. If the portal monitor alarmed, use a portable contamination monitor instead.
- Question to determine if person has had a nuclear medicine scan, radio-pharmacotherapy or radiotherapy implant recently.
- If not and there are suspicious circumstances:
  - Isolate the person until radiological triage completed.
  - Key ED staff involved in patient treatment should wear personal dosimeters.
  - Holding the monitor probe 30cm from the casualty, conduct a radiation survey to establish the maximum dose rate.
  - If the maximum dose rate 30 cm from casualty is **less than** 1 millisievert/hour (mSv/H) as indicated on area monitor display there is no need for rotation of staff, as the annual occupational dose limit (20 mSv) would not be exceeded for at least 20 hours.
  - If the maximum dose rate 30 cm from casualty is **greater than** 1 mSv/h as indicated on area monitor display – staff to rotate when cumulative dose indicated by dosimeter is 20 mSv.

- Provide treatment and care to patient whilst observing these exposure guidelines for the treating staff.
- Contact: (1) hospital Radiation Safety Officer via hospital switchboard, and (2) health department radiation adviser.
- Using the portable contamination monitor, establish the extent and bodily location of contamination.

Hospital decontamination procedures

The medical stabilisation of casualties has first priority and takes precedence over any radiological consideration, including decontamination.

Decontamination should only be as thorough as practical. Reduction of radiation levels to background is not always possible. Careful removal of clothing will reduce contamination by about 90%. Avoid unnecessary exposure of the face as clothing is removed, in order to minimise further internal contamination.

Collect samples from the nose, mouth and wounds. Ensure all samples are bagged, labelled and marked as a radiation hazard.

Ambulatory patients

Small areas of superficial contamination can be decontaminated using a sink or basin. If extensive body areas are contaminated, the patient can be showered under the direction or with the assistance of the hospital health physicist or radiation safety officer. Caution the patient to avoid splashing water into the eyes, nose, mouth, or ears. Repeated showers might be necessary, and clean fresh towels provided for drying after each shower.

Stretcher patients

Decontaminate open wounds first

- Remove temporary dressings, place in a plastic bag and label
- Change outer gloves
- Survey the wound with the Geiger-Müller counter and record the results on the chart
- Drape wound with waterproof material
- Gently irrigate with saline or water
- Remove any visible foreign bodies with long-handled forceps, if clinically appropriate to do so. Take care not to touch or handle metallic foreign bodies
- Remove contaminated drapes and dressings as necessary as decontamination proceeds
- Repeat until there is no further reduction in radiation level
- If radiation level cannot be reduced to near background levels, debride wound, if clinically appropriate, and bag and label debris
- Change outer gloves and re-dress wound

Decontaminate body orifices

- Oral cavity – encourage brushing the teeth with toothpaste and frequent rinsing of the mouth.

- Pharyngeal region – gargling with a 3% hydrogen peroxide solution is suggested in some texts. Evidence for this recommendation is not cited.

- Radioactive material swallowed – gastric lavage is unreliable, with negligible benefit if performed more than one hour after ingestion.

- Eyes – rinse by directing a stream of water from the inner canthus to the outer canthus of the eye while avoiding contamination of the nasolacrimal duct

- Ears – external rinsing; an ear syringe can be used to rinse the auditory canal, provided the tympanic membrane is intact. Caution: detonation of an explosive device to disperse radioactive material carries the risk of barotrauma to the ears.

External decontamination of intact skin

- Wash under a stream of water, gently scrubbing at the same time with a soft disposable brush or surgical sponge. Special attention should be given to nails, skin folds and hair

- Use gentle, neutral pH soap if required

- Scrub for 3–4 minutes, rinse for 2–3 minutes and then dry

- Monitor

- Repeat if necessary

- Decontamination stops when no further significant reduction in radiation level can be achieved

Avoid excessive scrubbing. Even minimal abrasions may result in a greater than ten-fold increase in incorporation of radioactive material.

After decontamination

Replace the sheet beneath the patient. Move casualties from 'contaminated' stretcher to a clean stretcher across control line for transport of casualty to definitive treatment area.

Waste management

Waste water

Ideally waste water from decontamination procedures would be collected. However, this is unlikely to be practical. The installation of a holding tank is almost certainly not justified because of the infrequency of this event. Any radiation hazard to the public or the environment from the comparatively small volume of waste water will be massively diluted in the sewer system.

Bagged waste

At the conclusion of the decontamination of the patient soiled linen, dressing materials, etc. should be surveyed by the hospital radiation safety officer for residual contamination. Contaminated linen and waste should be double-bagged and labelled 'radioactive'. Bagged contaminated waste should then be stored in a secure, isolated area, free from human interference, until decay has occurred

naturally, rendering the waste no longer radioactive. The time for this to occur is dependent on the specific radioisotope. In the case of waste with a long half-life, contact the radiation regulator or the health department radiation adviser in your state or territory for advice on arrangements for the proper disposal of the waste.

Contaminated buildings and equipment

Cleaning staff should wear the same PPE as the decontamination team. Disposable floor coverings and other coverings should be rolled up and placed in plastic bags. The entire area should then be thoroughly surveyed for residual contamination. In most cases, normal cleaning methods will remove the material. Vacuum cleaners that can handle wet material and have high efficiency filters are useful. Some surfaces may require repeated scrubbing and vacuuming before they are free of contamination.

Disposal of waste

All waste materials should be disposed in accordance with prescribed procedures. Hospital radiation safety officers can obtain further advice from the health department radiation adviser.

Obtaining specialist advice

- Contact the hospital on-call health physicist or radiation safety officer (RSO) to attend at the ED.
- Contact the health department radiation adviser in your state or territory for advice and to ensure notification of the incident has occurred. Whilst the regulation of radiation may not rest with State or Territory health departments in every jurisdiction, health departments will provide initial public health advice, links to appropriate radiation expertise and overall coordination of health resources in emergencies.
- Clinical advice on the care of victims with acute radiation injury or illness can be obtained from radiation oncologists in each State and Territory. The Peter MacCallum Cancer Centre, Melbourne, is the clinical part of the Australian Collaborating Centre for Radiation Protection and Radiation Emergency Medical Assistance, and a member of the World Health Organisation Radiation Emergency Medical and Assistance Network.
    - Contact Peter MacCallum switchboard on 03 9656 1111. Request the on-call radiation oncologist.
- Inpatient care may require the coordination of a multidisciplinary team of medical and support specialists including, but not limited to:
    - Medical health physicist
    - Nuclear medicine physicians
    - Radiation oncologists
    - Haematologist/oncologist
    - Intensivist
    - Trauma surgeon
    - Clinical toxicologist
    - Infectious control specialist.

Role statement: Radiation safety officer

Often, the hospital radiation safety officer is a member of the diagnostic radiology department. Occasionally this role is fulfilled by the occupational health and safety unit. The radiation safety officer supports safe operations in a radiological emergency, assisting responding staff to ensure their doses are as low as reasonably achievable, and providing technical support and documentation.

Responsibilities pre-event

- Advise management on matters relating to radiation safety including:
    - Radiation monitoring programs.
    - Condition of and need for radiation monitoring and protective equipment.
    - Action to be taken to reduce the radiation exposure of employees or members of the public to as low as reasonably achievable.
    - Action to be taken in the event of an emergency or accidental exposure.
    - Prescribed standards for discharge of radioactive waste.
- Prepare safe working procedures with respect to radiation protection for use in routine operations or in an emergency or accidental exposure.
- Be responsible for instruction of employees in radiation hazards, safe working procedures to ensure radiation protection, the proper use of radiation monitoring and protective equipment, and measures to limit radiation exposure.
- Maintain sufficient radiation monitoring and radiation protection equipment and ensure that equipment is calibrated and in a ready and working condition.
- Ensure that prescribed radiation signs are maintained in good condition and located in places where they will be easily seen.
- Investigate sources of radiation exposure, the radiation protection equipment and working procedures and recommend any change that would reduce exposure to employees and members of the public.
- Maintain detailed records on all the above matters.

Responsibilities during event

- Ensure that appropriate radiation protection monitoring surveys are carried out as required.
- Implement personal monitoring systems for the determination of effective doses for any employee or class of employees as required.
- Assess accumulated effective dose and committed effective dose of any employee or class of employees.
- Ensure compliance with prescribed standards for radioactive waste handling.
- Ensure that radiation signs are located in places where they will be easily seen.
- Monitor transport containers and ensure they comply with the [Code of Practice for the Safe Transport of Radioactive Material (2001)](#) or later as amended.
- Maintain detailed records on all the above matters.

Role statement: Medical health physicist

Medical health physicists work in the areas of radiography, nuclear medicine, or radiation oncology. They can provide advice to clinicians managing radiological casualties.

Responsibilities pre-event

- Contribute to the development of radiological emergency response plans for their hospital, based on health physics principles. Ensure these are consistent with local state and territory arrangements.

- Contribute to staff development, training and exercising for radiological emergencies. Coordinate activities with the radiation safety officer.

- Through professional bodies such as Australian Radiation Protection Society (ARPS), Australian and New Zealand Society of Nuclear Medicine (ANZSNM), Australian and New Zealand Society of Nuclear Medicine Technologists (ANZSNMT), the Australian Institute of Radiography (AIR), Australasian College of Physical Scientists and Engineers in Medicine (ACPSEM) and others, develop mutual aid arrangements and consensus educational and operational guidelines for radiological emergencies.

- Nuclear medicine physicians and technologists should familiarise themselves with Anigstein R, et al. Use of radiation detection, measuring, and imaging instruments to assess internal contamination from inhaled radionuclides; part 1: feasibility studies. 2007. Available from: https://www.cdc.gov/nceh/radiation/emergencies/clinicians/evaluation/supportdocs.htm

Responsibilities during event

- Orient medical staff with the principles of dealing with radiological contaminants.
  - Consider the use of 'just-in-time' training resources available from the US Centers for Disease Control Prevention at https://www.cdc.gov/nceh/radiation/emergencies/justintime.htm?CDC_AA_refVal=https%3A%2F%2Femergency.cdc.gov%2Fradiation%2Fjustintime.asp
  - See also the resources on the US Department of Health and Human Services Radiation Emergency Medical Management website at https://remm.hhs.gov/

- Evaluate the level of external or internal contamination of casualties.

- Assist clinical staff to evaluate and understand the significance to patient and staff of the levels of radiological contamination with which they are dealing,
  - Particularly with respect to the stabilisation of life-threatening injuries in a timely way consistent with safety of personnel.
  - Assist with advice regarding special precautions required to provide patient care where there are shrapnel fragments with significant radiological activity.

- Provide guidance on the decontamination of casualties, facilities and the vehicles involved in transporting casualties to hospital.

- Oversee the recalibration of hospital gamma cameras, thyroid cameras, etc for use in evaluating internal contamination.

- Make preliminary dose estimates and communicate these to treating clinicians. Include an explanation of the uncertainty in the dose estimate.
- Inform communications with patients, staff and management on radiological issues.
- Assist public health authorities in monitoring people who are not injured but are concerned they have been exposed to radiation or radiological material.

Role statement: Haematologist/oncologist

A consequence of exposure to high dose radiation is myelosuppression. Experience from radiation accidents, shows that it is possible to salvage casualties with myelosuppression under the care of a haematologist/oncologist.

Responsibilities pre-event

- Contribute to the development of radiological emergency response plans for their hospital.
- Through professional bodies such as the Royal Australasian College of Physicians (RACP), Haematology Society of Australia and New Zealand (HSANZ), Medical Oncology Group of Australia (MOGA) and others, develop consensus guidelines for the evaluation and clinical management of myelosuppression in radiation exposure casualties.

Responsibilities during event

- Make a preliminary dose estimate utilising available clinical information for each individual. See Radiation Dose Assessment.
  - Establish the symptom and location history.
  - Assess the degree of myelosuppression based on lymphocyte depletion kinetics.
  - Seek the advice of a health physicist in interpretation of bioassays and dicentric analysis, when these results are available.
- Stratify casualties into risk groups:
  1. Will not require medical intervention
  2. Could benefit from supportive care with G-CSF or GM-CSF to facilitate autologous marrow recovery.
  3. Needs further evaluation for haematopoietic stem cell transplant.
  4. Not able to be salvaged.
- Provide ongoing clinical management of patients with myelosuppression in conjunction with the multidisciplinary management team.
  - Implement colony stimulating therapy in eligible patients as early as feasible, ideally in the first 24 hours.

References

1. Anigstein R, Erdman MC, King SH, Mauro JJ, Miller KL, et al. Use of radiation detection, measuring, and imaging instruments to assess internal contamination from inhaled radionuclides; part 1: feasibility studies. 2007. Available from: http://emergency.cdc.gov/radiation/clinicians/evaluation/pdf/Part_I.pdf

2. Armed Forces Radiobiology Research Institute. Medical management of radiological casualties handbook, military medical operations. 2nd ed. Bethesda: Armed Forces Radiobiology Research Institute; 2003.

3. Miller CW, Whitcomb RC, Ansari A, McCurley C, Guinn A, et al. The roles of medical health physicists in a medical radiation emergency. Operational Radiation Safety. 2007; 93(s3): S187-S190.

4. Radiation Safety Program, Department of Human Services. Radiation safety officer typical duties. 2009. Available from: https://www.health.vic.gov.au/environment/downloads/radiation/reqs_rso.pdf

5. Solomon S, McKean N, Drummond R, Tai KH (editors). Medical management of individuals involved in radiation accidents, technical report series no. 131. Australian Radiation Protection and Nuclear Safety Agency (ARPANSA). Yallambie. 2000.

6. Victorian Government Department of Human Services. Decontamination guidance for hospitals. Victorian Government Department of Human Services, Melbourne. 2007.

7. Victorian Government Department of Human Services. Health services personal protective equipment and decontamination hospital staff training course presenters guide. Victorian Government Department of Human Services, Melbourne. 2006.

8. Weinstock DM, Case C, Bader JL, Chao NJ, Coleman CN, et al. Radiological and nuclear events: contingency planning for hematologist/oncologists. Blood. 2008; 111(12): 5440-5445.

9. Raphael B. CBRN safe, psychosocial guidelines. Psychosocial guidance for emergency workers during chemical, biological, radiological and nuclear incidents.

10. Weisdorf D, Apperley J, Courmelon P, Gorin N-C, Wingard J, et al. Radiation emergencies: evaluation, management, and transplantation. Biology of Blood and Marrow Transplantation. 2007; 13: 103-106.

11. Wingard JR, Leahigh AK, Confer D, Edwards J, Billups RL, et al. Preparing for the unthinkable: emergency preparedness for the hematopoietic cell transplant program. Biology of Blood and Marrow Transplantation. 2006; 12: 1229-1238.

12. Mettler FA. Medical resources and requirements for responding to radiological terrorism. Health Physics. 2005; 89(5):488-493.

Public health management

Introduction

This chapter is concerned with management of populations exposed to low level radiation. The clinical management of significant exposure and injury due to radiation is discussed in other chapters. In a radiological emergency, the population is likely to be divided into categories of varying risk of suffering harm. These include:

a) People close to a source of radioactive material and/or the site of a radiological/nuclear emergency who are at highest risk. These people may require radiation protection measures, such as shelter and evacuation, and medical treatment, if there is significant irradiation or contamination.

b) People who are exposed to measurable amounts of radiation, but the exposure is likely to cause very low and/or unquantifiable risks to health in the short to medium term.

c) People with no significant exposure to radiation from the emergency, but whose behaviour is adversely affected by their perception of the event, the risk to themselves or loved ones, or other psychological factors amenable to management by effective communication.

When an emergency is centred on a site, like a reactor fire, then these groups will form concentric zones at increasing distance from radioactive material. If the community is unknowingly exposed to a lost or stolen radioactive source, then these categories may not be geographically defined, but there is still likely to be a gradation of risk based on activity of the source, expected proximity to the source and duration of exposure.

The management of radiation protection and medical treatment for people in the highest risk (a) category is conducted by appropriate medical and scientific specialists. Public health may be important in these operations, as, for example, they may need to ensure adequate safe food, sanitation and medical services to evacuation centres, but does not generally form part of the management of the incident itself.

In lower risk populations (b and c), not at immediate risk of adverse health effects, public health agencies have an important role to play in managing a radiation emergency. This is because:

a) The public perception of radiation hazards, combined with the lack of definitive information which may occur in the early stages of managing a radiation emergency, can engender significant anxiety in the wider population.

b) The degree of exposure of people to radioactive material may not be known, such as if radioactive material is dispersed in the atmosphere, water or food.

c) There may be a need to prepare the general population to move away from areas of risk if an emergency worsens without causing undue alarm or mass 'self-evacuation'

Failure to manage the response of lower risk groups to a radiological emergency can lead to a dysfunctional response from the public in response to a radiological emergency. Poorly planned decisions by the public to move away from an area when there is a low risk from radiation exposure can be dangerous and may impair the response to an emergency. Unintended harms of risk avoidance on a population scale has been noted in other situations; several thousand lives were lost through the choice of travellers to avoid flying in the US after the 9/11 attacks in favour of more

hazardous forms of travel[4]. Similarly, refusal to enter an area or workplace, as well as lack of confidence in food, water or other products, can cause unnecessary economic damage. It is important to note, however, that public health communication is not purely a matter of 'calming people down'. It may be necessary to simultaneously provide reassurance to many people, while providing some quite alarming information to others. These approaches should be integrated to avoid inconsistent information, confusion and a lack of confidence in the management of an incident.

The role of public health agencies in managing population response to lower levels of radiological risk

The issue in managing public behaviour in an emergency is rarely panic per se. Panic involves 'irrational, groundless or hysterical flight that is carried out with a complete disregard for others'[5]. What is more often observed in emergencies is a response to fear, which is rational from the perspective of a person with an incomplete understanding of a situation and/or the belief that their actions are the way to control a threat to their safety. Providing information about the scale of a threat and measures necessary to remain safe can alleviate a lot of what appears to be irrationally motivated behaviour.

Radiation can be accurately detected in minute amounts, allowing for a precise assessment of the physical risk posed to the population. The risk which public health agencies must manage in groups 2 and 3, however, is often 'distorted' by psychological factors which include:

- *The risk from a radiation emergency is involuntary*. People will tolerate more risk when it is adopted by choice, such as using mobile phones while driving.

- *The risk from radiation is not under personal control.* People will tolerate risks when they feel they can do something to reduce its impact, such as wearing a mask in an influenza outbreak.

- *Radiation is unfamiliar and produced by technology that few people understand.* This increases people's perception of the likely danger compared to risks which they understand, such as the risk of physical injury from a fire.

- *Radiation causes dread diseases.* Cancer and birth-defects are both associated with radiation exposure and are diseases which inspire a high degree of fear. As was observed in the 2009 pandemic, people worry less about a high risk of developing a minor illness.

- *Fairness.* People will tolerate risks if they perceive they benefit from the activity. This may not be the case where a radiation emergency involves an industrial or military facility.

- *Morality.* There are many people concerned about pollution in general, whose perception of risk from a radiological emergency is coloured by their views on the morality of the nuclear or other industry.

- *Trust:* There may be a low level of trust for public authorities, standards and 'experts' in communicating risk. This is in the context of trusted networks of friends, media, popular wisdom, and other sources of information about radiation.

---

[4] G. Blalock et al, Driving Fatalities After 9/11: A Hidden Cost of Terrorism, Applied Economics, 2009 (Vol. 41, Issue 14).
[5] Auf de Heide, E, Common Misconceptions about Disasters: Panic, the 'Disaster Syndrome,' and Looting, chapter 27 of The First 72 Hours: A Community Approach to Disaster Preparedness, M O'Leary (ed), published iUniverse 2007

- Diffusion in time and space. Risks which kill people 'anonymously' by being dispersed throughout the community and occurring at random intervals, such as household falls, engender less concern than those which are localised to a particular incident. A small risk from a radiological emergency with identifiable 'victims' localised to one area is less tolerable.

Adapted from Peter Sandman, Risk Communication: Facing Public Outrage, US EPA Journal November 1987.

Managing risk in these terms involves functions which public health agencies and/or environmental protection agencies routinely apply to the management of environmental risks of population significance. Particularly:

- Risk communication to the public and other significant stakeholders of the risk poses by exposure to radioactive material in the environment. This can be done by a wide range of agencies, but public health agencies usually have established links with local doctors, schools, and government departments and experience in communicating risk from environmental/communicable disease hazards.

- Surveillance or case-finding to identify people exposed to significant amounts of radiation, who may need medical treatment or an assessment of long-term health risks from exposure. Surveillance and case-finding are routine aspects of the response to communicable disease and food poisoning outbreaks and can be modified to manage environmental hazards.

- Involvement in the development and implementation of evacuation plans from areas of risk. Moving large numbers of people requires planning to avoid public health risks.

There is a level of complexity introduced to the management of radiological emergencies by the overlap of Commonwealth, State and Territory responsibility for some of these areas. A radiological emergency would almost certainly be considered an incident of national significance and have a large degree of Commonwealth involvement, including the involvement of specialist agencies such as the Australian Radiation Protection and Nuclear Safety Agency (ARPANSA) and the Australian Nuclear Safety and Technology Organisation (ANSTO), as well as State/Territory radiation regulators. It is, therefore, important that there be a clear delineation of the role of public health agencies in an incident, which includes what they are not doing, to avoid confusion between levels of government and specialist agencies.

Risk communication to the public and stakeholders

Public health authorities should be tasked with developing communication for any radiological emergency which involves the release of radioactive material into the environment. This recognises the likelihood that the population whose risk perception needs to be managed is far larger the population that is likely to be exposed to acutely dangerous levels of radiation.

Key messages

Public health agencies should anticipate needing to provide public and media information on, at least, the following information immediately a release of radioactive material into the environment is confirmed:

a. What is the risk to the health of the population from exposure to radiation?

This depends on the type of radionuclide released and the dose the population is exposed to. Probability should be explained in 'naturalistic' terms, which compare to a risk that can be envisaged, rather than a mathematical abstraction like '1 in 1 million'. Both the comparative radiation exposure, and the human health risk which results, need to be conveyed.

Where radiation exposure is very low, it can be useful to compare it to relatively innocuous activities like international flight or medical procedures such as chest X-rays. A comparison of radiation environmental exposures with other 'safe' radiation exposures has its limits, however, because it relies on the public perception of the safety of medical radiation. The peak radiation levels in Tokyo in March 2011 were about 0.3-0.5 µSv/hr, which is a very low risk to human health but is equivalent to a chest X-ray every two days to one week (20-100 µSv), which is not reassuring to everyone. A CT sounds like an innocuous comparator but, at up to 10mSv exposure, it is associated with a 1/2000 increase in lifetime risk of cancer, which is less reassuring[6].

For this reason, it can be useful to provide comparisons of the health impacts of probabilities as well as the doses associated. For example:

Table 6.1 Risk comparison table

Some comparative risks to a radiation exposure of 1 millisievert (mSv) (Risk of death 1 in 20,000)
• Lifetime risk of death by eating 2000 tablespoons of peanut butter
• Lifetime risk of death by eating 5000 charcoal barbecued steaks
• Lifetime risk of death by eating 1000 extra calories for an overweight person
• Lifetime risk of death by living 100 days in New York*
• Lifetime risk of death by smoking 75 cigarettes
• Annual risk of death from an accident at home
• Risk of death travelling a distance of 5000 km in a car in NSW*
• Risk of a car crash when travelling a distance of 60 km in a car in NSW*

* Suggested best comparator

From Northern Central Sydney Area Health Service Radiation Safety Council research guide 2006

This is useful because the objectively tiny increase in the risk of developing cancer from being exposed to 0.35 µSv per hour for 30 days, for example, can be compared to a range of events which many people perceive as rare but generally accept without great concern.

b. Is it dangerous to eat produce/drink water?

Radiation is invisible to the senses and is therefore viewed as an insidious hazard that may be present in food and water.

---

[6] US Food and Drug Authority, 'What are radiation risks from CT?', http://www.fda.gov

It must be positively established early in a radiological emergency whether radioactive material is present in water or food, as discovering this later can fatally undermine trust in the management of a radiological emergency. If there is no contamination of food or water, then the issue of public communications is simple. If, however, there is a low level of contamination then it is important that the degree of risk to health this poses is immediately put into context.

Authorities are likely to measure and report the total amount of radioactivity in bulk food or water in Becquerels. This unit can be problematic because 1 Becquerel is a very small unit of radioactivity and so even low levels of contamination produce 'big' numbers. A measure in Becquerels also has no direct relationship to absorbed dose, or the human health impact of ingesting food or water, and so is confusing in the context of other units such as microsieverts. Public health agencies may find it useful to request a radiation physicist calculate an absorbed dose from the expected elements present in food or water for a given amount of food or water ingested to equal the normal background level of radiation.

It is also important to convert the total activity in food and water into an assessment of the health impact of ingesting this material, because radioactivity may be reported in terms of the amount it exceeds 'normal'. As there is no 'normal' amount of many radioactive substances in the environment, the emissions limits for a nuclear power station, the limit of detection for radioactivity or the 'action limit' for investigation of a source of radioactivity are likely to be taken as a 'proxy' figures. These are set at a precautionary level, which is many times lower than the level of radiation that has a measurable health impact but may lead to contamination being reported by authorities or the press as 'x thousand' times normal. This can cause unnecessary concern.

c.   What can I do to avoid radiation exposure?

One aspect of anxiety about radiation can be the perception that exposure is unavoidable and therefore the individual is not in control. It is important, therefore, to provide advice about shelter, safe exposure times in the environment and distance from the source of a radiological emergency to the population who are outside the immediate area of acute health concern.

The public may not be aware that substantial buildings, such as brick houses, offer 2 to 10-fold reduction in the absorption of radiation, and that basement car-parks can have much higher levels of protection. Simple advice about minimising unnecessary travel outdoors, closing windows and air- conditioning to reduce radiation exposure to As Low As Reasonably Achievable (ALARA) can be useful in providing people with measures they can undertake themselves, even if the underlying health risk is very low.

If there is an airborne distribution of material in a radiological emergency, then public health advice should be provided on issues such as water-tanks and home-grown food. The public health agencies in most jurisdictions have generic advice for the management of home water collection and washing of home-grown food after bushfires or chemical fires, which can be adapted for use in areas under a potential plume of radioactive material. It should be pointed out that filtering, boiling or adding decontamination tablets to water may not reduce levels of radiation.

People in any area where there is contamination from detectable amounts of radioactive material from a radiation emergency should be provided simple advice on what they can do if an emergency worsens. This is likely to be fairly simple advice about sheltering, providing water and related matters, but it is important to avoid an information vacuum of how to respond in the context of potentially inflammatory media reporting of an unstable emergency becoming worse.

d. What are the risks to pregnant women/unborn children/breast-feeding women?

The risk of a given level of environmental radiation to pregnant women/unborn children should be provided regardless of the scale of risk. Of particular importance may be advice around breast feeding and the excretion of radionuclides in breast-milk. While this is unlikely to lead to significant doses of radiation, factual information is likely to be expected, given the perception that radiation is acutely dangerous for unborn children.

Some radioactive substances, such as Iodine-131, can accumulate in breast milk if ingested during lactation, particularly soon after birth. Given that the overall dose to a mother is likely to be very small, this will probably be a negligible increase in absolute exposure to breast-feeding children.

Table 6.2 Transfer of radionuclides to breast milk following intakes during pregnancy or lactation

Radionuclide	Transfer to milk as per cent reaching blood, for intake in:		
	Early pregnancy[1]	Late pregnancy[2]	Lactation[3]
^{45}Ca	0.7	18	67 (20)[4]
^{90}Sr	0.7	9	31 (9)
^{131}I	–	0.06	29 (29)
^{137}Cs	0.5	10	24 (24)
^{210}Po	0.01	0.7	1.5 (0.7)
^{239}Pu	0.2	0.2	5 (0.002)
^{241}Am	0.2	0.2	2 (0.002)

[1] Intake at 5 weeks post-conception
[2] Intake at 35 weeks post-conception (3 weeks prior to birth)
[3] Intake within 1st week after birth
[4] Figures in brackets for intakes during lactation are percentage ingested activity

From Harrison, JD, Smith, TJ, Phipps, AW, Infant doses from the transfer of radionuclides in mother's milk, Radiation Protection Dosimetry, (105) 2003

Table 6.3 Comparison of doses following chronic maternal ingestion of radionuclides throughout pregnancy and lactation

Radionuclide	Ratio of offspring: adult dose[1]	
	Foetus[2]	Infant, in milk[3]
^{45}Ca	12	2.7
^{90}Sr	1.5	0.8
^{131}I	1.0	2.4
^{137}Cs	0.4	0.4
^{210}Po	0.1	0.2
^{239}Pu	0.04	< 0.001

Radionuclide	Ratio of offspring: adult dose[1]	
	Foetus[2]	Infant, in milk[3]
^{241}Am	0.01	< 0.001

[1] Committed effective dose (environmental exposures)

[2] Includes doses received in utero and from activity retained by the child at birth

[3] Includes doses from activity transferred to milk as a result of maternal intakes during pregnancy and lactation

From Harrison, JD, Smith, TJ, Phipps, AW, Infant doses from the transfer of radionuclides in mother's milk, Radiation Protection Dosimetry, (105) 2003

e. Do I need iodine tablets?

Information about the need to take Potassium Iodide (KI) tablets, in an area with low levels of radioactive contamination or no exposure to radiation, may do little alleviate interest in having tablets ready 'just in case'. This can be a problematic public health issue because people may take Potassium Iodide in response to media reports of a situation or personal perception of risk and suffer unnecessary adverse effects. In the United States, where KI is available without prescription, the California Public Health and Emergency Management Agency issued advice to the population to stop taking KI[7] in March 2011 in response to the Fukushima accident because cases of acute toxicity were being reported by poisons centres.

The protective effect of KI in managing exposure to radioiodines is established, but significant exposure is required to justify the use of this drug. Unfortunately, public perceptions of KI as 'radiation tablets' may lead to confusion about circumstances when KI should be used. Public health messages need to clearly identify when the radionuclide is NOT a radioiodine with emphatic advice that KI is ineffective for management of these exposures.

Adverse effects of KI include gastrointestinal disturbance (nausea, diarrhoea, and abdominal pain), transient hypothyroidism, skin reactions or allergic reactions. While these are generally mild, widespread inappropriate use of KI on a population level can cause significant harm. KI should not be provided to populations at low (or no) risk of exceeding the amount of radiation from radioiodines necessary for protection against thyroid cancer, particularly not on a precautionary 'just in case' basis or for psychological reassurance.

f. Are people or things which have been near a radiological emergency safe?

Radioactivity may be viewed as 'contagious' in terms of people from an area close to an emergency being radioactive themselves or objects being contaminated with radioactive material. This is quite distinct from the issue of people internally or externally contaminated with large amounts of radioactive material who may require decorporation treatment or formal decontamination measures.

Advice about food or water from the vicinity of a radiation emergency should be based on monitoring and control of the distribution of contaminated material. General advice about what to do with material which has come from an area of low radiation risk, such as cars driven by evacuees, clothes and so forth, should be provided.

---

[7] California Emergency Management Agency, press release, 17 March 2011

People from the affected area, who have been effectively decontaminated (which in vast majority of cases just required removal of clothing and showering), are not a radiation risk.

Coordination of communications

In an incident affecting Australia, there are three levels of government and, potentially, several portfolios at both the Commonwealth and state level that will have 'ownership' of the issue. Media interest and pressure to provide commentary is likely to be intense.

In this environment, public health messages should be:

- consistent
- measured
- applicable to a local area, given its distance from an incident, weather, water and food supply
- presented in a manner that allows people to make contact to seek further information about health concerns

Public health agencies usually maintain close links with local clinical networks, public interest groups and media. It is proposed, therefore, that messages follow a process by which core information is cleared 'centrally' through the Commonwealth Department of Health and Ageing (probably AHPPC) but distributed locally through state health departments and public health agencies. This would allow public locally relevant information to be added while working off a common set of agreed facts, such as the amount of radioactive material that has been released, progress in containing an incident and national measures undertaken. A system for sharing information between states, including material such as call-centre scripts, often assists smaller jurisdictions with limited resources in developing local information.

Surveillance

Public health agencies usually monitor or undertake infectious disease and environmental health surveillance for state health departments. Surveillance, or case-finding, can also be used to identify people exposed to significant amounts of radiation. In a radiological emergency, information should be provided on how to recognise injury caused by exposure to radiation in two distinct circumstances:

- To provide medical practitioners and the public information on the signs and symptoms of radiation injury so that they exclude this as a diagnosis and counsel concerned patients. This is the most likely use of this information and it is important to avoid the 'worried well' presenting in large numbers for medical assessment with perceived symptoms of radiation injury.

- To find people in a population, who may have been exposed to significant quantities of radiation from a lost/covert source of radiation, such as a source concealed in a public place. In this case, it is necessary to communicate to doctors and the public a case-definition of early radiation sickness and advice on where people should go for further assessment.

In either of these cases, the case-definition must be consistent across an area affected by an incident and should ideally be agreed at a national level. However, the case definition should be distributed locally because how to manage people who may meet it will depend on local health systems. Public health agencies are usually well integrated into lines of clinical reporting, discussion

of case definitions with general practitioners, laboratory testing, and referral of patients for assessment and collation of epidemiological data.

Surveillance of 'ambient' radiation levels

Part of the anxiety provoked by radiation is that it is invisible to the senses. Monitoring of ambient radiation levels in areas with low levels of risk of contamination can provide reassurance to the public that radiation is not present. During the 2011 Fukushima reactor incident, Japanese public health authorities provided real- time web-based information on levels of radiation detected in urban centres. Apart from being very useful to medical and other professionals advising people in these areas, these readings provided a transparent and real-time source of information that members of the public could access themselves and use to plan their activities.

Daily radiation monitoring could potentially be arranged through radiation physics departments at hospitals, academic institutions, companies specialising in the remediation of environmental health issues, or government reference laboratories. In the absence of an established process, the ability to provide survey meters to staff to quantify low or absent levels of radiation can be useful. This should obviously not replace specialist assessment of radiation present in the environment when, and if, significant contamination by radioactive material occurs.

Development and implementation of evacuation plans

Evacuation of areas where people receive high doses of radiation (approximately >1mSv/hr[8]) is a fundamental part of the repertoire of responses to a radiological emergency. While the decision whether people need to evacuate an area would rest with expert advisory groups with experience in radiation safety, managing the evacuation of large populations raises many public health issues.

The aim of an evacuation process is to reduce the overall hazards to human health, but evacuation of large numbers of people is itself hazardous. In 2005, Hurricane Rita was responsible for 111 deaths in the Texas gulf; 3 of these were from wind-blown trees and 108 were attributable to complications of evacuation, such as hyperthermia, dehydration, decompensation of chronic health conditions and vehicle accidents[9].

This balance is particularly important in radiological emergencies because the public perception of the risks associated with radiation may be disproportionately high compared to the actual risks from a mass evacuation. There may also be the perception that evacuation from areas of low risk is the only way of reducing exposure to radiation.

To address the potential public health impacts of an evacuation plan, public health agencies should prepare information relevant to people in their area which details:

a. When should people evacuate?

Instructions to shelter-in-place may be preferred to evacuation. The Incident Controller is responsible for the decision to evacuate an affected area or disseminate advice on sheltering-in-place. If a population may be impacted by a 'plume' or change in weather, then a plan for response

---

[8] ARPANSA Radiation Protection Series Number 7
[9] Zacharia, A, Patel, B, Deaths related to hurricane Rita and mass evacuation, Chest, 2006 Slide Presentations.

to this scenario needs to be communicated. Failing to address this issue may lead to large numbers of people self-evacuating in response to media, weather reports or rumour and suffering the complications of evacuation. The difference between a 'cloud of deadly fallout' and a 'rain-front which contains measurable quantities of radiation from a fire' will not be understood without this message being clear.

If evacuation is a possibility, then the signal which indicates people should evacuate also needs to be clear to people in the community. The use of emergency messaging systems specified jurisdictional emergency plans, such as radio, television, SMS or sirens, should be planned in advance. Ad hoc communication from non-local authorities should not replace standard emergency warning systems.

b. How to evacuate

It is not possible to completely remove a significant urban population from an area quickly and safely. While the general public expectation may be for people to leave a city by motorised transport ahead of a 'cloud' of radiation, this is not practical. The mass evacuations ahead of Hurricanes Rita and Katrina in the USA in 2005 resulted in '100 mile traffic jams' in which cars became immovable obstacles due to running out of fuel or suffering accidents7. A significant proportion of these populations did not have access to cars as they normally used public transport. Buses were available for use in Hurricane Katrina, but mass use was limited by the availability of drivers who had also evacuated. Public expectations about what can be achieved in a mass evacuation must therefore be actively managed ahead of a real or perceived need.

In this context, public health agencies should work with emergency planners to effectively communicate the degree of the immediate threat to human health a change in weather, plume direction, or severity of a radiological emergency presents. If a town is threatened by a change in the direction of a plume carrying material from a radiological emergency, for example, then peak levels of radioactivity are likely to be transient. Levels of radiation at which people might be advised to move, such as 40 µSv/hr[10], will still take several weeks of unshielded exposure to exceed a maximum yearly radiation worker exposure standard of 20 mSv. In these situations, advice to shelter in place and evacuate in due course, rather than evacuating ahead of a particular storm or weather change, can potentially reduce some of the hazards of mass evacuation.

c. Where to evacuate

It is unlikely that a significant urban population can be relocated to another single town or city, and attempting to do so can worsen congestion issues. In the 2005 evacuation of New Orleans ahead of Hurricane Katrina, one issue in the severe congestion experienced on the highway was the concentration of vehicles at destinations such as Houston[11]. What is important in an evacuation is the distance from a source of exposure to radiation, and the required distance should be communicated with as many options for destinations as this allows.

The movement of people with chronic diseases, who are technology dependent or who have impaired mobility poses particular challenges. Evacuation centres with high radiation shielding

---

[10] ARPANSA Radiation Protection Series 7 p33; Recommends temporary resettlement at a dose of 30mSv in the first month, which equates to 42 uSv/hr.
[11] Litman, TA, Lessons From Katrina and Rita: What Major Disasters Can Teach Transportation Planners,' Journal of Transportation Engineering, 132 (2006)

qualities can be implemented in buildings with basement levels and may be better than transporting vulnerable people even if the wider population does evacuate. In setting up evacuation centres, public health agencies should provide advice on sanitation, food preparation, water supply and the provision of medical care. A system of tracking the arrival of people in evacuation centres is essential.

d.   What to do if you do not evacuate

Where advice to evacuate is a remote possibility, people should be provided with information about how to protect themselves, so they don't self-evacuate when it's unnecessary. Where evacuation is advised, people should be provided with information about how to protect themselves in the event they cannot leave an area.

In either case, providing information, which empowers an individual to take protective action, can avoid a poor outcome from self-evacuation or poorly planned sheltering. This includes how to identify areas of a house or building that provides optimal shielding, how to prepare water and food supplies to avoid contamination by rain or particulates, and activities to avoid. With the exception of not having to actively defend a house against a radiation plume, many of these messages are similar to those required in bushfires, floods, storms and other environmental emergencies managed under jurisdictional emergency plans which include public health input.

Response zones

Advice may be given to people on the basis of being in a 'zone' at a distance from a source of radiation. Zones for immediate evacuation (precautionary action zone) or protective action (urgent protective action zone) are designated ahead of time around US nuclear facilities[12] and visiting nuclear-powered warships, and similar zones were declared at 20km and 80km around the Fukushima reactor after the 2011 tsunami. These involve giving people the advice described above based on their location rather than a specific 'signal' to evacuate or take action.

In establishing a response based on response zones, care should be taken to communicate:

- **Why the zone is being established**; is it precautionary, based on measured exposure, or a zone in which people should be prepared to take further action?
- **How the zone affects movement**; are people in the zone to leave and can people enter?
- **What is the advice for people outside a zone**; it is difficult to convince people on the margin of a zone that their risk falls to zero. This is particularly so if there are highly visible protective measures being taken (monitors, distribution of printed material, increased presence of emergency services) in close proximity to an area nominally outside a risk zone.

If a zone is precautionary, it is necessary to make this clear because otherwise later reducing the size of a zone raises concerns about how contamination has been excluded and the area declared 'safe'. This can lead to entirely unnecessary requirements for testing to exclude material which was only ever potentially present, which is drain on public health and/or environmental health resources.

The naming of zones can assist in communicating its intent to the public. If people in the zone do not have to leave but people outside are to avoid entering unnecessarily, then the term 'evacuation

---

[12] ARPANSA Radiation Protection Series 7, p18

zone' is unhelpful. Similarly, if residents are being asked to confine themselves to essential travel into an area but otherwise shelter in place within it then the term 'exclusion zone' is misleading[13]. It can be assumed the media will choose the most alarmist or confusing names, such as 'no-go zone', 'death zone' and 'disaster zone' with reference to the 20km and 80km zones around the Fukushima site. Comparatively bland names such as the 'Precautionary Zone' or 'Protective Action Zone' may be preferable if they are used consistently in communications and explained.

---

[13] 'The fire forced the closure of several schools as authorities this morning enforced a 10-kilometre exclusion zone around the factory', 'Huge Canberra Blaze Now Under Control', Sydney Morning Herald, September 16 2011.

Laboratory capacity

Australia has approximately ten laboratories able to measure fission products in samples following a nuclear detonation. Laboratory radiation measurements fall into two types:

- Detailed measurements of radionuclide content for detailed dose assessment. This would use gamma counting systems.

- Alpha/beta screening of samples to assess compliance with radiation limits.

The Australian Nuclear Science and Technology Organisation (ANSTO) and the Australian Radiation Protection and Nuclear Safety Agency (ARPANSA) are the only Australian laboratories with a routine and traceable capability to measure fission products. Between them they have maximum of 60 gamma counting systems. Not all of these would be available for use. Initial gamma counting capacity of 500 to 3000 samples per day, could increase to a maximum of 1000 to 5000 samples per day as other laboratories are brought on-line.

The other laboratories between them have a further 30 gamma counting systems which could be brought on- line for fission product measurement by providing the appropriate calibration standards to each of the laboratories.

Additionally, ANSTO and ARPANSA have up to 50 alpha/beta counting systems, out of a total of approximately 110 systems within Australia.

While it is certainly the case that while ARPANSA and ANSTO have a large proportion of Australia's radioanalytical capacity, there are other Australian Government (ERISS for example), State and Territory (QLD FSS for example) and commercial laboratories that could support an Australian response to a radiation emergency. The experience with Fukushima demonstrates that the need for radioanalytical capacity for assessment of medical, environmental, and food samples would be overwhelming and there would be a need to make use of all available resources. Both ARPANSA and ANSTO have links to international networks to develop methods and standards programmes. ARPANSA is working on its own methods for radiation emergency response with the understanding that these could form the basis for establishing consistent methods across other laboratories

Sample collection and preparation may be a limiting factor. A sample with environmental levels of radioactivity requires around 2 hours of counting time. Contaminated samples might require a fraction of this counting time. Throughput would 10 to 60 samples per day per measurement system (assumes minimal sample preparation required).

Dry samples (such as soil, powder, grain, etc.) requiring minimum sample preparation can be screened in approximately 10 minutes per sample. Liquid samples require specialised sample preparation which would limit throughput. It may be possible for sample preparation to be out sourced to increase throughput.

Laboratory requirements

Immediate (several days)

Laboratory-based radiation-related testing would be relatively limited in the initial days as most decisions would be made on field-based testing (say 100 samples and 200 tests to calibrate field

instruments). Blast/radiation victims admitted to hospitals would require diagnostic pathology workup and would quickly overwhelm the system (say 5% of total injured, 10,000 samples and 40,000 tests). Thousands of 'worried well' will present for investigation and/or treatment (say 5% would be processed, 1,000 samples and 4,000 analyses).

Short-term (remainder of first week)

Additional laboratory calibration of field-based radiation monitors would be required (say 100 samples and 200 tests). There would be an increasing backlog of diagnostic pathology because of delayed testing as well as additional hospitalisations and out-patients patients (say 40,000 samples from former and 10,000 from the latter, making 200,000 tests). Whole-body radiation testing would begin as part of the secondary treatment phase (say 500 samples). Forensic investigations would be ongoing but limited (10 samples, 40 tests) and disaster victim identification (DVI) would begin (100 samples and 200 tests). The initial batch of soil, water, pasture, milk, sediment and other materials would be collected and analysed as a means of determining the extent of contamination (say 100 samples and 200 tests).

Medium term (second week)

Laboratory calibration of radiation monitors would continue (say 100 samples and 200 tests). Additional facilities brought on board would begin to deal with the diagnostic pathology workload associated with the backlog and new patients (say 50,000 samples from the former and 5,000 from the latter, making 220,000 tests). Whole-body radiation testing would be ongoing (say 1,000 samples). Forensic investigations would be ongoing (25 samples, 100 analyses) and DVI would be ramping up (250 samples and 1,000 tests). Additional soil, water, pasture, milk, sediment and other materials would be collected and analysed (say 100 samples and 200 tests)

Medium to long term (third to sixth weeks)

Laboratory calibration of radiation monitors would continue (say 200 samples and 400 tests). Diagnostic testing would be performed on samples from 'old' and 'new' patients, including return testing (say 100,000 samples and 400,000 tests). Whole-body radiation testing would be ongoing (say 1,000 samples) as would forensic investigations (say 10 samples, 40 tests). DVI capacity would be stretched and other countries' capabilities would be brought on stream (say 1500 samples and 3,000 tests). Collection and analysis of soil, water, pasture, milk, sediment and other materials would be ongoing (say 100 samples and 200 tests).

Long term (greater than six weeks)

Laboratory calibration of radiation monitors would be an ongoing commitment (say 400 samples and 800 tests). Diagnostic testing would be continuing (say 200,000 samples and 800,000 tests). Whole-body radiation testing continues (say 20,000 samples) as would forensic investigations (say 25 samples, 100 analyses). DVI would be dealing with a backlog as more bodies are recovered from highly contaminated areas (10,000 samples and 20,000 tests). Large scale collection and analysis of soil, water, pasture, milk, sediment and other materials would be implemented in order to refine the radiation dose assessments and for use as part of the remediation and recovery process.

(say 5,000 samples and 10,000 tests). This scenario is assumed to end at six months (26 weeks) although the impact will be felt for years and even decades

Specialist advice

Australian WHO collaborating centre for radiation protection

The Australian Radiation Protection and Nuclear Safety Agency (ARPANSA) was designated a World Health Organization (WHO) Collaborating Centre for Radiation Protection in 1985, and redesignated in 2007 with new Terms of Reference for the Collaborating Centre. Under these terms of reference the Agency, jointly with the Peter MacCallum Cancer Centre (PMCC), participates as a member of the WHO Radiation Emergency Medical Preparedness and Assistance Network (REMPAN). The main roles of WHO REMPAN Collaborating Centres are summarised in ANNEX E.

The Terms of Reference for ARPANSA and PMCC as a WHO Collaborating Centre for Radiation Protection are to:

- collaborate in programmes related to radiation protection and radiation health, including:
  - development of radiation protection standards and codes of practice for the safe and effective use of radiation
  - provision of technical advice and organisation of training in radiation health
  - dissemination of information on radiation health
- participate (jointly with the Peter MacCallum Cancer Centre) as a member of the WHO Radiation Emergency Medical Preparedness and Assistance Network (REMPAN) by:
  - provision of medical assistance to exposed persons, both on-site and in specialised clinics
  - provision of consultation and technical advice on the public health and medical response to radiological emergencies or nuclear accidents
  - assisting WHO Member States in elaborating their plans for medical preparedness
  - promotion of training in developing countries

ARPANSA maintains an emergency response capability with field teams modelled along International Atomic Energy Agency (IAEA) standards. These include:

- radiation source localisation, identification and recovery
- analysis of measurements, modelling and advice
- mapping of perimeter spread and sampling for laboratory analysis
- radiation health support

ARPANSA supports Australian arrangements for the medical treatment of internal contamination. ARPANSA maintains a transportable lung monitoring system and is developing analysis methods for assisting in the treatment of individuals with internal contamination of radioactive material.

WHO Radiation Emergency Medical Preparedness and Assistance Network (REMPAN)

The specific role of WHO in the family of United Nations (UN) organizations is to address aspects directly relevant to the medical community and health authorities in the Member States. For the promotion of radiation emergency medical preparedness and for practical medical assistance and

advice to countries in the case of overexposure from any source of radiation, WHO has established the **Radiation Emergency Medical Preparedness and Assistance Network** (REMPAN).

REMPAN was established to strengthen medical aspects of preparedness and response to radiological and nuclear emergencies in WHO Member States. Two types of actions are involved for major radiation accidents:

- Medical – prevention, diagnosis, treatment and rehabilitation of acute radiation injuries in persons exposed to radiation at high doses
- Public health – prevention or mitigation of stochastic effects from low doses of radiation (sheltering, iodine prophylaxis, evacuation, restrictions on consumption of certain foods (e.g. milk), minimization of psychological effects, etc.

Key objectives of REMPAN include:

- Strengthening national, regional and global radiation emergency medical preparedness and assistance in order to recognize radiation injury and to treat and follow up on acutely exposed individuals.
- Improving public health advice to mitigate possible long-term effects of exposure to low and protracted doses of radiation that might accrue in populations living in territories contaminated by radioactive materials.
- Analysis of radiation emergencies and development of recommendations for long-term follow-up studies of health risks of radiation.

REMPAN has collaborating institutions worldwide. They include REMPAN Collaborating Centres (CCs) and Liaison Institutions (LIs) that are being considered for designation as a WHO CC in future.

Clinical guidelines

Overview of radiation injury

Background

Risk refers to the potential for a harmful event, a hazard, to have an adverse impact on health. Exposure to radiation poses a health hazard, but the amount of risk to a person depends on many individual and environmental factors. These may not be precisely known at the time of an uncontrolled radiation exposure, but an attempt should be made to assess the elements of radiological risk systematically.

In general an assessment of the risk posed by radiation exposure should comprise the following elements:

- Identify the hazard: the level of exposure and/or contamination which has occurred.
- Identify the risk: estimate the potential health impacts of the amount of exposure and/or contamination which has occurred.
- Communicate the risk: effectively communicate the potential health impacts of the exposure and/or contamination which have occurred.
- Manage the risk: where possible reduce the impacts of the exposure and/or contamination which have occurred.

Identifying the hazard will generally involve the expert advice of a radiation physicist or other personnel able to measure and characterise the dose of radiation released from a source. Translating this into risk requires an assessment of individual factors which influence the probability a person will suffer injury from a given exposure. These include the timing of exposure, whether a whole or partial body dose of radiation was received, the age of the person and underlying physical illness. Risk communication is complex because there is no simple relationship between the perception of harm and the objective measurement of a hazard. It is, however, essential to communicate risk if measures to mitigate harm like decontamination, administration of medical countermeasures or evacuation are to operate effectively. This is especially the case where large numbers of casualties are exposed to potentially harmful radiation and mass intervention is required en mass.

Identification of hazard

The hazard posed by irradiation is determined by several interacting factors:

a.   Absorbed dose.

Radiation can be absorbed by a person if they are exposed to a source without adequate protection, or if their body becomes contaminated with radioactive material. Absorbed dose is measured in grays (Gy), where one gray corresponds to one Joule of energy absorbed per kilo of tissue. One gray is a large unit of radiation which may be associated with signs of acute radiation syndrome (ARS).

b.   Type of radiation absorbed.

The amount of damage caused by exposure to radiation depends on the efficiency with which it transfers energy into body tissues. Radiation comprised of particles with relatively high mass

delivers a greater proportion of their energy into tissues than do electromagnetic radiation, such as X-rays and gamma-rays, which may pass through the body. Doses of different types of radiation are, therefore, converted into 'equivalent doses' using a weighting factor for each kind of radiation.

Table 9.1 Weighting factors for different types of ionising radiation

Radiation	Energy transfer	Weighting factor
Alpha particle	High	20
Neutron	High	5–20
Beta particle, electrons	Low	1
Gamma ray, X-ray	Low	1

Reference: Recommendations for limiting exposure to ionizing radiation (1995) and national standard for limiting occupational exposure to ionizing radiation (republished 2002); Radiation Protection Series No. 1; ARPANSA.

Equivalent doses are measured in Sieverts (Sv), which is equal to the absorbed dose in grays multiplied by the weighting factor. A dose of 1/100 g

c.   Full or partial body irradiation

Only rarely will a person will be exposed to the same dose of radiation equally across their body. In general, accidental radiation exposures cause a person may receive the majority of a radiation dose to only part of their body. This may occur because of the orientation of the person in relation to the source, or because of partial shielding. Sometimes only one part of the body is sufficiently close to a radioactive source to be injured, as with a small radioactive fragment contaminating a wound or with inadvertent handling of an intact source injuring the fingers or hand. Alternately, radioactive material may be distributed to a particular part of the body if it is, for example, inhaled into the lungs or localises to bone. In the case of partial body exposure the relevant dose is that absorbed by exposed tissue, not the dose averaged across the whole body.

d.   Tissue susceptibility

Tissues differ in their susceptibility to radiation and a given absorbed. The 'effective dose' is calculated by multiplying the absorbed dose by a tissue weighting which represents the sensitivity of each tissue to radiation.

Table 9.2 Tissue weighting factors by organ

Organ	Tissue weighting factor $_T$
Gonads	0.20
Colon	0.12
Bone marrow (red)	0.12
Lung	0.12
Stomach	0.12
Bladder	0.05

Organ	Tissue weighting factor $_T$
Chest	0.05
Liver	0.05
Thyroid gland	0.05
Oesophagus	0.05
Skin	0.01
Bone surface	0.01
Adrenals, brain, small intestine, kidney, muscle, pancreas, spleen, thymus, uterus	the weighting factor 0.05 is applied to the average dose of these organs

Reference: Recommendations for limiting exposure to ionizing radiation (1995) and national standard for limiting occupational exposure to ionizing radiation (republished 2002); Radiation Protection Series No. 1; ARPANSA

e.   Rate at which dose is absorbed.

The body has some capacity to repair the cellular and genetic damage caused by radiation exposure. This means that the amount of injury evident from radiation exposure will be less if the same dose is received gradually over a period which allows some healing to occur rather than the dose being received rapidly.

f.   Presence or absence of contamination.

A person may be irradiated by proximity to radioactive material with which they have no contact. In this case the person will cease to absorb radiation when they leave the vicinity of the radioactive material. If radioactive material enters the environment, however, this may contaminate the surface of a person's body (clothes, hair, and skin) or be absorbed into the body through ingestion, dermal absorption or inhalation. This may be the situation in an accidental or deliberate release of radioactive material as liquid, explosive debris or smoke. In this case irradiation will continue either until the radioactive source is removed from the person's body through decontamination and excretion, or the source decays. Contamination is, therefore, a hazard for ongoing exposure to radiation.

If the type of radiation source, the location of a person while exposed, and the environment in which irradiation occurred are known then the dose of radiation a person is exposed to can be accurately reconstructed after the event. This is, however, only likely in controlled environments such as a nuclear reactor or laboratory and where small numbers of people are involved. If a deliberate release of radioactive material occurs, or large numbers of people are exposed to radiation, then reconstructing the dose received by each based on physics may be impossible. In this case the dose of radiation received may have to be estimated from the measurable effect of radiation after exposure has occurred. Dose assessment is discussed in the next chapter.

Assessment of risk

Risk refers to the potential for a radiation hazard to cause harm. Irradiation can cause two classes of harmful: deterministic and stochastic. Deterministic effects of radiation are those whose severity

is dependent on the dose of radiation received. These effects can be acute, occurring within hours or days, or delayed for months or years. Stochastic radiation effects are those whose probability of occurring is related to dose, but whose severity when they do occur is not dependent on the initial dose of radiation. Cancer is highly unlikely to result from exposure to low-dose radiation, for example, but is a severe disease whenever it does occur. The main stochastic effect of concern is carcinogenesis.

The likelihood of a person suffering stochastic or deterministic effects of radiation exposure is modified by individual risk factors, including age, sex, exposure to other carcinogens, susceptibility to DNA damage, nutritional and hormonal status. Because the impact of these factors has not been quantified, absolute risk cannot be assessed with certainty for most radiation exposures.

Deterministic effects of radiation

Death

Death from acute radiation exposure can result from several syndromes which may occur in isolation or combination.

- Haematopoietic syndrome caused by cell death in bone marrow resulting in a failure to maintain circulating blood components.

- Gastrointestinal syndrome caused by death of the gastrointestinal lining resulting in haemorrhage and sepsis.

- Cerebrovascular syndrome in which CNS function is disturbed resulting in altered consciousness and coma.

- Pulmonary syndrome caused by damage to the lung from alpha or beta emitters resulting in fibrosis, fluid leakage and reduced gas exchange.

- Cutaneous syndrome in which exposure of skin results in burns, particularly from beta radiation (beta- burns) which is able to penetrate skin but delivers most of its energy into the dermal layer.

Table 9.3 Acute radiation syndromes

Syndrome	Acute dose (Gy)	Characteristics/sequelae
Subclinical	< 2	Subclinical
Haemopoietic	2–4	Neutropaenia, thrombocytopaenia, haemorrhage, infection, electrolyte imbalance
Gastrointestinal	6–10	Lethargy, diarrhoea, dehydration, necrosis of bowel epithelium, death in 10 to 14 days
Cerebrovascular/cardiovascular	> 30	Agitation, apathy, disorientation, disturbed equilibrium, vomiting, opisthotonus, convulsions, prostration, coma, death in 1 to 2 days

Syndrome	Acute dose (Gy)	Characteristics/sequelae
Pulmonary	> 10	Radiation pneumonitis
Cutaneous	> 40	Severe ulceration of the skin, necrosis, fibrosis, sepsis

Reference: NCRP Report No. 98

Figure 9.1 Alteration in fatal outcome for different rates of radiation dose delivery
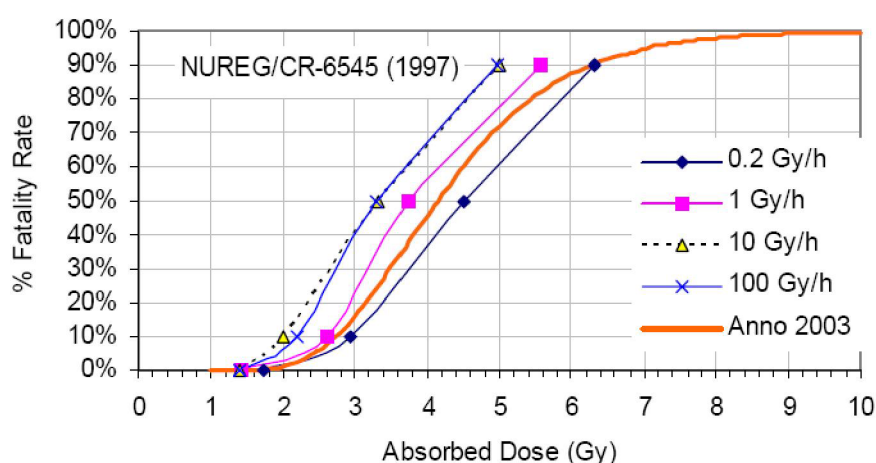
Figure 5. Central results from the NRC/EUR uncertainty analysis for 4 dose rates plotted along with analysis by Anno et al. (2003). All cases represent no medical care.

Death is more likely to occur for a given dose if that dose is absorbed rapidly. The death rate can be reduced if high-level supportive care is available.

Table 9.4 LD50 values (Gy) as a function of dose rate and degree of medical treatment

Gamma dose rate (Gy/h)	Minimal medical treatment	Supportive medical treatment without growth factors	Supportive medical treatment with growth factors
0.2	4.50	6.42	7.81
1	3.72	5.76	7.29
10	3.32	5.27	6.47
100	3.29	5.15	6.13

Reference: Haskin et al (1997)

Chronic radiation syndrome

Chronic radiation syndrome (CRS) is a poorly defined syndrome which occurs in people exposed to whole body irradiation of more than 1 gray over a period of at least 3 years. It has been reported in poorly regulated industrial exposure to highly radioactive material. A dose this high could result from malicious use of radioactive material if the exposure was covert, such as with a source that is hidden or where radioactivity is introduced into a food-supply. Removal from ongoing radiation exposure results in slow improvement of CRS but the completeness of recovery varies. Clinical symptoms of CRS are non-specific and include:

- Sleep and appetite disturbance
- Generalised weakness and fatigability
- Cognitive changes: altered mood, poor memory, reduced concentration
- Neurological signs: vertigo, ataxia, parasthesias
- Headache
- Syncopal episodes
- Hot flashes or chills

Laboratory findings include pancytopenia and bone dysplasia.

Cataracts

Cataracts are opacity of the ocular lens which impairs vision by reducing the amount of light that enters the eye. Cataracts occur naturally and the risk is increased by age, genetic factors and exposure to certain medicines. Cataracts have been observed to be more common in astronauts and airline pilots, who are exposed to relatively low doses of radiation for prolonged periods. The rate of cataract formation is estimated as 10% in people receiving a 2 gray dose of radiation, 50% in people receiving 5 gray radiation and 90% in people receiving 10 gray.

Impairment of fertility

Ionising radiation has the capacity to reduce fertility by damaging spermatogenesis or reducing ovulation.

Table 9.5 Effects of acute exposure on ovarian function

Ovarian dose (Gy)	Effect
0.6	No effect
1.5	Some risk for ovulatory suppression in women > 40 years of age

Ovarian dose (Gy)	Effect
2.5–5.0	In women aged 15 to 40 years, 60% may suffer permanent ovulatory suppression; the remainder may suffer temporary amenorrhoea. In women > 40 years, 100% may have permanent ovulatory suppression. Menopause may be artificially produced
5–8	In women aged 15 to 40 years, 60% may suffer permanent ovulatory suppression; the remainder may suffer temporary amenorrhoea. There is no data for women > 40 years
> 8	100% ovulation suppression

Reference: United States Nuclear Regulatory Commission (1989)

Table 9.6 Effects of fractionated testicular irradiation on sperm count

Testicular dose (Gy)	Effect
0.1–0.3	Temporary oligospermia
0.3–0.5	100% temporary aspermia from 4 to 12 months post- exposure. Full recovery by 48 months
0.5–	100% temporary aspermia from 3 to 17 months post- exposure. Full recovery beginning 8 to 38 months
1–2	100% temporary aspermia from 2 to 15 months post- exposure. Full recovery beginning 11 to 20 months
2–3	100% temporary aspermia from 1 to 2 months post- exposure. No recovery observed up to 40 months

Reference: United States Nuclear Regulatory Commission (1989)

Stochastic effects of radiation

Cancer

Radiation can cause cellular damage which increases the risk of a person developing cancer. The risk of developing cancer increases with the dose of radiation received, but not all people will develop cancer even at high levels of irradiation.

Estimates of the cancer risk associated with radiation exposure are based on longitudinal cohort studies in two populations: survivors of the atomic bombing of Japan in 1945 and nuclear industry workers. Both have been exposed to low life-time doses of radiation although, in the atomic bomb, people received their entire dose in a matter of seconds. This data reflects risk associated with external, whole body radiation doses.

It is not known whether there is a 'threshold' below which radiation causes no increase risk in risk of cancer. Cytogenetic abnormalities can be observed at doses as low as 100 mGy but there may be non-detectable damage at lower doses which is able to cause cancer in some individuals.

Because cancer also occurs in people without excess exposure to radiation, the increase in risk resulting from irradiation is described in relative terms. The excess relative risk (ERR) is the ratio of the extra cases cancer observed in people exposed to radiation compared to the cases observed in people not exposed to additional radiation. If 15 cases of cancers were observed in every 1000 nuclear workers and 10 cases in every 1000 of the general population, the ERR would be (15-10)/10 or 0.5.

A longitudinal study has followed survivors of the atomic bombing of Japan, the majority of whom were exposed to doses <100mSv over a period of seconds. This study estimated the excess relative risk (EER) of developing solid cancers as between 0.47 and 0.50 per Sievert of radiation dose. A person exposed to a dose of 100mSv would, for example, have an ERR of 0.05.

An analysis of several large studies which have examined the risk of cancer in nuclear workers estimated the ERR for all solid tumours as 0.87/Sv.

The absolute risk of developing fatal cancer for anyone in the general population has been estimated at 20% over a lifetime. A person with an excess in relative risk (ERR) of 0.05 therefore has a 5% increase in this underlying 20% risk of developing a solid tumour, or 21%. This would mean that a population of 5000 people exposed to 100 mSv of radiation might expect an increase from 1000 cancers to 1050 cancers over the life of this population.

Communication of risk

In most radiological incidents the majority of people are likely to be exposed to doses which do not cause immediate and severe physical effects. Although moderate and low doses of radiation can cause illness in some people, there are limited options for intervening to reduce this risk once irradiation has occurred. The main objective in most people is, therefore, to manage the psychological consequences of this risk and effective communication is a key aspect of this. Providing information about the magnitude and severity of health risks will help reduce distress and the inappropriate use of medical interventions which are potentially harmful. If mass casualties occur then managing the anxiety of people is particularly important to allow triage for appropriate management and prevent medical facilities being overwhelmed.

The general objectives of risk communication are:

- To engender understanding of the probability and nature of adverse health effects faced by the person.
- To produce an understanding of the limitations of medical intervention in reducing this risk.
- To allow decisions to be made about the appropriate management of a person's risk.
- To reduce psychological distress by engendering trust in the validity of the risk assessment.

Reduction of risk

The only way to reduce the health risks which result from irradiation is to minimise the total dose of radiation a person receives. Depending on the situation this can be achieved by a range of means:

- Evacuation from a contaminated site, terminating ongoing exposure
- Providing sheltering to reducing contact with radioactive material or exposure to radiation
- Surface decontamination (removal of clothes, washing) to remove radioactive material
- Internal decontamination to increase the rate at which radionuclides are removed from the body, or block their uptake into the body

The aim of risk reduction measures is to achieve an acceptable level of risk, not eliminate the risk from radiation entirely. It is assumed that there is a linear relationship between radiation dose and health risks and therefore there is no absolutely 'safe' dose of radiation which is free of adverse effects. Risk should be minimised by reducing the total radiation dose received by the public to a level As Low As Reasonably Achievable (ALARA). What is reasonably achievable depends on the availability of facilities for removing people from a contaminated site and providing decontamination. It is also reasonable to accept a higher dose of radiation if this is necessary to achieve a reduction in other risks faced by the person. In people who have suffered trauma in an explosion, for example, complete decontamination may be a lower priority than preventing death from these injuries. Similarly, the health risks posed by some medicines, such as DTPA, used for internal decontamination may exceed the risks from low-level radiation exposure.

In defining ALARA it is useful to consider how this has been applied to the public or those working with radiation. An average exposure of 1 mSv per year is considered an acceptable risk for the general public and reflects environmental exposure to radiation. This may be exceeded in some years provided the 5-year average is 1mSv. Occupational exposure among nuclear industry workers/radiologists etc. is acceptable at 20mSv per year averaged over five years. A bone scan, a medical procedure which involves a relatively high dose of radiation, involves exposure to about 30 mSv of radiation, compared to a dental X-ray at 20 μSv. The medical use of radiation is a situation in which an increased risk from irradiation has been 'traded off' or justified against the benefit from performing an investigation.

Radiation dose assessment

The health effects of ionising radiation exposure to individuals, through external exposure or internal contamination, are dependent on the dose received as well as individual prior disease state. In the investigation of accidental radiation exposure, an estimation of the absorbed dose is needed. Estimates may be used for treatment planning, prognostic advice, epidemiological investigation and reassurance of affected persons, as well as for the management of occupational health and safety.

Methods available to estimate absorbed dose include:

- Dosimetry readings, if available
- Physical reconstruction of events to enable dose estimation on the basis of time and proximity to the source
- Clinical symptoms and signs
- Lymphocyte depletion kinetics
- Measurement of radionuclides distributed to specific tissues and contained in excretions
- Measures of chromosomal aberration in peripheral lymphocytes
- Measurement of the effects of radiation on tissues such as teeth and nails
- Analysis of selected materials in the vicinity of the event or carried by the affected person
- Measurement of sodium activation in humans exposed to a neutron source

Biodosimetry is the direct measurement of radiation induced biological or physical effects within the body to assess the radiation dose to an individual. Such measurements include certain blood tests, urine and faecal radionuclide assays, and whole body and specific organ counts.

Multiple assay techniques are required to refine dose estimates and to address various scenarios and casualty numbers.

Physical dosimetry

Dosimeter readings

The availability of personal dosimeter readings provides the best measure of cumulative exposure, assuming whole body exposure from an external source. Limitations of personal dosimetry relate to:

- awareness of potential exposure and proper wearing of the device
- the device type. Film badges and thermoluminescent badges must be analysed in a laboratory, delaying the availability of results. However, immediate results can be obtained from electronic personal dosimeters.
- partial body exposures due to proximity to the source (handling a source, for instance, must result in a localised exposure), or shielding
- exposure from internal contamination is not effectively measured by personal dosimetry
- does not account for biological differences in susceptibility to the DNA damaging effect of radiation, which is the fundamental cause of the resulting morbidity and heightened cancer risk.

Physical reconstruction of events

Following identification of the source and its location, health physicists can reconstruct the field intensity and calculate the likely dose received by individuals in that environment adjusted for their proximity to the source and duration of exposure.

The time taken to perform a reconstruction of events is dependent on:

- recognition of an illness as possibly due to radiological exposure
- determination of the likely exposure history
- the search for the source and establishment of radiological safety
- identification of the properties of the source
- evaluation of the physical environment in which the exposure took place
- measurement or calculation of the field intensity, and
- calculations based on individual movements around the environment.

Dose calculations need to be repeated for each person or similarly-behaved group exposed in that environment.

Biological dosimetry

Clinical symptoms and signs

Whilst the symptoms and signs of radiation exposure are non-specific, the timing, severity and pattern characterise the dose received. The main disadvantage is the time required for symptoms and signs to develop.

For known exposures to total body irradiation, the likely severity and timing of the manifest illness can be predicted, particularly from the time of onset of nausea and vomiting. Onset of vomiting less than 4 hours after exposure is consistent with progression to haematopoietic syndrome. Onset of vomiting within 1 hour is characteristic of lethal exposures. Other causes of vomiting, e.g. psychogenic, need to be excluded.

The time to onset of vomiting is the most sensitive clinical sign corresponding to absorbed radiation dose. Importantly, this and the absolute lymphocyte count may be the only means to predict the absorbed dose for affected individuals during the initial days following exposure.

Figure 10.1 Time to onset of vomiting and dose
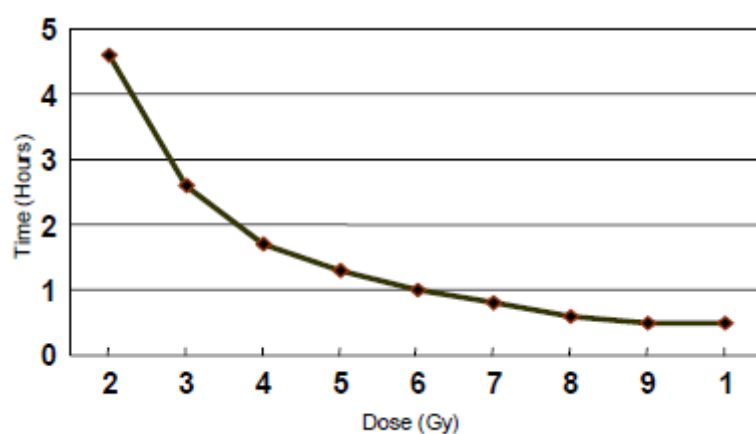
Adapted from the Medical Effects of Ionising Radiation Course, presented by the U.S Armed Forces Radiobiology Research Institute.

Table 10.1 Symptom characteristics and timing for various doses of absorbed radiation to the whole body.

Acute Radiation Syndrome

Phase of syndrome	Feature		Effects of whole-body irradiation by dose range (Gy)						
			0–1	1–2	2–4	4–6	6–8	8–30	>30
Prodromal	Nausea, vomiting	Affected persons	None	5–50%	50–100%		75–100%	90–100%	100%
		Time of onset		3–6 hr	2–4 hr		1–2 hr	< 1 hr	Minutes
		Duration		< 24 hr	< 24 hr		< 48 hr	< 48 hr	N/A
	Diarrhoea	Affected persons				< 10%	> 10%	100%	
		Time of onset				3–8 hr	1–3 hr	< 1 hr	
		Severity				4–6 stools/d, occasional blood, severe cramping	7–8 stools/d, persistent blood, severe cramping	> 10 watery, bloody stools/d, excruciating pain	
	Headache	Affected persons				50%	80%	80–90%	
		Time of onset				4–24 hr	3–4 hr	1–2 hr	
		Severity		slight	mild	moderate	severe	severe	

Phase of syndrome	Feature		Effects of whole-body irradiation by dose range (Gy)						
			0–1	1–2	2–4	4–6	6–8	8–30	>30
	Temperature	Affected persons			10–80%	80–100%	100%	100%	
		Time of onset			1–3 hr	1–2 hr	< 1 hr	< 1 hr	
		Severity			< 38°C	38–40°C	> 40°C for < 24 hr	> 40°C for > 24 hr	
	Conscious state	Severity	No impairment	No impairment	Routine task performance. Cognitive impairment for 6–20 hr		Simple task performance. Cognitive impairment for > 20 hr	Rapid incapacitation. May have a lucid period of several hours	
Latent	No symptoms		> 2 wk	7–15 d	0–7 d		0–2 d	None	
Manifest illness		Symptoms, signs	None	Moderate leucopaenia	Severe leucopaenia, purpura, haemorrhage, pneumonia. Hair loss > 3 Gy			Diarrhoea, fever, electrolyte disturbance	Convulsions, ataxia, tremor, lethargy
		Organ system	None		Haemopoietic, respiratory mucosa			Gastrointestinal	CNS, CVS
		Time of onset		> 2 wk	2 d to 2 wk			1–3 d	

Adapted from AFRRI. Medical management of radiological casualties handbook. 2nd ed. 2003.

Localised radiation exposures may result in cutaneous injury. The characteristic symptoms and signs are described in Table 10.2. Photographs are useful to document the progress of the injury.

Table 10.2 Symptom characteristics and timing for various doses of absorbed radiation to the skin

Cutaneous Radiation Syndrome

Phase of syndrome	Feature	Time of onset for effects of local irradiation by dose range (Gy)						
		< 3	3–6	6–10	10–15	15–30	> 30	> 50
Prodromal	Transient erythema or abnormal sensation (pruritis or pain)	None	None		12–24 hr	8–15 hr	3–6 hr	
	Oedema						3–6 hr	
Latent	Duration		2–5 w			1–3 w		0–2 w
Manifest illness	Epilation		14–21 d					
	Erythema		20–30 d	14–21 d	20–24 d	15–20 d	8–14 d	4–6 d
	Dry desquamation		6–7 w		14–21 d			
	Blisters					20–25 d	10–18 d	6–8 d
	Moist desquamation					2–3 w	10–18 d	6–8 d
	Ulceration						20–30 d	
	Overt radionecrosis						> 90 d	> 4 w

Adapted from IAEA. Diagnosis and treatment of radiation injuries. 1997

Lymphocyte depletion kinetics

Lymphocytes are the most radiation-sensitive haemopoietic element. Predictable decline in lymphocytes occurs following exposure to radiation. The absolute lymphocyte count should be measured 6 hourly for the initial 48 hours and periodically thereafter.

A fall of 50% in the first 24 hours is suggestive of a potentially lethal radiation exposure.

Table 10.3 Biodosimetry based on acute photon equivalent exposures

Dose	Lymphocyte count (x109/L) at day						Lymphocyte depletion rate
Gy	0.5	1	2	4	6	8	Rate constant
0	**2.45***	**2.45**	**2.45**	**2.45**	**2.45**	**2.45**	–
1	**2.30**	**2.16**	**1.90**	**1.48**	1.15	0.89	0.126
2	**2.16**	**1.90**	**1.48**	0.89	0.54	0.33	0.252
3	**2.03**	**1.68**	1.15	0.54	0.25	0.12	0.378
4	**1.90**	1.48	0.89	0.33	0.12	.044	0.504
5	**1.79**	1.31	0.69	0.20	0.06	.020	0.63
6	**1.68**	1.15	0.54	0.12	0.03	.006	0.756
7	**1.58**	1.01	0.42	.072	.012	.002	0.881
8	**1.48**	0.89	0.33	.044	.006	<.001	1.01
9	1.39	0.79	0.25	.030	.003	<.001	1.13

The normal range for lymphocytes in human blood is between 1.4 and 3.5 x 10⁹ per litre

Adapted from the Medical Effects of Ionising Radiation Course, presented by the U.S Armed Forces Radiobiology Research Institute.

Measurement of specific radionuclides

In addition to the techniques discussed in this chapter, in circumstances of internal radiological contamination, dose may be assessed by:

- contamination survey (including nasal swabs and wound dressings)
- whole body and specific organ counts, and
- bioassay of bodily fluids (urine, faeces, pulmonary lavage washings)

The principles of dose assessment following internal contamination are discussed in detail.

Cytogenetics

Cytogenetics is indicated when:

- time to emesis is less than 2 hours after exposure
- lymphocyte counts are depleted to less than 50% within 12 hours of exposure
- geographical location-based physical dosimetry indicates a dose of > 3 Gy
- there are multiple clinical symptoms indicative of acute radiation syndrome.

Cytogenetics may also be used in evaluating asymptomatic exposed persons in an epidemiological evaluation of an incident, for prognostic advice and to plan longer-term surveillance.

Dicentric assay

Chromosomal dicentrics and ring forms are formed during cell division in cells affected by radiation. These can be identified during metaphase. The frequency of formation corresponds to the absorbed dose of radiation.

Figure 10.2 Dicentric and fragment
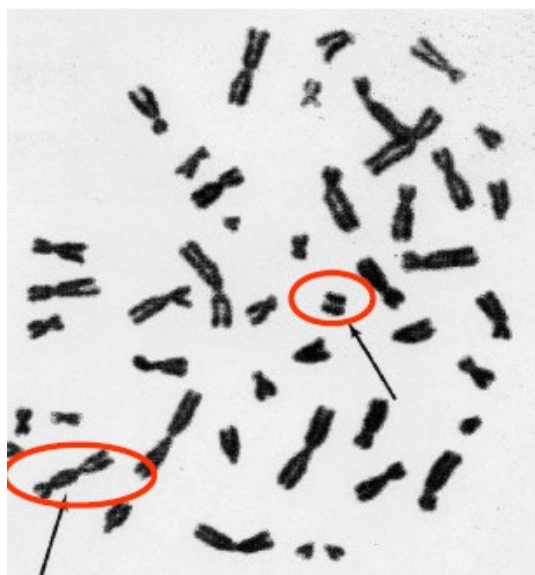
This assay is the most specific and sensitive method for determining absorbed doses from recent (from within days up to six months) exposures to ionising radiation. Dicentric and ring chromosomes are identified from slide preparations of activated lymphocytes arrested in metaphase. From 500 to 1000 cells may require scoring, requiring 2–3 person-days at the microscope. At least 100 dicentrics should be identified. The dose is estimated from calibration curves developed by irradiating in vitro samples of blood. The range of absorbed dose detectable using this technique is 0.2 to 5.0 Gy.

The usefulness of dicentric analysis is limited to exposures occurring in the previous six months because of the half-life of the cells containing the chromosomal aberrations. As lymphocyte activation requires cell culture and mitosis, the result is not especially timely, taking 4 to 5 days to complete, and up to 2 weeks for results to become available if the sample is sent overseas. Capacity is also limited with cytogenetics laboratories able to process a maximum of 50 to 200 samples per week.

Dicentric analysis is a labour intensive technique that can be adapted for application to mass casualties. The technique can be modified, by reducing the number of metaphases scored to 50, in order to increase throughput of samples. Reporting of this sample triage provides a likely absorbed dose range useful for identification of individuals requiring medical intervention. These individuals can have repeat dicentric assays to more precisely determine their absorbed dose.

It is expected that the reporting format for dicentric analysis sample triage would be expressed as a range. For example:

- < 1.0 Gy
- 1.0–3.5 Gy
- 3.5–5.0 Gy
- > 5.0 Gy

Table 10.4 Comparison of dicentric assay techniques for dose assessment

Dose estimate (Gy)	Dicentrics in human peripheral blood lymphocytes	
	Per 50 cells (sample triage)	Per 1000 cells (dicentric assay)
0	0.05–0.10	1–2
1	4	88
2	12	234
3	22	439
4	35	703
5	51	1024

Adapted from Wasalenko JK, et al. Ann Int Med. 2004; 140: 1037–1051.

Present arrangements for dicentric assay require specimens to be transported overseas. Under the International Health Regulations, the World Health Organisation is developing a global biodosimetry network of reference and supporting laboratories. This network will facilitate common standard operating procedures and surge capacity arrangements.

Dicentric assay is available within Australia at the CSIRO DNA Damage Diagnostics Laboratory in Adelaide and will soon be made available for radiation biodosimetry purposes. This laboratory is participating in the WHO Biodose network to comply with the standard protocol with a view to being established as a reference laboratory in the network. The test is expected to be made available for radiation biological dosimetry purposes by mid-2010.

There are other Australian clinical cytogenetics laboratories performing assays for prenatal screening, developmental delay and cancer investigation. These laboratories may be able to assist under protocols for mass screening.

Laboratories performing dicentric assay should meet the International Organisation for Standardisation (ISO) standard – Performance criteria for service laboratories performing biological dosimetry by cytogenetics (ISO 19238).

Cytokinesis block micronucleus (CBMN) assay

Micronuclei are formed when acentric chromosomal fragments caused by exposure to ionising radiation do not integrate into the nuclei of daughter cells during ex vivo division in cultured lymphocytes from peripheral blood. In this assay it is also possible to measure nucleoplasmic bridges that are formed from dicentric chromosomes induced by ionising radiation.

This technique requires less skill and time than dicentric assay, and is suitable for automated imaging of binucleated cells. Dose estimation correlates well to dicentric assay using appropriate calibration curves.

The sensitivity of this technique is limited to thresholds of 0.3 Gy, due to the presence of background micronuclei from other environmental causes. This is still sufficiently sensitive to identify persons needing medical intervention from those requiring continued surveillance.

This assay is available in Australia at the DNA Damage Diagnostics Laboratory led by Prof. Michael Fenech at CSIRO Human Nutrition in Adelaide using both visual and automated scoring.

Figure 10.3 (A) Bi-nucleated lymphocyte containing a micronucleus (MN); (B) Bi-nucleated cell containing a nucleoplasmic bridge (NPB) and a micronucleus (MN).
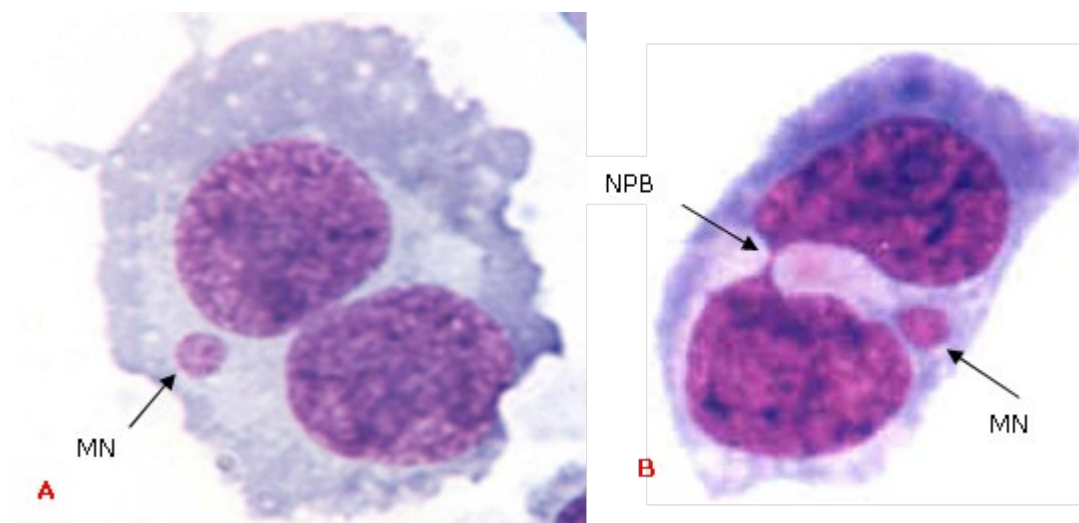
This photomicrograph was kindly provided by Prof. Michael Fenech from the Genome Damage Diagnostics Laboratory at CSIRO Human Nutrition, Adelaide, South Australia

Fluorescence in situ hybridisation (FISH) assay

Stable chromosomal translocations caused by radiation can persist over decades, unlike dicentrics. These can be identified using fluorescent microscopy using chromosome-specific fluorescently-labelled DNA probes. This research tool is limited by availability, turnaround time, and cost. Additionally, translocations may occur due to other environmental factors, limiting accuracy without pre-event samples.

Figure 10.4 Fluorescent labelling of chromosomal translocations
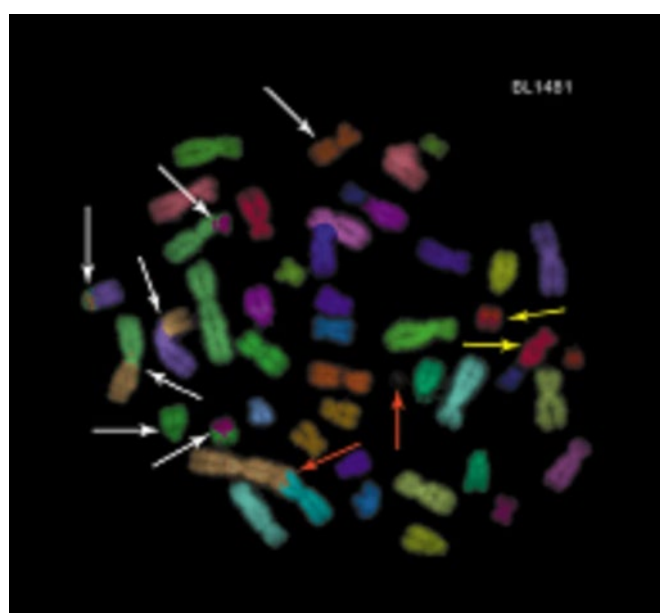
This image from Sykes P, and Bain S; Laboratory capacity for cytogenetic analysis in Australia. Presented at the National Workshop on Biodosimetry Assessment, Yallambie, Victoria, August 2008

Premature chromosome condensation (PCC) assay

At radiation doses > 5 Gy, cells may never progress to mitosis because of the extent of damage. This may result in an underestimate of the absorbed dose at higher exposures where lymphocyte activation is a step in the assay.

Fusion of human lymphocytes with Chinese hamster ovary mitotic cells allows the identification of chromosomal aberration without lymphocyte activation.

Electron paramagnetic resonance (EPR)/Electron spin resonance (ESR)

When radiation causes ionisation of materials, most electrons recombine. However in relatively non-aqueous materials, some become trapped. In a magnetic field, the trapped electrons can be induced to provide a resonance spectrum.

This technique can be applied to relatively dry materials, such as teeth, bones and fingernail clippings. This is a validated technique with application in palaeontology. It has also been used in studies of atomic bomb survivors, Chernobyl victims and investigation of radiological over-exposures.

Radiation-induced changes in teeth are extremely stable, enabling measurement at any time after exposure. Naturally exfoliated teeth have been utilised in retrospective studies. Dental biopsies can also be used. However, rapid techniques have been developed for examination of teeth in situ, although this is not widely available. Molar teeth are preferred as they are not subject to UV radiation exposure. Dental disease may also alter the mineralisation of teeth, affecting measurements.

The dose range that can be detected using EPR on teeth is 0.1 Gy to several thousand Gy.

Bone has been used in retrospective analysis of amputated limbs in circumstances of localised radiation injury. Fingernail clippings are readily available, although children's nails may have insufficient volume for this technique. Fingernail clippings need to be collected within 30 days.

The measurement obtained is the dose received by those specific tissues (teeth, bone or fingernails). If the exposure to the individual was not homogeneous, or occurred from internal contamination, this may not reflect the total dose received.

EPR on dental biopsies may be used to verify dose when considering heroic treatment measures for life-threatening exposures.

Luminescence

Luminescence is a technique that can apply to event reconstruction, as well as direct and indirect biodosimetry.

When radiation causes ionisation of materials, most electrons recombine. However some become trapped and will recombine only under an appropriate light or thermal stimulus. On recombining, a photon is released. The quantity of photons (luminescence) produced is equivalent to the number of trapped electrons, which is proportional to the absorbed radiation dose.

It is applicable to materials such as quartz, feldspar, mortar, concrete, gypsum, brick, ceramics, salt and many others. This is a validated technique with extensive applications in palaeontology, art authentication, soil science and UN nuclear weapons inspections.

Research is underway to validate the forensic application of this technique for examination of sites used to construct or store radiological and nuclear material, even when there is no residual radioactive contamination. It could be applied to retrospective examination of a location where a population was exposed to a covert source, identifying and quantifying the extent of exposure by an examination of the building materials. It enhances modelling of the field intensity of a removed source, by determining how long the source was in situ, and therefore the duration of exposure of affected persons.

There is potential for luminescence to be used to examine materials carried by people, such as credit cards, glass (in spectacles and watch covers), and jewellery to provide indirect biodosimetry.

Luminescence can also be applied to tooth enamel, bone and fingernail clippings to provide direct biodosimetry.

The objective of the Australian research program is the extension of protocols to new materials and the development of standard operating procedures to enable analysis to occur rapidly and flexibly.

Comparison of laboratory techniques for biodosimetry

The selection of appropriate laboratory tests to support dose estimation relates to a number of factors, summarised in Table 10.5. In a mass exposure event, the most suitable techniques for mass screening are clinical evaluation, lymphocyte depletion kinetics, dicentric assay sample triage, and automated cytokinesis block micronucleus assay.

Table 10.5 Comparison of laboratory techniques for biodosimetry

Technique	Dose range detectable (Gy)	Measurement period	Specimen	Purpose	Available in Australia	Turnaround time	Sample capacity per week
Dicentric assay	0.2 to 5.0	1st six months after exposure	Whole blood	Definitive test	From mid-2010	2 weeks	50–200
CBMN assay	0.3 to 5.0	1st six months after exposure	Whole blood	Triage cytogenetics, definitive test	Yes	2–3 days	80* 300#
FISH		Decades	Whole blood	Retrospective cytogenetics	Research or special interest only		
PCC		1st six months after exposure	Whole blood	Confirmation of doses >5.0 Gy			
EPR/ESR	0.1 to 1000s	Teeth indefinite; Fingernails < 30 days (or clipped and stored at low temperature)	Teeth, fingernail clippings	Confirmation of doses >5.0 Gy	Yes, in vitro only	In situ dental readings < 5 minutes	
Luminescence	0.1 to 1000		Building materials, etc	Event reconstruction	Forensic protocols in development		

* Visual scoring.
\# Automated scoring.

Neutron activation

Where there is exposure to a neutron source, such as a reactor or critical assembly or selected industrial radiography sources, sodium activation may occur. Briefly holding a gamma survey instrument against the umbilicus to measure sodium activation is a straightforward indicator of the severity of the exposure and a useful screening tool. More precise measurement can be obtained with a whole-body counter, subsequently.

Biodosimetry Assessment Tool (BAT)
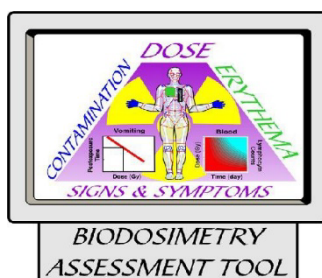
The U.S. Armed Forces Radiobiology Research Institute (AFRRI) has developed a software tool to assist in the dynamic recording of clinical and other data, interpret key parameters for estimation of dose, and summarise diagnostic and therapeutic information.

The tool is structured around sets of information pertaining to physical dosimetry, anatomical distribution of contamination, wound type, skin changes, prodromal symptoms, haematological indicators, and signs of manifest illness. The dose estimation is based on the available patient data compared with documented radiation dose responses and revised as additional information is entered.

The software application can be accessed at www.afrri.usuhs.mil. The software is also available on cd-rom. A series of templates can be downloaded to assist in documenting relevant information.

Summary

Unavailable or inaccurate initial absorbed dose estimates can result in suboptimal medical intervention.

In instances of suspected radiological exposure, a number of indicators and measures may be used to determine the likely absorbed dose of ionising radiation. Each provides an estimation of dose range with recognised limitations in sensitivity, specificity and accuracy. Collectively the multi-parameter approach is used to create the best statistical evaluation of dose.

Where overexposure is suspected:

- obtain a clinical and a location history
- observe and document all prodromal symptoms and signs, including erythema. Photograph cutaneous injuries
- obtain a full blood examination and differential cell count with absolute lymphocyte count immediately. Repeat every 6 hours for the first 48 hours, and 12 hourly for the subsequent 2 days
- perform measurement and bioassay, if appropriate, for internal contamination
- contact a qualified laboratory for dicentric assay. Seek guidance from the state or territory radiation safety unit with regard to assistance in arranging this.
- consider other opportunistic dosimetry approaches as available
- consider data entry into the Biodosimetry Assessment Tool

Dose assessments contribute, but should not be used alone to dictate life-saving medical treatment decisions. Factors such as dose rate and radiation quality can profoundly influence clinical outcome.

References

1. Alexander GA, Swartz HM, Amundsen SA, Blakely WF, Buddemeier B, et al. BiodosEPR-2006 meeting: acute dosimetry consensus committee recommendations on biodosimetry applications in events involving uses of radiation by terrorists and radiation accidents. Radiation Measurements. 2007; 42: 972-996.
2. Armed Forces Radiobiology Research Institute. Medical management of radiological casualties handbook, military medical operations. 2nd ed. Bethesda: Armed Forces Radiobiology Research Institute; 2003
3. Barabanova AV. Local radiation injury. In Gusev IA, Guskova AK, Mettler FA, editors. Medical management of radiation accidents, 2nd ed. CRC Press; 2001: 223-240.
4. Blakely WF, Carr Z, Chu MC, Dayal-Drager R, Fujimoto K, et al. WHO 1st consultation on the development of a global biodosimetry laboratories network for radiation emergencies (BioDoseNet). Radiat Res. 2009; 171(1): 127-139.
5. Blakely WF, Salter CA, Prasanna PGS. Early-response biological dosimetry – recommended countermeasure enhancements for mass-casualty radiological incidents and terrorism. Health Physics. 2005; 89(5):494-504.
6. Fenech M. The Cytokinesis-Block Micronucleus Cytome Assay and its application in Radiation Biodosimetry. Health Physics Journal 2009
7. International Atomic Energy Agency. Cytogenetic analysis for radiation dose assessment – a manual. Technical reports series, no 405. Vienna: IAEA; 2001
8. International Atomic Energy Agency. Diagnosis and treatment of radiation injuries. Safety reports series, no 2. Vienna: IAEA; 1998
9. Prasanna PGS, Martin PR, Subramanian U, Berdycheviski R, Krasnopolsky K, et al. Cytogenetic biodosimetry for radiation disasters: recent advances. NATO RTG-099. 2005.
10. Wasalenko JK, MacVittle TJ, Blakely WF, Pesik N, Wiley AL, et al. Medical management of the acute radiation syndrome: recommendations of the strategic national stockpile radiation working group. Ann Int Med. 2004; 140: 1037-1051.
11. World Health Organization. Consultation on the development of global biodosimetry laboratories network for radiation emergencies: BioDoseNet, meeting report. WHO, Geneva. 2007

Appendices

Appendix A: Biodosimetry sample collection instructions

Dicentric assay

As partial body exposure is more likely in accidental exposures, peripheral blood should not be collected in the initial 24 hours following the accident, to ensure irradiated and non-irradiated blood have mixed and reached equilibrium. However, the sample must be collected before the lymphocyte count is diminished or transfusions have occurred.

For overseas shipment

Collect 8–10 mL of peripheral blood into each of 4 to 5 vacutainer lithium-heparin tubes. The additional tubes are collected in case of breakage or leakage during transport. Clean any blood from the top of the tube with an alcohol wipe. Ensure complete mixing in the sample tubes by gently inverting the tubes several times. Label with patient's name, hospital ID, date of birth, date and time of blood collection. Transfer at room temperature immediately. Do not freeze.

Label the package URGENT DIAGNOSTIC SAMPLES. FRAGILE. BIOHAZARD. DO NOT FREEZE. DO NOT X-RAY. Include a film badge or thermo-luminescent dosimeter in the package. Ship immediately.

For international transit, specimens may be sent by air cargo. The laboratory should be advised of the flight number and airway bill number to enable the specimen to be traced through cargo handling and customs. It is often convenient to use a courier service that provides a 'door-to-door' service.

For air transport, the International Air Transport Association (IATA) stipulates packaging for blood samples that conforms to regulations for transporting dangerous goods class 6.2, infectious substances. The plastic or glass lithium heparin tubes should be placed in a secondary rigid, crush-proof, watertight container. This container should also contain cushioning and sufficient absorbent material to absorb the entire contents. This secondary package should be placed in rigid outer packaging appropriately labelled. The outer packaging should be of thermal insulation material such as polystyrene. If cooling packs are used, these should be placed in the outer packaging, not the secondary package. The label should include the name and contact details of the responsible person and have a Regulation Class 6.2 Hazard Label.

For shipment within Australia

Prior to shipment notify DNA Damage Diagnostics laboratory, CSIRO Human Nutrition (contact Prof. Michael Fenech michael.fenech@csiro.au, tel 03 8303 8880)

The requirements for both the dicentric and CBMN assays are as follows: 8 mL of blood collected in lithium heparin tubes, stored at 10-20°C, and delivered within 24 hours of collection. In the case of children, babies and neonates, the CBMN assay can be performed on finger-stick or heel-prick blood.

Deliver to the CSIRO laboratory at the following address: CSIRO Human Nutrition, Gate 13 Kintore Avenue, Adelaide SA 5000. The delivery should be marked 'Attention Prof. Michael Fenech and/or Dr. Philip Thomas'.

The samples should be kept in an appropriate box to ensure that temperature is maintained between 10–20°C during storage and transit. The IATA packaging requirements for blood samples are applicable for all air transport, including domestic.

Nail clippings

Information to be collected from the donor:

- identity details, including age, gender and occupation
- estimation of time elapsed since exposure
- estimation of donor position relative to the source
- donor activities since irradiation (hand washing, shower, manual activities, sweating activities – type, frequency, time)

Collection of nail clippings:

- donors should not wash their hands
- collect nail clippings as large as possible, with the minimum of cuts
- collect separately the clippings from each limb (4 collections from each donor)
- do not wash or clean the clippings
- store in a dry, sealed container at the lowest possible temperature
- note the time of collection, and the temperature
- note variations of temperature during storage and transportation

External contamination

External radiation does not cause external contamination -the rays/particles either pass straight through the body or are absorbed and deposit their energy. Contamination can only occur if particulate radioactive materials come into contact with clothing, skin, or body tissues. The most likely way for this to occur is if dust or bomb debris becomes contaminated and is deposited onto persons nearby.

The amount of contamination by radioactive material on a person's body indicates the amount of ongoing exposure to radiation. Heavy contamination suggests a high total dose of radiation is likely to be absorbed.

Surface contamination by material on clothes, hair or skin can be measured using external detectors, although these may not detect all kinds of radiation emitted by a radioactive substance

The principle of radiological decontamination is to remove particles from the person without dispersing them into the atmosphere or onto previously clean surfaces. This is a lot more difficult than it sounds, and staff will have to practise regularly if they are to have any chance of success. An

indicator substance, such as a dye or coloured powder, can be used in training to show staff just how easy it is to transfer contamination from one surface to another.

The following sections give guidance on decontamination equipment and procedures. Each hospital should develop their own protocols in consultation with local health authorities and emergency services.

Requirements

Whether on-site or offsite, for mass decontamination or individual, the general requirements for decontamination are the same:

- Detection and monitoring equipment
- Protection for equipment, staff and site
- Replacement clothing for patient
- Waste containment

Detection equipment

Detection equipment is used to assess the level and location of contamination, which may be localised to small, circumscribed areas. At the very minimum, it will include a Geiger-Müller counter (for beta and gamma radiation) and an alpha probe (for alpha radiation). It is advisable to have disposable covers for the detection probes, especially the alpha probe, to prevent contamination and loss of function.

Monitoring

Monitoring is done via personal dosimeters (for all decontamination staff), and, if available, an area detector.

Protective equipment

Protective equipment aims to prevent the spread of contamination around the decontamination site and to staff and surfaces. In a hospital setting, it is preferable to carry out decontamination outside the building to minimise the risk of contaminating the interior. For decontamination of non-ambulatory patients, which may have to be carried out in the ER or triage area, protection may be provided by applying temporary coverings to floors, benches doors and essential equipment.

All decontamination staff will require protective clothing: hats, masks, gowns, boots, aprons and gloves. Eye protection is advisable. A second pair of gloves allows for rapid change between patients or replacement if contamination occurs.

Replacement clothing

Replacement clothing of some sort will be required for patients following decontamination. Depending on the ambient temperatures and cultural factors, this may be anything from a simple disposable shift to a full-length coverall and blankets.

Waste containment

Waste containment is essential to prevent the spread of contaminated particles. All contaminated clothing, dressings and protective garments must be bagged and tagged. Any water used for washing or for cleansing wounds must be collected. Water collected from a mass decontamination site should, ideally, be contained in a holding tank; however, it is unlikely that the amount of radiation in the water will constitute a significant hazard to the sewer system, particularly in comparison with the effect of rain or fire-fighting liquids at the incident site.

Procedures

At assessment, patients are deemed to be contaminated or clean. Clean patients do not require decontamination. Given the length time and manpower that assessment takes (especially for alpha particles), it may be deemed expedient in a mass casualty incident to assume that all patients with dust or shrapnel are contaminated, and defer individual assessment to the post-decontamination line.

Patients should be divided into ambulatory and non-ambulatory decontamination lines. Ambulatory patients can go through mass decontamination units (dedicated or improvised), while non-ambulatory patients will have to be decontaminated by teams, probably close to the receiving hospital. A detailed protocol for decontamination of non-ambulatory patients is included in the chapter on hospital management.

Decontaminating patients

Decontaminating patients is relatively straightforward in comparison with chemical decontamination, as there is no vapour hazard. Removal of the outer layers of clothing will account for approximately 80% of contamination, and washing exposed skin and hair with ordinary soap and water will account for another 10–15%. Removal of particles from wounds and body crevices such as the ears and nostrils may require a little more effort. Care must be taken to remove clothing in a fashion that does not create aerosols of contaminated particles, and all discarded clothing should be bagged. Contaminated personal effects may be suitable for cleaning or may have to be discarded.

Care must be taken to provide mass decontamination in a manner that is suitable for the climate and the culture. In particular, it is advisable to have the disrobing, showering and dressing facilities screened from the outside, and to provide same-sex supervisors in each section.

Emergency cases

There may be occasions, particularly in an incident involving explosives, when contaminated patients require immediate treatment. In these cases, treatment should not be delayed until decontamination has taken place, but care should be taken to minimise the spread of contamination as much as possible, by covering the patients during transport, minimising the number of exposed corridors and rooms, and covering doors, door handles and essential equipment with plastic or tape. Inside the OT, the usual no-touch rules and clothing should be sufficient to protect surgical teams, but additional precautions must be taken to assess any foreign material for radiation and to collect potentially-contaminated run-off.

Internal contamination

Internal contamination may occur when radioactive materials are accidentally or intentionally released into the environment, and inhaled, ingested or incorporated via wounds. The first priority for care is the stabilisation of any life-threatening injury, followed by decontamination of external contamination.

Assessment of internal contamination will be dependent on the history of the incident, consideration of potential routes of exposure, and information regarding the identification and chemical form of the radionuclide. There may be delays to obtaining confirmation of the nature of the radionuclide.

Treatment decisions need to be based on an understanding of the properties of the identified radionuclide including metabolic behaviour, the route of exposure and absorption characteristics, estimates of body burden, available treatments (including effectiveness, contraindications and risks) and individual patient status.

Treatment is maximally effective if commenced early. A clinical decision may need to be based on an estimation of whether exposure potential is low, medium or high and an understanding of the risks of treatment. Detailed dosimetry can be completed subsequently.

Radionuclide properties

The **physical half-life** is the time for half the amount of a substance to undergo radioactive decay.

The **biological half-life** is the time for half the amount of a substance to be eliminated from the body following absorption.

The **effective half-life** is the time taken for the radiological effect of the substance absorbed into the body to be reduced by half by biological elimination and radioactive decay.

Identifying potential intakes

The initial evaluation for potential internal contamination is directed at establishing whether or not there is alpha or beta/gamma radiation as this determines approach to detection in nasal swabs and wounds.

Circumstances for potential inhalation of radionuclides may be identified by:

- Sampling for air-borne contaminants
- The presence of external contamination of the upper body, especially the face.
- Activity on nasal smears. Nasal swabs are collected using separate moistened cotton swabs for each nostril as soon as the patient's condition allows, then dried and counted.

Activity detected on nasal smears is usually an indication of an inhalation intake. Exceptions to this include:

- Delay to obtaining nasal smears of 30 to 60 minutes from the time of exposure may be sufficient for nasal clearance.
- Showering or washing the face may result in nose blowing and clearance of the nasal passages.

- Mouth breathing may bypass the nasal passages for deposition.
- Particle size

Counts in excess of 500 disintegrations per minute (dpm) of alpha emitters are considered significant exposures, whereas results less than 50 dpm suggest a low order exposure. A rule of thumb is that the combined activity of both nasal swabs approximates 5% of lung deposition. Substantial difference in the amount of activity between the two swabs suggests inadvertent contamination of one nare, rather than inhalation, and caution in interpreting the estimated results. It is unlikely that a patient will reach hospital in time for useful information to be obtained from the nasal swabs.

Wounds must be surveyed for the presence of contamination. The presence of dressings, soil, blood, or irrigation fluids is likely to interfere with the detection of alpha particles.

Confirmation of inhalation of radionuclides may be achieved by performing lung counts for retained substances. Ingestion may be confirmed by the presence of incompletely absorbed radionuclides in the faeces.

Absorption of radionuclides may be confirmed with the appropriate detection technique or bioassay.

Assessment of dose

Following internal contamination, the radionuclide is distributed to various organs and tissues where it is retained until it decays or is excreted. The dose that is received this way from the radionuclide, from initial exposure until it is gone, is the *committed dose*. The calculated dose over 50 years is the *committed effective dose equivalent* (CEDE). The sum of the committed effective dose equivalent and any external dose received is the *total effective dose equivalent* (TEDE).

Dose may be assessed by:

- physical reconstruction of events
- the evolution of clinical symptoms
- laboratory measurement of key clinical indicators (absolute lymphocyte count and dicentric assay)
- contamination survey (including nasal swabs and wound dressings)
- whole body and specific organ counts, and
- bioassay of bodily fluids (urine, faeces, pulmonary lavage washings).

Some radioisotopes are widely prevalent in the environment, and are incorporated into the air that is breathed, and water, animal products and plants that are ingested. Uranium, radium, strontium and polonium are examples. Tiny amounts may be present on bioassay in otherwise unexposed persons.

Initial (first 24 hours) urine and faecal samples may be of little value, as they may comprise residual bladder and bowel contents present prior to exposure or redistribution and excretion of absorbed radionuclide. Further, laboratory turnaround times may be several days. Variation in individual excretion rates and day-to-day variations may result in 3 to 4-fold errors in estimation of body burden using urine and faecal measurements. Use of chelation agents further complicates excretion patterns.

Lung burden can only be measured accurately by in vivo counting. Where this is not feasible because of deposition of an inhaled pure alpha emitter, the measured urinary and faecal excretion values and the assumed values from theoretical biokinetic models are used to estimate the residual lung burden. Considerable uncertainty is likely with such estimations. Measurement uncertainties for plutonium lung burdens have been estimated at +/- 100%.

Whole body counters are extremely sensitive and may detect residual external contamination that is unable to be detected by handheld detectors. This may result in over-estimation of lung or whole body burden in the first few days after a contamination event. The measurements are generally accurate to within 30% for gamma emitters.

Interpretation of whole body and organ counts and bioassays to determine dose will require the assistance of health physics experts.

Biokinetic models

The isotope and chemical forms of radionuclides are classified according to solubility and rate of transfer from the alveoli. Rate of transfer includes movement into the circulation and lymphatics, as well as mechanical clearance by ciliary action. These classes are described in ICRP 30 as inhalation classes D, W and Y (days, weeks, years). These were replaced in ICRP 66 with absorption types F, M and S (fast, medium, slow). Absorption rates apply only to the solubility of particles deposited in the alveoli.

Expressed as approximate half-times for clearance, the assumed absorption rates are: type F 10 minutes (100%); type M 10 minutes (10%), 140 days (90%); type S 10 minutes (0.1%), 7000 days (99.9%).

Estimation of dose following internal contamination is dependent on understanding the nature and form of the radionuclide. Dose estimation is modelled using bioassay results and reference tables, manual and computer calculations. The tables and calculations utilise standard organ system models, such as the ICRP respiratory tract model.

Standard organ system models have limitations. It is difficult to determine precise aerosol aerodynamics, individual respiratory physiology and anatomy. Additionally, there is a range of variation within inhalation classes and absorption types.

The estimates produced need to be interpreted with regard to specific individual criteria such as age, pregnancy, and pre-existing medical conditions.

Toxicity

The biological effects of incorporated radionuclides are dependent on the dose, route of entry, chemical form, and distribution within the body. Susceptibility to the biological effects may be increased by host factors such as age and co-morbidities.

Pulmonary injury

Radiological pulmonary injury may occur due to irradiation of a large volume (> 10%) of lung at high doses (daily dose >2.67 Gy, or high cumulative dose). Threshold and LD50 values for death due to radiation pneumonitis occur at dose rates of about 5 and 10 Gy respectively. Radiation pneumonitis

may also develop following the deposition of sufficient radioactive particulates which are retained in the lung due to insolubility.

Alpha emitting radionuclides are especially concerning because their high linear energy transfer (LET) increases the local tissue damage twenty-fold compared to gamma emissions.

Aerosol size is a major determinant of retention of particles in the respiratory tract. Particles larger than 5 to 10 µm are filtered by nasal hairs or deposited in the nasopharynx. Particles from 2 to 5 µm deposit in bronchioles and bronchi, where they are removed by ciliary action to the nasopharynx. From the nasopharynx, they may be swallowed or expectorated. Swallowed particles contribute to ongoing gastrointestinal contamination. Particles < 3 µm reach the alveoli.

Route of inhalation is another important determinant. Of particles larger than 10 µm, 100% deposit in the nasopharynx during nasal breathing, and 65% during mouth breathing. Deeper penetration of larger particles occurs during mouth breathing.

Once in the alveoli, the chemical form of the radionuclide determines its solubility. Soluble forms are absorbed into the alveolar capillaries. The rate of transfer is dependent on the precise chemical form. Insoluble forms may be retained for many years. Small amounts may be phagocytosed, move into lymphatics and drain to regional lymph nodes.

Following phagocytosis by alveolar macrophages, inhaled particulates may trigger a chronic inflammatory response with release of cytokines and leukotrienes, and proliferation of inflammatory cells. Stimulation of fibroblasts and deposition of extracellular collagen lead to pulmonary fibrosis.

The development of acute radiation pneumonia follows a latent period of 1 week to 7 months after radiation exposure. The onset may be insidious with non-productive cough dyspnoea, fever, pleuritic pain, malaise and weight loss. Auscultation may be normal. Chest X-ray demonstrates peri-vascular or alveolar opacities in 45% of patients. Atypical pneumonia and malignant change must be excluded.

Fibrosis may follow radiation pneumonia or develop gradually without other clinical manifestations. There is no proven therapy for radiation fibrosis. Prolonged treatment with corticosteroids is advised to mitigate against the chronic inflammatory reaction.

Elevated risk of lung cancer is associated with the biological effects of ionising radiation as well as the chemical activity of the particular substance inducing free radicals, reactive oxygen species, mobilisation of intracellular iron, and chronic inflammatory reaction. The spectrum of radionuclide-induced cancers, in decreasing frequency of occurrence, is adenocarcinoma, bronchiolo-alveolar carcinoma, and combined epidermoid and adenocarcinoma. Mesothelioma and fibrosarcoma have been observed in some animal models.

Gastrointestinal injury

Many radionuclides are not absorbed from the gastrointestinal tract. Injury is limited to the combination of the amount ingested, the specific activity of the radionuclide, and the gastrointestinal transit time. If the amount is significant or the activity of the substance is high, there is a likelihood of mucosal damage to the GIT, or whole body irradiation.

Ingestion in pelletised form or as a solid metal, such as iridium, may lead to localised gastrointestinal burns, with consequent perforation or stricture formation.

Polonium has a propensity to form colloids, and will deposit on the mucosal surface of the intestine. On autoradiographs, the polonium accumulates at the tips of villi but the alpha radiation does not reach the basal stem cells in the crypts. It is thought that this contributes to the earlier development of the gastrointestinal syndrome following polonium ingestion, than is accounted for by the whole body irradiation effect.

Target organ injury

Some radionuclides are isotopes of essential elements normally absorbed by the body, such as iodine and cobalt. Others behave as analogues or substitutes for other elements. Strontium, radium and plutonium follow calcium metabolism pathways, and caesium behaves like potassium.

The distribution of radionuclides following absorption into the bloodstream relates to the normal or analogous behaviour of that element. Hence, the thyroid takes up radioiodine preferentially, leading to eventual hypothyroidism and thyroid tumours. The calcium analogues are distributed to the skeleton where they affect haematopoiesis (bone marrow hypoplasia and aplasia, and leukaemia), bone turnover (osteonecrosis and osteosarcoma) and local soft tissue (rhabdomyosarcoma).

Radionuclides that are deposited in the reticuloendothelial system (americium, polonium) may cause local injury due to the biological effects of ionising radiation to the liver, spleen and kidneys manifesting as organ failure.

Uranium damages the kidneys where it precipitates in the renal tubules in acid urine, because of its chemical, rather than its radiological properties.

Whole body irradiation

Because of wide intracellular distribution, radioactive potassium analogues such as caesium cause whole body irradiation. This is also seen with any other radionuclide with distribution throughout the body, such as tritium, cobalt and polonium.

Contaminated wounds

Intact skin is a barrier to most radionuclides.

Absorption of contamination from wounds is dependent on the physicochemical properties of the radionuclide such as solubility, pH, reactivity and particle size. Solubility may be altered by prolonged contact with body fluids. The contaminant may:

- absorb into the bloodstream
- transfer to regional lymph nodes
- migrate along fascial planes, potentially making it difficult to localise
- incorporate into coagulated tissue following acid or caustic exposure
- incorporate into the eschar following full thickness burns
- incorporate into the scab over an abrasion
- remain in the wound causing local irradiation, and development of fibrotic nodules

Treatment options

The clinical decision to undertake any specific treatment must consider the risks and benefits of the therapy in the specific clinical scenario. Ideally, this is informed by evidence of effectiveness.

Gastrointestinal decontamination

The amount of a substance able to be removed from the stomach by emesis or gastric lavage is unreliable, and negligible if performed more than one hour after ingestion. The risks of pulmonary aspiration or physical injury with emesis or lavage are considerable. The benefit of these procedures for gastrointestinal decontamination of radionuclides is unproven.

Whole bowel irrigation is occasionally considered for life-threatening ingestions of metals such as lead and iron prior to established severe toxicity, where supportive care and antidotes alone may not result in good clinical outcome. However, there are significant contraindications (uncooperative patient, uncontrolled vomiting, inability to place a nasogastric tube, ileus or bowel obstruction, and potential impairment of conscious state or development of seizures) and complications of therapy (nausea, vomiting, abdominal distension, pulmonary aspiration, and metabolic acidosis). It is unlikely to be tolerated by patients with injury or significant illness. The efficacy of whole bowel irrigation for radionuclide ingestions is unknown.

Catharsis is an ineffective means of reducing gastrointestinal transit time and not used in current clinical toxicological practice.

Enhanced elimination

Metals are poorly bound to activated charcoal. Therefore charcoal is not likely to be effective in reducing absorption of radionuclides. Alginates and antacids complex with a number of radionuclides (polonium, radium, strontium, uranium) and are relatively non-toxic, if oral therapy is not contraindicated.

^{137}Cs is secreted and reabsorbed via the enterohepatic circulation. Prussian blue acts as an ion exchange resin to form non-absorbable complexes with ^{137}Cs which are excreted in the faeces.

Urinary alkalinisation promotes the ionisation of uranium, preventing reabsorption across the renal tubular epithelium and promoting urinary excretion. The resultant metabolic alkalosis is usually well tolerated, however serum potassium may be lowered.

Urinary acidification promotes the ionisation of strontium, preventing reabsorption across the renal tubular epithelium and promoting urinary excretion. However, acidification of urine cannot be achieved without metabolic acidosis, which may not be desirable in the context of intercurrent illness or injury. The associated metabolic acidosis has seen this form of therapy fall into disuse for any other indication.

Extracorporeal techniques are invasive with significant complications. No controlled clinical trials have been undertaken in poisoned patients. Efficacy and optimal application are unknown. Dialysis may be useful to remove a substance with a small volume of distribution, particularly in the presence of renal failure.

Methods to reduce lung burden include:

- Nebulised DTPA is comparable in effectiveness to parenteral therapy with the same chelation agent.
- Pulmonary lavage is described in the literature, but limitations include lack of pre-existing respiratory disease, and a recommendation that the procedure be limited to those under 30 years of age. It is not a suitable procedure for casualties with potential blast lung injury. The effectiveness in humans is based on a single case report in which 13% of inhaled plutonium was removed with repeated bronchopulmonary lavage, however studies in beagles demonstrated efficacy of 25 to 50% and in baboons 60 to 90% with repeated treatments. It is suggested where large amounts (> 100 ALI, see section on antidotes) of insoluble radionuclides with long retention times, chiefly plutonium, are deposited in the lungs and may result in major pulmonary compromise. It is described in the following section.

Wound care

Irrigation and surgical debridement of contaminated wounds reduces the direct-to-bloodstream absorption and transfer of the contaminant to regional lymph nodes. Wound decontamination should not take precedence over resuscitation and stabilisation of life-threatening injuries. Specially designed probes may be required to assist in localising the contaminant within the wound.

Irrigation using decorporation agents such as DTPA has been proven to be ineffective in increasing the amount of radionuclide removed from the wound. Sterile water or saline are adequate. The criteria for surgical excision must have regard to the location and nature of the wound and quantity of contaminant in the wound.

Removal of radioactive shrapnel should only be undertaken using long-handled instruments. Such fragments should never be directly touched or handled because of the risk to the fingers or hand of the surgeon, and should be placed into a lead pot, which should be obtainable from the hospital nuclear medicine department.

Where contamination is associated with full thickness burns, the radionuclide will be fixed in the eschar and mostly removed with excision of the eschar.

As surgical instruments, swabs and dressings become contaminated, they should be replaced. Excised tissue should be retained for radiological survey. Systemically absorbed radionuclide should be managed with the relevant decorporation therapy.

Annual follow up of wounds with residual contamination is required to detect and excise nodules. Pathology and radiochemistry analysis of excised nodules is recommended.

Blocking agents

The metabolic behaviour of selected radionuclides provides opportunity for decreasing uptake with the appropriate stable isotope (iodine) or relevant analogue (calcium for radium and strontium) by saturating the target organ and diluting the radionuclide proportionately. For maximal effectiveness, these agents need to be given without delay.

Antidotes

The decision to use decorporation agents is dependent on:

- The chemical form of the radionuclide and the route of exposure, as both affect the biokinetics of absorption and distribution throughout the body.

- Assays including nasal smears, whole body or specific organ counts, and 24 hour urine and faeces collections.

- An estimation of the amount of retained radionuclide. This requires expert interpretation and advice from a nuclear medicine physician or health physicist following bioassay.

- The advice is usually expressed relative to the annual limit of intake (ALI) for occupational exposure. One ALI is the maximum permissible exposure each year, without detectable health risk. One ALI corresponds to a committed effective dose equivalent of 0.05 Sv, or a committed effective dose equivalent of 0.5 Sv to any individual organ or tissue, whichever is the more limiting.

- The age of the patient, as the relative biological effect for children is increased.

- The contraindications to, and side effects from, decorporation agents. Use of the decorporation agent itself must be weighed against the clinical scenario and projected health risk from the estimated burden of radionuclide.

- The rationing of resources in a mass casualty scenario may influence treatment rationale.

- In general, decorporation treatment is not required for < 1 ALI, but should be considered for 2 to 10 ALI dependent on clinical circumstances and resource availability, and is recommended for > 10 ALI.

Treatment effectiveness is likely to be greatest when commenced as soon as possible. The immediate decision to treat is likely to be based on incomplete information, as bioassay results are likely to be unavailable initially, or even for days. An evaluation of the incident details, especially the presence of air-borne contaminants, the identity and nature of the radionuclide, and the amount of contamination on the face and nares, may be all that is available to inform the initial decision to treat.

Following initial treatment, more accurate assessment of internal contamination can be made with repeated bioassay and physical measurements. This will allow more considered treatment decisions to be made, based on the probability of radiation-induced disease occurring in the patient's lifetime.

References

1. Alexander GA, Swartz HM, Amundsen SA, Blakely WF, Buddemeier B, et al. BiodosEPR-2006 meeting: acute dosimetry consensus committee recommendations on biodosimetry applications in events involving uses of radiation by terrorists and radiation accidents. Radiation Measurements. 2007; 42: 972-996.
2. Armed Forces Radiobiology Research Institute. Medical management of radiological casualties handbook, military medical operations. 2nd ed. Bethesda: Armed Forces Radiobiology Research Institute; 2003.

3. Crawford SW. Diagnosis and management of pulmonary problems associated with radiation injury. In: Ricks RC, Berger ME, O'Hara Jnr FM, editors. The medical basis for radiation-accident preparedness. The Parthenon Publishing Group. 2002: 131-8.

4. Dagle GE, Sanders CL. Radionuclide injury to the lung. Environmental Health Perspectives 1984; 55: 129-137.

5. Dart RC, editor. Medical toxicology. 3rd ed. Lippincott, Williams & Wilkins; 2004.

6. Gerber GB, Thomas RG, editors. Internal contamination guidebook, Radiation Protection Dosimetry 1992; 41 (1): 1-49.

7. Goans RE. Update on the treatment of internal contamination. In: Ricks RC, Berger ME, O'Hara Jnr FM, editors. The medical basis for radiation-accident preparedness. The Parthenon Publishing Group; 2002: 201-16.

8. Guilmette RA, Muggenburg BA, Cambron BL. Bronchoalveolar lavage: a new bioassay tool for plutonium inhalation exposures. Journal of Occupational Medicine. 1986; 28: 492 – 496.

9. Harrison J, Leggett R, Lloyd D, Phipps A, Scott B. Polonium-210 as a poison. J Radiol Prot. 2007; 27: 17-40

10. Inchiosa MA. Toxicokinetics: deposition, absorption, distribution, and excretion. In: Salem H, Katz SA, editors. Inhalation toxicology, 2nd ed. Taylor & Francis Group, CRC Press; 2006: 405-38.

11. International Atomic Energy Agency. Methods for assessing occupational radiation doses due to intakes of radionuclides, safety reports series, no. 37. Vienna: IAEA; 2004.

12. Marcus CS, California Disaster Medical Assistance Team-9, Western National Medical Response Team, Los Angeles County Department of Health Services Emergency Medical Services Agency. Administration of decorporation drugs to treat internal radionuclide contamination: medical emergency response to radiologic incidents. UCLA and Los Angeles County Department of Health Services.

13. Marcus CS, Siegel JA, Sparks RB. Medical management of internally radiocontaminated patients. Los Angeles County Department of Health Services, Emergency Medical Services Agency; 2006.

14. Medical Preparedness and Response Sub-Group, Department of Homeland Security Working Group on Radiological Dispersal Device (RDD) Preparedness. Medical guidelines. United States Department of Homeland Security; 2003

15. Methods of Treatment. In Radiation Protection Dosimetry. Nuclear Technology Publishing; 1992; 41(1): 27-36

16. Murray L, Daly F, Little M, Cadogan M, editors. Toxicology handbook. Elsevier Australia; 2007.

17. National Council on Radiation Protection and Measurements. Management of persons accidentally contaminated with radionuclides, NCRP Report No. 65. Bethesda: National Council on Radiation Protection and Measurements; 1980.

18. O'Connell KP, Salem H. Health Aspects of Bioaerosols. In: Salem H, Katz SA, editors. Inhalation toxicology, 2nd ed. Taylor & Francis Group, CRC Press; 2006: 913-32.

19. Pacific Northwest National Laboratory. Methods and models of the Hanford internal dosimetry program, radiation and health technology. Richland, Washington: Pacific Northwest National Laboratory; 2003. Available from: http://www.pnl.gov/eshs/pub/pnnl552.html

20. Smith H. Assessment of and therapy following contamination through the lungs or gastrointestinal tract. J Soc Radiol Prot; 1985; 5 (1): 15-20.

21. Smith JM, Spano MA. Interim guidelines for hospital response to mass casualties from a radiological incident. United States Department of Health and Human Services, Centers for Disease Control and Prevention; 2003.

22. Voelz GL. Assessment and Treatment of Internal Contamination: General Principles. In: Gusev IA, Guskova AK, Mettler FA, editors. Medical management of radiation accidents, 2nd ed. CRC Press; 2001: 319-36.

Appendix B: Internal contamination sample collection instructions

Spot urine

Use standard pathology urine collection containers. Instruct the patient to do the following:

- Wash their hands with soap and water
- Remove the cap from the container when ready to void
- Do not touch the inside of the container or cap at any time
- Collect at least 60 mL of urine in a non-contaminated area
- Recap the specimen tightly

Label the container with the patient ID, time and date of collection.

Store in a freezer or refrigerator immediately after collection, until shipment.

For transport:

- Freeze specimens prior to shipment.
- Place in a ziplock bag, along with sufficient absorbent for 500 mL of fluid.
- Place specimens upright in the shipping container, then cover with bubble-wrap.
- Add at least 5 kg of dry ice to the shipping container.
- Fill any residual space in the shipping container with additional bubble-wrap to prevent movement of the specimens during transport.

24-hour urine

Use a standard 2000 – 3000 mL urine collection container with a disposable funnel. Instruct the patient to do the following:

- Wash their hands with soap and water
- Remove the cap from the container when ready to void
- Do not touch the inside of the container or cap at any time
- Collect all the urine for 24 hours in a non-contaminated area.
- Recap the specimen tightly
- Store the container in the refrigerator or freezer during the collection period

Label the container with the patient ID, time and date of collection. Store in a refrigerator immediately after collection, until shipment.

- Place in a ziplock bag, along with sufficient absorbent for 3000 mL of fluid.
- Place specimens upright in the shipping container, then cover with bubble-wrap.
- Add several cold packs to the shipping container.

- Fill any residual space in the shipping container with additional bubble-wrap to prevent movement of the specimens during transport.

Nasal swab

Use standard cotton or polypropylene applicator swabs with a container. Instruct the patient to do the following:

- Wash their hands with soap and water
- Moisten the swab with water or sterile saline
- Swipe each nostril with a separate swab
- Place each swab in a separate container

Label the container with the patient ID, time and date of collection.

Store in a refrigerator or freezer immediately after collection, until shipment.

- Place in a ziplock bag.
- Place specimens in the shipping container, then cover with bubble-wrap.
- Add several cold packs to the shipping container.
- Fill any residual space in the shipping container with additional bubble-wrap to prevent movement of the specimens during transport.

Faecal sample

Since insoluble compounds pass through the gastrointestinal tract rapidly post exposure, faecal samples should be collected within 5 days of a suspected acute exposure.

Use a 4 to 5 L new plastic bag with either a ziplock or twist tie closure. Instruct the patient to do the following:

- Wash their hands with soap and water
- Collect the specimen in a non-contaminated area
- Avoid contact with the inner surface of the bag
- Defaecate directly into the bag.
- Seal the bag and store in a cardboard carton. Refrigerate.
- Repeat for all bowel actions over a 24 hour period.
- Store each bagged and sealed sample in the same cardboard box.

Label the container with the patient ID, time and dates of collection.

Store in a refrigerator or freezer immediately after collection, until shipment.

Pulmonary lavage

Introduction

Bronchopulmonary lavage as a procedure for washing out the lungs was developed as an experimental procedure in the 1920s. The clinical indications for human use have been evolving since the 1960s.

For treatment of inhaled insoluble radionuclides, bronchopulmonary lavage aims to reduce the lung burden using sequential whole lung lavage, repeated as tolerated on alternate lungs over an extended period.

On review of the literature a search for the term 'bronchopulmonary lavage' reveals a number of procedures.

1. Diagnostic pulmonary lavage: the instillation of 5–15 mL of isotonic saline into the trachea or bronchi and removed by suction. There may be a number of instillations. The effluent is sent for further analysis; cytological, microbiological or biochemical. This technique could be utilised to estimate lung burden of inhaled radionuclides.
2. Segmental lung flooding: following the positioning of a single lumen endotracheal tube within the selected bronchus under local anaesthesia, up to 100 mL of isotonic saline is introduced. The fluid is removed by suction or expectoration, the objective being to loosen material within a segment or lobe of lung.
3. Bronchopulmonary lavage or whole lung lavage is a procedure performed under general anaesthesia. A double lumen endotracheal tube isolates one lung, into which sufficient saline is instilled to fill the entire volume of one lung. The lung undergoing lavage is drained and repeatedly filled with fluid, and finally suctioned. The procedure is repeated on the alternate lung at another time. The objective of this procedure is to remove as much material from the lung as possible.

It is whole lung lavage which is discussed in this chapter. The term pulmonary lavage will be used to mean bronchopulmonary lavage or whole lung lavage.

Experimental uses of pulmonary lavage included:

- membrane
- analysis of pulmonary surfactant
- removal of radionuclides from the

Clinical trials of pulmonary lavage have included:

- obstructive airways disease
- cystic fibrosis
- status asthmaticus
- pulmonary alveolar proteinosis
- removal of accidentally inhaled ^{239}Pu from a human subject in a single case report

Only in pulmonary alveolar proteinosis, a condition with an incidence of 0.5 per 1,000,000 for the acquired form, is there continued substantive clinical experience of pulmonary lavage. In this condition, whole lung lavage is considered the gold standard for treatment.

The procedure for pulmonary lavage contained in the appendix to this chapter is taken from descriptions of the procedure as applied to pulmonary alveolar proteinosis. These procedures are consistent with the pulmonary lavage undertaken in experimental animals and the solitary case report of a human who accidentally inhaled plutonium. Additionally, the description of the procedure as applied to pulmonary alveolar proteinosis is consistent with current standards for monitoring under anaesthesia.

Efficacy

Pulmonary lavage is applied to inhaled materials with long lung retention times, generally those which are relatively insoluble. The technique appears to be equally effective for a variety of insoluble radionuclides. Inhaled material with a short retention time in the lung is generally removed by mucociliary clearance or absorption before it can be adequately removed from the lung by pulmonary lavage.

Experiments in beagle dogs, where each animal underwent 10 pulmonary lavage procedures from the second to the 56th day post exposure to various radionuclides, demonstrated removal of 23 to 59% (mean 44%) of the initial lung burden.

A single pulmonary lavage conducted sequentially on both lungs on the second day post exposure to various radionuclides in beagles and baboons demonstrated a reduction of 18 to 31% of the initial lung burden. Additional pulmonary lavages 3 to 7 days apart removed an average of 6% of initial lung burden on each of the 2nd to 6th occasions. This dropped to removal of 2% of initial lung burden on the 7th to 10th occasions, and 1% or less on the 11th to 20th occasions in other studies.

Further studies in dogs demonstrated that the efficacy of a single pulmonary lavage between day 2 and day 196 post exposure removed 8 to 40% consistently, compared with the residual lung burden immediately prior to each occasion of lavage. Hence the effectiveness of pulmonary lavage is not dependent on time after exposure where the substance has a relatively long biological half-life in the lung.

In dogs exposed to radionuclides with long retention times in lungs, the administration of DTPA (10 to 18 treatments) increased urinary excretion of radionuclides 3 to 5-fold compared with controls. However, the amount removed by chelation was only an average of 1.6% of the initial lung burden compared to 39 to 49% removed by pulmonary lavage (10 treatments) in the same animals.

The use of DTPA in the lavage fluid was equal in efficacy to intravenous administration and conferred no advantage.

In the single case report of a human with accidental inhalation of ^{239}Pu, he underwent pulmonary lavage of the right lung on days 8 and 17, and left lung on day 12 after exposure. Intravenous DTPA was begun on day 8. Of the initial lung burden, 14% was removed by lavage, and 17% in the urine. The plutonium mixture was thought to be heterogeneous in solubility.

Experiments in beagles have demonstrated that the distribution of inhaled radionuclide by activity and weight is usually 58% to the right lung and 42% to the left lung. The proportions are likely to be

similar in humans. Thus, the right lung should be preferentially lavaged first in a series of pulmonary lavages in order to maximally reduce the initial lung burden.

With regard to the total volume of lavage fluid recommended, a total of 40 to 50 litres is advised for an adult patient. This is consistent with current guidelines for pulmonary alveolar proteinosis and can be extrapolated from the volumes used in animal experiments for radionuclide removal by pulmonary lavage. Analysis of the radionuclide content of the lavage effluent in beagles, demonstrated that a significant proportion of the total radionuclide removed was contained in each fraction. Six litres was lavaged into each dog, with average weight of the dogs at 8.5 kg. Average values for each litre of lavage effluent of the percentage of radionuclide removed are contained in Table 13.1. The large volume ensures adequate washing. It is strongly recommended that, in humans, no less than 40 to 50 litres of lavage fluid be used.

Table 13.1 Burden of deposited radionuclide removed by lavage by episode of treatment

Lavage effluent fraction	1st	2nd	3rd	4th	5th	6th/final
% of total radionuclide activity removed per lavage	44	29	9.3	4.9	3.5	9.8

Adapted from Boecker et al. Removal of [144]Ce in fused clay particles from the beagle dog lung by bronchopulmonary lavage. Health Physics. 1974; 26: 505-517.

Benefits of pulmonary lavage

In a study comparing the efficacy of treatment in beagles exposed to [144]Ce aerosols with pulmonary lavage and intravenous DTPA against untreated controls, 3 of 4 untreated animals died of pulmonary fibrosis, whereas 2 of the 8 treated dogs died. Only one of the surviving treated animals developed pulmonary fibrosis despite being observed for an appropriate period. Lung function was preserved in the other treated survivors.

In another study of beagles exposed to [241]Am, treatment with pulmonary lavage (10 treatments) and intravenous DTPA (18 treatments) reduced absorbed radiation doses to lung, liver and skeleton by 50, 90 and 85% respectively.

Sequelae of pulmonary lavage

Pulmonary lavage results in improvement of lung function, including arterial oxygenation, in patients with pulmonary alveolar proteinosis. Therefore, significant functional impairment is not expected for patients undergoing pulmonary lavage to remove inhaled radionuclides.

Chest films immediately following pulmonary lavage demonstrate diffuse opacification, which resolves within 24 to 48 hours post-procedure. Some transient atelectasis may occur.

Histological evidence of mechanical injury to lung parenchyma is minimised using a volume-controlled technique of pulmonary lavage.

Risks of pulmonary lavage

Mucociliary clearance of larger inhaled particles occurs in the initial period after inhalation. It has been demonstrated that greater than 60% of the inhaled dose deposited in the airways may be cleared in the first 2 days by this means. A theoretical risk exists of washing contaminants more deeply into the lungs with immediate pulmonary lavage. Although there is no experimental evidence to confirm this, a delay of several days to the initiation of pulmonary lavage has been recommended.

Premorbid conditions must be considered in evaluating the risk versus benefit for an individual patient with this procedure. The primary consideration is the risk of general anaesthesia against the future risk of radiation induced injury or neoplasia.

Leakage of fluid into the ventilated lung is of greatest concern. This is recognised by fluid in the lumen of the ventilated lung and air bubbles in the lavage fluid. The procedure must be stopped immediately, placing the patient in the lateral decubitus position with the lavaged side down, suctioning out both lungs and rechecking the position of the double lumen tube.

Electrolyte and fluid balance changes may occur due to the dialysate effect of the lavage fluid.

Transient right bundle branch block appears to be the most commonly reported electrocardiographic abnormality during the procedure.

Summary

Pulmonary lavage is effective at removing inhaled insoluble radionuclides. A single lavage will remove approximately 12% of the initial lung burden from one lung. Repeated lavage will remove up to 45% on average. The removal of insoluble radionuclide particles from the lungs decreases the cumulative dose, preventing radiation-induced injury.

The effectiveness of pulmonary lavage is not altered by delay after inhalation of the radionuclide. However, the radiation injury accumulates with increasing duration of exposure. Pulmonary lavage is a treatment aimed at reducing the likelihood of future injury. Current injuries and illnesses should be stabilised as a priority before lavage is undertaken.

Key determinants of the need for pulmonary lavage are:

- the isotope and chemical form of the radionuclide inhaled (half-life and solubility known)
- the particle size (which affects the likelihood of alveolar deposition)
- the quantity of material inhaled (estimated from nasal swabs, lung and whole body counts, and/or indirectly from other bioassays)

The chemical form and particle size of the aerosol is likely to vary if the radionuclide is dispersed during an explosion or fire as multiple temperatures and chemical reactions occur within the combustion process.

The procedure is justified for an insoluble radionuclide with a long retention time in the lungs where the cumulative dose is greater than 100 ALI. (Annual limit of intake for occupational exposure. One

ALI is the maximum permissible exposure each year, without detectable health risk. One ALI corresponds to a committed effective dose equivalent of 0.05 Sv, or a committed effective dose equivalent of 0.5 Sv to any individual organ or tissue, whichever is the more limiting. The threshold dose for radiation pneumonitis is 5 Gy.)

There is no other technique available that will effectively reduce the lung burden of inhaled insoluble radioactive materials.

References

1. Anantham D, Jagadesan R, Tiew PEC. Clinical review: independent lung ventilation in critical care. Critical Care. 2005; 9 (6): 594 – 600.
2. Beccaria M, Luisetti M, Rodi G, Corsico A, Zoia MC, et al. Long-term durable benefit after whole lung lavage in pulmonary alveolar proteinosis. Eur Resp J. 2004; 23: 526 – 531.
3. Boecker BB, Muggenburg BA, McLellan RO, Clarkson SP, Mares FJ, et al. Removal of 144Ce in fused clay particles from the beagle dog lung by bronchopulmonary lavage. Health Physics. 1974; 26: 505-517
4. Guilmette RA, Muggenburg BA, Cambron BL. Bronchoalveolar lavage: a new bioassay tool for plutonium inhalation exposures. Journal of Occupational Medicine. 1986; 28: 492 – 496.
5. Kylstra JA, Rausch DC, Hall KD, Spock A. Volume-controlled lung lavage in the treatment of asthma, bronchiectasis, and mucoviscidosis. American Review of Respiratory Disease. 1971; 103: 651 – 665.
6. McClellan RO, Boyd HA, Benjamin SA, Cuddihy RG, Hahn FF, et al. Bronchopulmonary lavage and DTPA treatment of an accidental inhalation 239Pu exposure case. Fission product inhalation program annual report (Lovelace Foundation for Medical Education and Research). 1971 – 1972; 45: 287-294.
7. Methods of Treatment. In Radiation Protection Dosimetry. Nuclear Technology Publishing; 1992; 41(1): 27-36
8. Morgan C. The benefits of whole lung lavage in pulmonary alveolar proteinosis. Eur Resp J. 2004; 23: 503505.
9. Muggenberg BA, Mauderly JL, Boecker BB, Hahn FF, McLellan RO. Prevention of radiation pneumonitis from inhaled cerium-144 by lung lavage in beagle dogs. American Review of Respiratory Disease. 1975; 111: 795-802.
10. Muggenburg BA, Felicetti SA, Silbaugh SA. Removal of inhaled radioactive particles by lung lavage -a review. Health Physics. 1977; 33: 213-220.
11. Muggenburg BA, Jones RK. Clinical and experimental uses of bronchopulmonary lavage: a review. Fission product inhalation program annual report (Lovelace Foundation for Medical Education and Research). 1970 – 1971; 44: 319-322.
12. Muggenburg BA, Mewhinney JA. Removal of inhaled 241Am oxide particles of various sizes from beagle dogs using lung lavage and chelation treatment. Health Physics. 1981; 41: 123-133.
13. Nolibe D, Nenot JC, Metivier H, Masse R, Lafuma J. Traitement des inhalations accidentelles d'oxyde de plutonium par lavage pulmonaire in vivo. In : International Atomic Energy Agency. Diagnosis and treatment of incorporated radionuclides, proceedings series. IAEA. Vienna; 1976: 373-385.

14. Pfleger RC, Wilson AJ, Cuddihy RG, McLellan RO. Bronchopulmonary lavage for removal of inhaled insoluble materials from the lung. Chest. 1969; 56: 524-530.
15. Ramirez-R J. Pulmonary alveolar proteinosis – treatment by massive bronchopulmonary lavage. Arch Intern Med. 1967; 119: 147-156.
16. Seymour JF, Presneill JJ. Pulmonary Alveolar Proteinosis. Am J Respir Crit Care Med. 2002; 166: 215-235.

Appendix C: Pulmonary lavage procedure

- Stabilise current injuries and illnesses prior to undertaking pulmonary lavage.

- Unless there are contraindications to doing so, the right lung should be preferentially lavaged first.

- The procedure is performed with the patient in the lateral decubitus position.
    - Whilst it is usually the dependent lung that is lavaged, one author describes lavage of the non-dependent lung, allowing easy access to that lung for chest wall percussion during drainage of the lavage fluid. Additionally, blood flow to the (lavaged) non-dependent lung is reduced resulting in less hypoxaemia due to cardiac shunt.

- A double lumen endotracheal tube is placed under general anaesthesia with muscle paralysis. Bronchoscopic confirmation of placement is recommended.

- Monitor pulse oximetry, end-tidal capnography, ECG, oesophageal stethoscope, invasive blood pressure, central venous pressure, core temperature, peak and plateau respiratory pressures and continuous spirometry.

- Absolute functional lung separation needs to be ascertained.
    - For the water bubble technique, the tracheal port of the double lumen endotracheal tube is placed under water whilst transiently maintaining a plateau pressure of 40cm through the bronchial port. The appearance of bubbles around the tracheal port signifies a leak around the bronchial cuff.
    - The balloon inflation technique substitutes a balloon for the underwater seal at the tracheal port. Any inflation of the balloon during positive pressure inflation through the bronchial cuff indicates a leak around the bronchial cuff.

- Clamp and degass the lung to be lavaged.

- Prior to commencement of the lavage, confirm that ventilation of the isolated lung will maintain adequate ventilation of the patient. Ventilate the isolated lung with a high inspiratory oxygen fraction, up to 1.0.

- Carefully monitor the volumes of lavage fluid instilled and drained.

- After pre-oxygenation, 500 to 1000 mL of warmed (37°C) isotonic saline is instilled at a time and allowed to efflux immediately. Gravity is used to instill and drain the lavage fluid via large bore tubing.
    - Descriptions of the volume of lavage fluids vary. Suggested aliquots equate with the total tidal volume (7 mL/kg) delivered to the lavaged lung, or as much as an amount equivalent to the vital capacity of the individual lung. (The total vital capacity is 65-75 mL/kg lean body mass, corrected for the volume of the respective lung, i.e. 0.45 left lung, 0.55 right lung).
    - Up to 40 to 50 L are lavaged over three hours for lavage of one lung.

- After lavage, carefully drain and suction the lung via fibreoptic bronchoscopy.

- Retain the effluent lavage fluid for radiological analysis.

- At the end of the procedure, positive end-expiratory pressure ventilation is performed.

- Leakage of fluid into the ventilated lung is of greatest concern. This is recognised by falling oxygen saturation, fluid in the lumen of the ventilated lung and air bubbles in the lavage fluid. The procedure must be stopped immediately, placing the patient in the lateral decubitus position

with the lavaged side down, suctioning out both lungs and rechecking the position of the double lumen tube.

- Electrolytic disturbance may be seen due to the dialysis effects of the lavage fluid, mainly hypocalcaemia and metabolic acidosis. Periodic laboratory analysis of plasma biochemistry is recommended during extended procedures.
    - Some fluid shift may occur due to absorption of the lavage fluid from the alveoli. Changes in central venous pressure should be noted.
- The process is repeated for the other lung after 2 to 3 days.
    - Some authors describe sequential pulmonary lavage of both lungs during the same procedure. The decision to undertake sequential pulmonary lavage is dependent on how the patient tolerates the procedure, and on resource demands (access to operating theatre and personnel, and competing patient priorities).
- At least 10 separate occasions of pulmonary lavage are recommended.
- The intervals between occasions of pulmonary lavage should be as brief as possible to facilitate the earliest possible lowering of the initial lung burden of the radionuclide and, therefore, the cumulative dose.

Appendix D: Selected radionuclides

Americium

Properties

- The isotopes of concern are ^{241}Am and ^{243}Am
- This is a crystalline, silver-white metal that is solid under normal conditions.
- It is used in medical devices, industrial thickness and density gauges, and smoke detectors.
- Emits alpha and weak gamma radiation
- The physical half-life of ^{241}Am is 458 years and the effective half-life is 139 years

Biokinetics

- 75% of an inhaled dose will be absorbed, and 10% retained in the lungs. Clearance from the lung takes 12 to 18 months.
- Gastrointestinal absorption is minimal
- Absorption from wounds is rapid.
- Once absorbed, 50% is deposited in bone with a clearance half-life of 50 years, and 30% in liver with a clearance half-life of 9 years. A tiny amount is deposited in the gonads. 20% is excreted.
- It is eliminated by urinary and hepatic excretion

Toxicity

- Hepatic failure may result from excessive americium deposition in the liver.
- Marrow suppression is seen with skeletal deposition.
- Tumours may result from deposition in liver and bone.
- The exposure limits for 1 ALI are 300W Bq/year for inhalation, and 3 x 104 Bq/year for ingestion.

Assay techniques

- Direct counting of the low energy gamma by germanium detector is a quick turnaround analysis for emergency circumstances. It is less sensitive than alpha spectrometry, but does not require americium chemical separation. This is applicable to both urine and faecal 24 hour samples.
- In vivo assays include chest counts, skeletal surveys by head counting, liver counts and wound counts.

Treatment

- Chelation therapy with DTPA is estimated to improve urinary excretion of americium 50-fold. One patient contaminated with more than 1 mCi (3.7 x 10^9 Bq) of americium had 99% of the total body burden removed with four years treatment with DTPA.

- Chelation is not required at < 1 ALI. It should be considered from 2–10 ALI, and is recommended at > 10 ALI.
  - Chelation with these agents is only effective for the soluble form of the target metal.
  - Effectiveness is best within 6 hours of exposure, although therapy may extend to years.
  - Ca-DTPA has ten-fold greater efficacy than Zn-DTPA in the first 24 hours and should be used initially unless there are contraindications. Zn-DTPA is as efficacious as Ca-DTPA after the initial 24 hours, and better tolerated.
  - Combined treatment with early inhaled DTPA followed by intravenous therapy is believed to be most effective for inhalational exposures.
    - Nebulised, 1gm in a 4 mL ampoule, 1:1 dilution with saline or sterile water, over 30 minutes.
    - Slow intravenous push or infusion initially with Ca-DTPA on the first day, then Zn-DTPA on subsequent days. 1 gm in 250 mL normal saline or 5% dextrose over 1 hour, once daily. The dose must not be fractionated.
    - The paediatric dose is 14 mg/kg of Zn-DTPA, not to exceed 1 gm daily.
  - Adverse effects occur as a result of chelation of other metallic cations such as zinc, manganese and other trace elements. Adverse effects include nausea, vomiting, diarrhoea, fever, chills, muscle cramps, pruritis and anosmia. Consider zinc replacement therapy in prolonged treatment.
  - Inhaled chelation therapy may exacerbate asthma
  - Obtain a urinalysis prior to, and monitor blood pressure during each administration of the drug.
  - Discontinue therapy if diarrhoea or abnormalities of urinalysis (proteinuria, haematuria, or casts) occur.
  - Ca-DTPA is contraindicated in pregnancy and children, as well as nephrotic syndrome or bone marrow suppression. Zn-DTPA can be safely administered in pregnancy (Class C drug) and children.

References

17. Armed Forces Radiobiology Research Institute. Medical management of radiological casualties handbook, military medical operations. 2nd ed. Bethesda: Armed Forces Radiobiology Research Institute; 2003.
18. Centers for Disease Control and Prevention. Radiation emergencies radioisotope brief: americium. Department of Health and Human Services, Centers for Disease Control and Prevention; 2004.
19. Dart RC, editor. Medical toxicology. 3rd ed. Lippincott, Williams & Wilkins; 2004.
20. International Atomic Energy Agency. Methods for assessing occupational radiation doses due to intakes of radionuclides, safety reports series, no. 37. Vienna: IAEA; 2004.
21. Marcus CS, California Disaster Medical Assistance Team-9, Western National Medical Response Team, Los Angeles County Department of Health Services Emergency Medical Services Agency. Administration of decorporation drugs to treat internal radionuclide

contamination: medical emergency response to radiologic incidents. UCLA and Los Angeles County Department of Health Services.

22. Marcus CS, Siegel JA, Sparks RB. Medical management of internally radiocontaminated patients. Los Angeles County Department of Health Services, Emergency Medical Services Agency; 2006.

23. MEDECOR PC: Medical decorporation PC [computer program]. Version 1.0. Ottawa: RadSci Research Inc., Defence R&D Canada; 2006. Available from: http://www.radsci.ca

24. Medical Preparedness and Response Sub-Group, Department of Homeland Security Working Group on Radiological Dispersal Device (RDD) Preparedness. Medical guidelines. United States Department of Homeland Security; 2003.

25. National Council on Radiation Protection and Measurements. Management of persons accidentally contaminated with radionuclides, NCRP Report No. 65. Bethesda: National Council on Radiation Protection and Measurements; 1980.

26. NDA 21-749 Pentetate calcium trisodium injection product information. Hameln Pharmaceuticals GmbH.

27. NDA 21-751 Pentetate zinc trisodium injection product information. Hameln Pharmaceuticals GmbH.

28. Pacific Northwest National Laboratory. Methods and models of the Hanford internal dosimetry program, radiation and health technology. Richland, Washington: Pacific Northwest National Laboratory; 2003. Available from: http://www.pnl.gov/eshs/pub/pnnl552.html

29. Peterson J, MacDonell M, Haroun L, Monette F, Hildebrand RD, Taboas A. Radiological and chemical fact sheets to support health risk analyses for contaminated areas. Argonne National Laboratory Environmental Science Division and U.S. Department of Energy. 2007.

30. Radioaction Info. In: POISINDEX® System [internet database]. Greenwood Village, Colo: Thomson Healthcare. 2008; 137

Caesium

Properties

- The isotope of concern is ^{137}Cs
- A liquid at an ambient temperature of 28°C, caesium readily combines with chlorides as a crystalline powder, which is highly dispersible.
- It is used to calibrate radiation detection devices, as well as in medical devices and industrial gauges. It is a by-product of nuclear fission.
- Emits gamma and beta irradiation
- The physical half-life is 30 years, and the effective half-life is 70 days
- The effective half-life may be as little as 12 days in infants and 57 days in older children

Biokinetics

- Absorbed completely via inhalation, ingestion & via wounds
- Metabolised as a potassium analogue
- Assumed to be distributed evenly throughout the body
- Urinary excretion
- The effective dose equivalent is 'equal to the whole body dose'

Toxicity

- Primary toxicity is whole body irradiation
- The exposure limits for 1 ALI are 2×10^6D Bq/year for inhalation, and 1×10^6 Bq/year for ingestion.

Assay techniques

- In vivo whole body counting is the preferred method of bioassay
- Urine sampling bioassay is also useful
- Faecal sampling is unreliable because of the extent of absorption via the gastrointestinal route
- Determine the annual limit of intake of the exposure with health physics assistance. For ^{137}Cs this corresponds to 100μCi

Treatment

- For treatment, a low level exposure would be considered to be 1–5 ALI, a moderate exposure 5–10 ALI, and a severe exposure as > 10 ALI
- The most effective means for removal of caesium from the body is by oral administration of Prussian blue (ferric cyanoferrate). Prussian blue is not absorbed from the intestines. It binds the caesium ions that are enterically cycled into the gastrointestinal tract, preventing the reabsorption of caesium. Treatment can reduce the biological half-life of caesium to one-third of

its expected value. The effectiveness of Prussian blue depends on its early administration. There are no contraindications.

- The daily dose of Prussian blue should be adjusted for the suspected level of internal contamination and administered orally in 3 divided doses with 100–200 mL water.
    - Low: 3 gm daily
    - Mid: 3–10 gm daily
    - High: 10–20 gm daily
    - Paediatric doses commence at 1–1.5 gm daily
    - The duration of therapy is dependent on the extent of the body burden on ^{137}Cs. It is recommended that treatment continue for at least 30 days.
    - Prussian blue may be given to pregnant women if clinically indicated and is classed as a Class C therapeutic agent. Patients should be advised of blue discoloration of their faeces. For those who are unable to ingest capsules, the capsule contents can be emptied into water, however this will temporarily stain the mouth and teeth blue.
- Doses above 10 gm may result in increased incidence of gastritis, constipation and diarrhoea.
- Prussian blue is not absorbed from the gastrointestinal tract, therefore no teratogenic effects or excretion into breast milk is expected.
- Patients receiving decorporation therapy, should receive whole body monitoring and urine and faecal bioassay daily to monitor ^{137}Cs elimination. Decorporation therapy should be adjusted in line with the decreasing whole-body burden.
- Prussian blue also binds sodium and potassium with less affinity than caesium. Electrolytes should be checked 12 hourly, initially, and vital signs should be monitored closely.
- Haemodialysis has been proposed as adjunctive therapy for severe caesium internal contamination.

References

31. Armed Forces Radiobiology Research Institute. Medical management of radiological casualties handbook, military medical operations. 2nd ed. Bethesda: Armed Forces Radiobiology Research Institute; 2003
32. Centers for Disease Control and Prevention. Radiation emergencies radioisotope brief: cesium. Department of Health and Human Services, Centers for Disease Control and Prevention, 2004
33. Dart RC, editor. Medical toxicology. 3rd ed. Lippincott, Williams & Wilkins 2004
34. International Atomic Energy Agency. Methods for assessing occupational radiation doses due to intakes of radionuclides, safety reports series, no. 37. Vienna: IAEA 2004
35. Marcus CS, California Disaster Medical Assistance Team-9, Western National Medical Response Team, Los Angeles County Department of Health Services Emergency Medical Services Agency. Administration of decorporation drugs to treat internal radionuclide contamination: medical emergency response to radiologic incidents. UCLA and Los Angeles County Department of Health Services.

36. Marcus CS, Siegel JA, Sparks RB. Medical management of internally radiocontaminated patients. Los Angeles County Department of Health Services, Emergency Medical Services Agency; 2006

37. MEDECOR PC: Medical decorporation PC [computer program]. Version 1.0. Ottawa: RadSci Research Inc., Defence R&D Canada; 2006. Available from: http://www.radsci.ca

38. Medical Preparedness and Response Sub-Group, Department of Homeland Security Working Group on Radiological Dispersal Device (RDD) Preparedness. Medical guidelines. United States Department of Homeland Security; 2003

39. National Council on Radiation Protection and Measurements. Management of persons accidentally contaminated with radionuclides, NCRP Report No. 65. Bethesda: National Council on Radiation Protection and Measurements; 1980.

40. Pacific Northwest National Laboratory. Methods and models of the Hanford internal dosimetry program, radiation and health technology. Richland, Washington: Pacific Northwest National Laboratory; 2003. Available from: http://www.pnl.gov/eshs/pub/pnnl552.html

41. Peterson J, MacDonell M, Haroun L, Monette F, Hildebrand RD, Taboas A. Radiological and chemical fact sheets to support health risk analyses for contaminated areas. Argonne National Laboratory Environmental Science Division and U.S. Department of Energy. 2007.

42. Radioaction Info. In: POISINDEX® System [internet database]. Greenwood Village, Colo: Thomson Healthcare. 2008; 137

43. Radiogardase Insoluble Prussian Blue product information. Berlin, Haupt Pharma Berlin GmbH.

Cobalt

Properties

- The isotope of concern is ^{60}Co
- It is a hard grey-blue metallic solid that can become magnetised.
- It is used in industrial gauges and radiology, cancer therapy, and food and product sterilisation. It is also a by- product of nuclear reactions.
- It emits beta and gamma radiation
- The physical half-life is 5.3 years, and the effective half-life is 10 days

Biokinetics

- Cobalt is rapidly absorbed from lung, but less than 5 to 10 % is absorbed from the gastrointestinal tract. Children may absorb up to 30 % via ingestion.
- Cobalt is an essential element, found in most tissues, with the highest concentration in the liver.
- Of the absorbed cobalt
  - 50% is rapidly excreted, with a biological half-life of 0.5 days.
  - 5% is taken up by the liver and 45% is distributed throughout the remainder of the body.
  - Of the cobalt deposited in liver, 60 % has a biological half-life of 6 days, 20 % has a biological half-life of 60 days, and 20% has a biological half-life of 800 days.
- 86% is excreted in urine and 14% via faeces.

Toxicity

- Whole body irradiation and acute radiation syndrome is the main form of toxicity.
- Exposure limits of 1 ALI are 2 x 10^6W Bq/year & 4 x 10^5Y Bq/year for inhalation, and 7 x 10^6W Bq/year & 3 x 10^6Y Bq/year for ingestion

Assay techniques

- Whole body counting using either sodium-iodide or germanium detectors is the preferred means of bioassay.
- Urine and faeces collections are not required unless there is internal contamination due to a mixture of radionuclides.

Treatment

- Treatment options for cobalt are limited in effectiveness.
- Penicillamine is used for the chelation of heavy metals such as copper, iron, lead, gold and others. It is estimated to increase urinary elimination of radionuclides by one third. It would only be considered for very significant cobalt exposures.
  - The adult dose is 250 mg 6 hourly, orally. This may be increased to 2 gm daily, in divided doses.

- The paediatric dose is 20 to 30 mg/kg/day in divided doses.
- Therapy needs to be administered promptly because the effectiveness of treatment decreases rapidly with increasing time post exposure.
- Adverse effects occur in 25 to 63% of patients. These include leucopaenia, thrombocytopaenia, haemolytic anaemia, agranulocytosis, aplastic anaemia, thrombotic thrombocytopenic purpura, cholestatic hepatitis, nausea, vomiting, abdominal pain, pancreatitis, myasthenia gravis, sensory and motor neuropathy, breast enlargement in males and females, nephrotic syndrome, Goodpasture's syndrome and obliterative bronchiolitis. Death has occurred. The risk of toxicity is increased at higher doses and with prolonged therapy.
- Hypersensitivity effects include urticaria, rash, pruritis, fever, haematuria, proteinuria, eosinophilia, erythema multiforme, and autoimmune bullous formations.
- Contraindications: renal failure, lupus erythematosus, penicillin allergy and pregnancy. Developmental connective tissue anomalies were noted in 8 out of 100 pregnancies.
- Monitor blood cell counts and urinalysis closely during therapy.

References

44. Armed Forces Radiobiology Research Institute. Medical management of radiological casualties handbook, military medical operations. 2nd ed. Bethesda: Armed Forces Radiobiology Research Institute; 2003.
45. Centers for Disease Control and Prevention. Radiation emergencies radioisotope brief: cobalt. Department of Health and Human Services, Centers for Disease Control and Prevention, 2005.
46. Dart RC, editor. Medical toxicology. 3rd ed. Lippincott, Williams & Wilkins 2004
47. International Atomic Energy Agency. Methods for assessing occupational radiation doses due to intakes of radionuclides, safety reports series, no. 37. Vienna: IAEA 2004.
48. Marcus CS, California Disaster Medical Assistance Team-9, Western National Medical Response Team, Los Angeles County Department of Health Services Emergency Medical Services Agency. Administration of decorporation drugs to treat internal radionuclide contamination: medical emergency response to radiologic incidents. UCLA and Los Angeles County Department of Health Services.
49. Marcus CS, Siegel JA, Sparks RB. Medical management of internally radiocontaminated patients. Los Angeles County Department of Health Services, Emergency Medical Services Agency; 2006.
50. MEDECOR PC: Medical decorporation PC [computer program]. Version 1.0. Ottawa: RadSci Research Inc., Defence R&D Canada; 2006. Available from: http://www.radsci.ca
51. Medical Preparedness and Response Sub-Group, Department of Homeland Security Working Group on Radiological Dispersal Device (RDD) Preparedness. Medical guidelines. United States Department of Homeland Security; 2003
52. National Council on Radiation Protection and Measurements. Management of persons accidentally contaminated with radionuclides, NCRP Report No. 65. Bethesda: National Council on Radiation Protection and Measurements; 1980.

53. Pacific Northwest National Laboratory. Methods and models of the Hanford internal dosimetry program, radiation and health technology. Richland, Washington: Pacific Northwest National Laboratory; 2003. Available from: http://www.pnl.gov/eshs/pub/pnnl552.html

54. Peterson J, MacDonell M, Haroun L, Monette F, Hildebrand RD, Taboas A. Radiological and chemical fact sheets to support health risk analyses for contaminated areas. Argonne National Laboratory Environmental Science Division and U.S. Department of Energy. 2007.

55. Radioaction Info. In: POISINDEX® System [internet database]. Greenwood Village, Colo: Thomson Healthcare. 2008; 137.

Iodine

Properties

- Isotopes of concern are ^{125}I and [131]I

- Iodine is a bluish-black, lustrous solid which becomes an irritant, purplish gas at ambient temperatures. Iodine is highly reactive and is usually found in compounds rather than in its pure form.

- Radioiodines are short-lived radionuclides used in diagnostics and therapy. They are also produced during nuclear fission in reactors and from nuclear detonation.

- Contaminated milk is an important pathway for exposure.

- Iodine emits beta and gamma radiation.

- The physical half-life of ^{125}I is 60 days and the effective half-life is 42 days. The physical and effective half-lives of ^{131}I are 8 days.

Biokinetics

- Radioiodine is rapidly and completely absorbed from the lungs, gastrointestinal tract and via wounds.

- The biological half-life in blood is considered to be 0.25 days

- 30% is distributed to the thyroid, and the rest is immediately excreted.

- Uptake by the thyroid is influenced by the availability of stable iodine in the diet (iodine deficiency increases uptake), and thyroid dysfunction (thyrotoxicosis increases uptake). Hence individual uptake may vary from 0 to greater than 50%.

- Clearance from the thyroid is age-dependent. The biological half-life ranges from 11 days in infants, to 23 days in 5 year old children, and 80 days in adults.

- The radioiodine is recycled from the thyroid via other tissues. Then it may be resorbed by the thyroid, or excreted in the faeces (20%) or urine.

- About 25 % of iodine absorbed by lactating women is secreted in breast milk.

Toxicity

- The foetus, neonate and child are most at risk for radiation-induced thyroid disease (cancer, adenomas, and hypothyroidism). A child's thyroid receives a higher radiation dose than an adult because the same amount of energy is deposited in a smaller mass of tissue for an equivalent amount of radioiodine:
  - 16-fold higher for newborns
  - 8-fold higher for children less than 1 year
  - 4-fold higher for children at 5 years of age

- Foetal thyroid uptake increases during the second and third trimesters.

- Pregnancy increases maternal thyroid uptake of iodine, especially during the first trimester.

- The delay from time of exposure to development of cancer is at least 10 years, with an average delay of 20 years.

- The sensitivity of adults greater than 40 years to radioiodines is considerably reduced. The time course for developing radiation-induced thyroid disease in this age group is several decades. Hypothyroidism may be seen with extremely high exposures to radioiodines. Thyroid function should be monitored at least annually over the decades subsequent to confirmed radioiodine exposure.

- The exposure limits for 1 ALI are 1×10^6 Bq/year for inhalation, and 8×10^5 Bq/year for ingestion.

Assay techniques

- Thyroid counting with a beta-gamma detector with a NaI crystal, appropriately calibrated, will provide accurate estimates of thyroid uptake. A qualitative estimate of exposure may be obtained from a thyroid scan in a hospital Nuclear Medicine department.

- Whole body counting is a very sensitive technique.

- Urine bioassay can be used to monitor excretion.

Treatment

- Potassium iodide (KI) is an effective blocking agent to reduce radioiodine absorption by the thyroid.

  - Blocking of thyroid uptake of radioiodines is most effective administered promptly after exposure, and rapidly diminishes in effectiveness with the passage of time. The FDA recommendation is that iodine should be administered not longer than 4 hours after exposure. An appropriate formulation must be available within this timeframe.

Fig. 1. Averted dose as a function of time stable iodine is administered relative to a 4-h intake of ^{131}I for different dietary iodine intakes
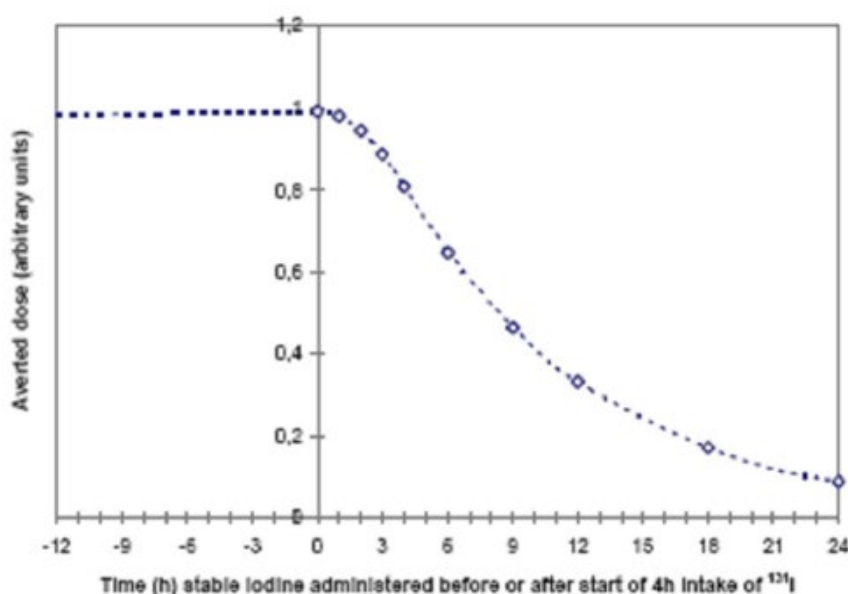
– The recommended dosing schedule is

- 130 mg for adults < 40 years and pregnant or lactating women
- 65 mg for children 3 to 18 years
- Adolescents approaching adult weight (70Kg) should take the adult dose
- 32 mg for infants 1 month to 3 years
- 16 mg for infants from birth to 1 month

– Potassium iodide is usually in the form of a scored tablet of 130 mg or 65 mg. The scoring does not facilitate breaking the tablet into eighths with any accuracy. Solution prepared from potassium iodide tablets is required to be freshly prepared, as it is stable for only one week. The American Academy of Pediatrics policy statement includes guidelines for home preparation of KI solution using both 130 mg and 65 mg tablets and advice on improving palatability. The guidelines for home preparation commence by grinding a whole tablet to a fine powder, and adding a measured quantity of liquid to achieve the desired solution strength to enable accurate dosing.

Table 1 Preparation of potassium iodide solution from tablets

Guidance for home preparation of KI solution using 130 mg tablet

- Put one 130 mg KI tablet in a small bowl and grind into a fine powder with the back of a spoon. There should be no large pieces.
- Add 20 mL (4 teaspoons) of water to the KI powder. Mix them together until the KI powder is dissolved in the water.
- Add 20 mL (4 teaspoons) of milk, juice, soft drink or cordial to the KI/water mixture. The resultant mixture is now
- 16.25 mg of KI per 5 mL (teaspoon).
- Age-based dosing guidelines:
- Newborn to 1 month of age: 5 mL (1 teaspoon) 1 month to 3 years of age: 10 mL (2 teaspoons)
- 4 to 17 years of age: 20 mL (4 teaspoons)
- The mixture will keep for up to 1 week if refrigerated. Discard unused portion after one week and prepare a fresh mixture.

Guidance for home preparation of KI solution using 65 mg tablet

- Put one 65 mg KI tablet in a small bowl and grind into a fine powder with the back of a spoon. There should be no large pieces.
- Add 20 mL (4 teaspoons) of water to the KI powder. Mix them together until the KI powder is dissolved in the water.
- Add 20 mL (4 teaspoons) of milk, juice, soft drink or cordial to the KI/water mixture. The resultant mixture is now
- 8.125 mg of KI per 5 mL (teaspoon).
- Age-based dosing guidelines:
- Newborn to 1 month of age: 10 mL (2 teaspoons) 1 month to 3 years of age: 20 mL (4 teaspoons)

Guidance for home preparation of KI solution using 130 mg tablet

- 4 to 17 years of age: 40 mL (8 teaspoons)
- The mixture will keep for up to 1 week if refrigerated. Discard unused portion after one week and prepare a fresh mixture.

Reference: American Academy of Pediatrics Committee on Environmental Health. Policy statement. Radiation disasters and children. Pediatrics 2003; 111(6): 1455-66.

- – Alternatively, a stable aqueous iodine solution exists with a shelf-life of two years containing 5% iodine and 10% potassium iodide, equivalent to 130mg of iodine per mL, or 8 mg per drop.
- – A single dose is recommended unless other protective measures (evacuation, sheltering and control of the food supply) are unavailable.
- – Transient hypothyroidism has been observed in 0.37% of neonates treated with potassium iodide. Even transient hypothyroidism may have potential consequences for intellectual development. Therefore, thyroid function should be monitored in neonates 2 to 4 weeks later, as thyroid hormone replacement may be required.
- – Adverse effects include gastrointestinal disturbance, rashes, allergic reaction and thyroid function alterations (thyrotoxicosis, goitre, and hypothyroidism). Caution should be exercised in those who have multinoduar goitre, Grave's Disease, or autoimmune thyroiditis.
- – Contraindications: iodine allergy, dermatitis herpetiformis or hypocomplementemia vasculitis.
- For patients with iodine sensitivity, anti-thyroid medications can be used to block the uptake of radioiodines.

References

56. Agency for Toxic Substances and Disease Registry. Case studies in environmental medicine: radiation exposure from iodine 131. US Department of Health and Human Services. 2002. Available from: http://www.atsdr.cdc.gov/HEC/CSEM/
57. American Academy of Pediatrics Committee on Environmental Health. Policy statement. Radiation disasters and children. Pediatrics 2003; 111(6): 1455-66.
58. Armed Forces Radiobiology Research Institute. Medical management of radiological casualties handbook, military medical operations. 2nd ed. Bethesda: Armed Forces Radiobiology Research Institute; 2003
59. Center for Drug Evaluation and Research. Guidance potassium iodide as a thyroid blocking agent in radiation emergencies. U.S. Department of Health and Human Services Food and Drug Administration; 2001.

60. Centers for Disease Control and Prevention. Radiation emergencies radioisotope brief: iodine-131. Department of Health and Human Services, Centers for Disease Control and Prevention, 2004

61. International Atomic Energy Agency. Methods for assessing occupational radiation doses due to intakes of radionuclides, safety reports series, no. 37. Vienna: IAEA 2004

62. Marcus CS, California Disaster Medical Assistance Team-9, Western National Medical Response Team, Los Angeles County Department of Health Services Emergency Medical Services Agency. Administration of decorporation drugs to treat internal radionuclide contamination: medical emergency response to radiologic incidents. UCLA and Los Angeles County Department of Health Services.

63. Marcus CS, Siegel JA, Sparks RB. Medical management of internally radiocontaminated patients. Los Angeles County Department of Health Services, Emergency Medical Services Agency; 2006

64. MEDECOR PC: Medical decorporation PC [computer program]. Version 1.0. Ottawa: RadSci Research Inc., Defence R&D Canada; 2006. Available from: http://www.radsci.ca

65. Medical Preparedness and Response Sub-Group, Department of Homeland Security Working Group on Radiological Dispersal Device (RDD) Preparedness. Medical guidelines. United States Department of Homeland Security; 2003

66. National Council on Radiation Protection and Measurements. Management of persons accidentally contaminated with radionuclides, NCRP Report No. 65. Bethesda: National Council on Radiation Protection and Measurements; 1980.

67. Pacific Northwest National Laboratory. Methods and models of the Hanford internal dosimetry program, radiation and health technology. Richland, Washington: Pacific Northwest National Laboratory; 2003. Available from: http://www.pnl.gov/eshs/pub/pnnl552.html

68. Peterson J, MacDonell M, Haroun L, Monette F, Hildebrand RD, Taboas A. Radiological and chemical fact sheets to support health risk analyses for contaminated areas. Argonne National Laboratory Environmental Science Division and U.S. Department of Energy. 2007.

69. World Health Organization. Guidelines for iodine prophylaxis following nuclear accidents update. Geneva, World Health Organization 1999.

Iridium

Properties

- The isotope of concern is ^{192}Ir
- It is a shiny, silvery-white, dense metal
- Iridium is used in industrial radiography in the form of tiny seeds or pellets contained within steel capsules, and medical radiotherapy, in the form of wires introduced via catheters.
- It emits beta and gamma radiation
- The physical half-life is 74 days, and the effective half-life is 200 days.

Biokinetics

- Internal exposure would most likely occur by swallowing the pellets, which would not be absorbed.
- The pellets would be excreted intact in the faeces.
- The duration of exposure would be dependent on the transit time of the pellet through the gut.
- If disseminated in particulate form, the potential intake routes are inhalation, ingestion and via wounds. Two cases of inhalation of iridium occurred when a worker cut into eight iridium pellets encapsulated in steel.
- Following ingestion or inhalation, most iridium is excreted from the body in the faeces.
- Iridium is rapidly cleared from the lungs.
- About 1% is absorbed following ingestion.
- Of the absorbed iridium, 20% is immediately excreted, 20% is deposited in liver, 4% in kidneys, 2% in spleen, and the remaining 54% is distributed evenly throughout the other tissues.
- Of the deposited iridium, 20% is excreted with a tissue half-life of 8 days, and 80% is excreted with a biological half-life of 200 days.

Toxicity

- Localised burns to the gastrointestinal tract may result from ingestion of the pellets.
- Potential deterministic and stochastic health effects would be dependent on the activity of the ingested pellets and the duration of exposure.
- The target organs in particulate exposure are lung and liver.
- Exposure limits of 1 ALI are 3.6 x 10^{6}S Bq/year for inhalation, and 14 x 10^6 Bq/year for ingestion.

Assay techniques

- Whole body counts obtained using either sodium-iodide or germanium detectors are preferred.

Treatment

- None of the chelation agents are expected to be effective for iridium.

- Iridium is in Group VIII of the periodic table of elements. This is the same chemical group as elements such as iron, cobalt, and platinum.

- Penicillamine is used for the chelation of heavy metals such as copper, iron, lead, gold and others. It is estimated to increase urinary elimination of radionuclides by one third. It has theoretical value and would only be considered for very significant iridium exposures.

  – The adult dose is 250 mg 6 hourly, orally. This may be increased to 2 gm daily, in divided doses.

  – The paediatric dose is 20 to 30 mg/kg/day in divided doses.

  – Therapy needs to be administered promptly because the effectiveness of treatment decreases rapidly with increasing time post exposure.

  – Adverse effects occur in 25 to 63% of patients. These include leucopaenia, thrombocytopaenia, haemolytic anaemia, agranulocytosis, aplastic anaemia, thrombotic thrombocytopenic purpura, cholestatic hepatitis, nausea, vomiting, abdominal pain, pancreatitis, myasthenia gravis, sensory and motor neuropathy, breast enlargement in males and females, nephrotic syndrome, Goodpasture's syndrome and obliterative bronchiolitis. Death has occurred. The risk of toxicity is increased at higher doses and with prolonged therapy.

  – Hypersensitivity effects include urticaria, rash, pruritis, fever, haematuria, proteinuria, eosinophilia, erythema multiforme, and autoimmune bullous formations.

  – Contraindications: renal failure, lupus erythematosus, penicillin allergy and pregnancy. Developmental connective tissue anomalies were noted in 8 out of 100 pregnancies.

  – Monitor blood cell counts and urinalysis closely during therapy.

References

70. Centers for Disease Control and Prevention. Radiation emergencies radioisotope brief: iridium-192 (Ir-192). Department of Health and Human Services, Centers for Disease Control and Prevention, 2004
71. Iridium Radioactive. In: Hazardous Substances Data Bank [online database]. National Library of Medicine TOXNET system; 2008. Available from: http://toxnet.nlm.nih.gov.
72. Nuclide Safety Data Sheet Iridium-192; www.nchps.org (accessed 15.07.2008)
73. Peterson J, MacDonell M, Haroun L, Monette F, Hildebrand RD, Taboas A. Radiological and chemical fact sheets to support health risk analyses for contaminated areas. Argonne National Laboratory Environmental Science Division and U.S. Department of Energy. 2007.

Plutonium

Properties

- The isotopes of concern are ^{238}Pu, ^{239}Pu, ^{240}Pu, ^{241}Pu and ^{242}Pu.

- Plutonium is usually found as a mixture of isotopes. Knowledge of the isotopic composition is required for accurate dose estimation.

- Plutonium is produced from uranium in nuclear reactors, and used in satellite power generation and nuclear weapons.

- It is a silvery metal which yellows on exposure to air. It forms compounds with various chemicals.

- It emits alpha radiation. As it is invariably accompanied by Americium, a daughter product, some weak gamma radiation will also be detectable. ^{241}Pu emits beta radiation.

- The physical half-life is 88 years for ^{238}Pu, 2.4×10^4 years for ^{239}Pu and 6564 years for ^{240}Pu. The effective half- life is 63 years for ^{238}Pu, and 197 years for ^{239}Pu.

Biokinetics

- Insoluble particles are retained in the lungs and will cause local irradiation. Plutonium oxide particles accumulate in tracheobronchial lymph nodes, and peribronchiolar and subpleural regions of the lung.

- Absorption following inhalation or ingestion is dependent on the chemical form of plutonium. Plutonium oxides belong to class Y, and all other plutonium chemical forms belong to class W.

- The gastrointestinal absorption fraction of plutonium ranges from 10^{-5} to 5×10^{-4}

- Wound absorption is variable.

- Once absorbed, 45% is deposited in bones with a clearance half-life of 50 years, and 45% in liver with a clearance half-life of 20 years. A tiny amount is deposited in the gonads. 10% is excreted.

- Plutonium is excreted into bile from the liver; however clearance from the respiratory tract dominates the faecal burden in inhalational exposures for a prolonged time. Following ingestion, it will be detectable in faeces after 24 hours, but not in urine for two weeks.

Toxicity

- The main form of toxicity from inhalation is radiation pneumonitis (early) or pulmonary fibrosis (late). Radiation pneumonitis is seen at a dose of 5 to 15 Gy.

- The target organ following absorption is bone.

- Lung, bone and liver cancers are seen with a latent period of 10 to 15 years.

- Fibrous nodules may develop in contaminated wounds.

- The exposure limits for 1 ALI are 300WY Bq/year for inhalation and 3×10^4 Bq/year for ingestion.

Assay techniques

- Initial measurements may not rule out the possibility of an acute intake, and follow-up measurements will be required.

- Nasal swabs may revert to background within 30 minutes of collection.

- Special low energy gamma detectors are required for counts from chest, skeleton, liver or wounds.

  – Interpretation of chest counts needs to be corrected for chest wall thickness.

- 24-hour urine samples should be collected immediately, 10 and 100 days post-exposure.

  – Exercise particular caution during urine collection. Trace amounts of external contamination, below the threshold of detection, can transfer to collected urine and interfere with the extremely sensitive urine analysis.

  – Urine analysis involves chemical separation, followed by quantitative alpha spectrometry.

- Faecal samples are of particular value following inhalation and ingestion in confirming and evaluating exposure.

Treatment

- Chelation is not required at < 1 ALI. It should be considered from 2–10 ALI, and is recommended at > 10 ALI. DTPA is the agent of choice.

  – Chelation with these agents is only effective for the soluble form of the target metal.

  – Effectiveness is best within 6 hours of exposure, although therapy may extend to years.

  – Ca-DTPA has ten-fold greater efficacy than Zn-DTPA in the first 24 hours and should be used initially unless there are contraindications. Zn-DTPA is as efficacious as Ca-DTPA after the initial 24 hours, and better tolerated.

  – Inhaled DTPA therapy is believed to be more effective than intravenous therapy for inhalational plutonium exposures.

    - Nebulised, 1gm in a 4 mL ampoule, 1:1 dilution with saline or sterile water, over 30 minutes.

  – Slow intravenous push or infusion initially with Ca-DTPA on the first day, then Zn-DTPA on subsequent days. 1 gm in 250 mL normal saline or 5% dextrose over 1 hour, once daily. The dose must not be fractionated.

    - The paediatric dose is 14 mg/kg of Zn-DTPA, not to exceed 1 gm daily.

  – Effectiveness in enhancing excretion should be monitored with follow-up urine samples. Decisions regarding continuation of chelation therapy should be based on these results.

  – Adverse effects occur as a result of chelation of other metallic cations such as zinc, manganese and other trace elements. Side effects include nausea, vomiting, diarrhoea, fever, chills, muscle cramps, pruritis and anosmia. Consider zinc replacement therapy in prolonged treatment.

  – Inhaled chelation therapy may exacerbate asthma.

  – Obtain a urinalysis prior to, and monitor blood pressure during each administration of the drug.

- Discontinue therapy if diarrhoea or abnormalities of urinalysis (proteinuria, haematuria, or casts) occur.
- Ca-DTPA is contraindicated in pregnancy and children, as well as nephritic syndrome or bone marrow suppression. Zn-DTPA can be safely administered in pregnancy (Class C drug) and children.
- Desferrioxamine may be used initially if DTPA is unavailable.
- Initial dose 15 to 25 mg/kg/hour intravenously. The duration of therapy is dependent on the total body burden of plutonium.
- Adverse effects: Hypotension is related to the rate of administration. A reversible, dose-dependent pulmonary syndrome with features of hypoxia, hypocapnia and bilateral interstitial infiltrates occurs with desferroxamine. Sensorimotor neuropathy, ocular and oto-toxicity are seen with chronic use. Hypersensitivity reactions also occur.
- Contraindications: Class C drug in pregnancy. There are no known reports of teratogenicity in humans.

- Bronchoalveolar lavage with DTPA in the lavage fluid has been described in beagles.

- Early excision is recommended for contaminated wounds.

References

74. Armed Forces Radiobiology Research Institute. Medical management of radiological casualties handbook, military medical operations. 2nd ed. Bethesda: Armed Forces Radiobiology Research Institute; 2003.
75. Centers for Disease Control and Prevention. Radiation emergencies radioisotope brief: plutonium. Department of Health and Human Services, Centers for Disease Control and Prevention; 2005.
76. Dart RC, editor. Medical toxicology. 3rd ed. Lippincott, Williams & Wilkins; 2004.
77. International Atomic Energy Agency. Methods for assessing occupational radiation doses due to intakes of radionuclides, safety reports series, no. 37. Vienna: IAEA; 2004.
78. Marcus CS, California Disaster Medical Assistance Team-9, Western National Medical Response Team, Los Angeles County Department of Health Services Emergency Medical Services Agency. Administration of decorporation drugs to treat internal radionuclide contamination: medical emergency response to radiologic incidents. UCLA and Los Angeles County Department of Health Services.
79. Marcus CS, Siegel JA, Sparks RB. Medical management of internally radiocontaminated patients. Los Angeles County Department of Health Services, Emergency Medical Services Agency; 2006.
80. MEDECOR PC: Medical decorporation PC [computer program]. Version 1.0. Ottawa: RadSci Research Inc., Defence R&D Canada; 2006. Available from: http://www.radsci.ca
81. Medical Preparedness and Response Sub-Group, Department of Homeland Security Working Group on Radiological Dispersal Device (RDD) Preparedness. Medical guidelines. United States Department of Homeland Security; 2003.
82. National Council on Radiation Protection and Measurements. Alpha-emitting particles in lungs, NCRP Report No. 46. Bethesda: National Council on Radiation Protection and Measurements; 1975.

83. National Council on Radiation Protection and Measurements. Management of persons accidentally contaminated with radionuclides, NCRP Report No. 65. Bethesda: National Council on Radiation Protection and Measurements; 1980.

84. NDA 21-749 Pentetate calcium trisodium injection product information. Hameln Pharmaceuticals GmbH.

85. NDA 21-751 Pentetate zinc trisodium injection product information. Hameln Pharmaceuticals GmbH.

86. Pacific Northwest National Laboratory. Methods and models of the Hanford internal dosimetry program, radiation and health technology. Richland, Washington: Pacific Northwest National Laboratory; 2003. Available from: http://www.pnl.gov/eshs/pub/pnnl552.html

87. Peterson J, MacDonell M, Haroun L, Monette F, Hildebrand RD, Taboas A. Radiological and chemical fact sheets to support health risk analyses for contaminated areas. Argonne National Laboratory Environmental Science Division and U.S. Department of Energy; 2007.

Polonium

Properties

- The isotope of concern is ^{210}Po.
- It is a naturally occurring decay product of radium, found in uranium-bearing soils.
- Polonium is a low-melting, fairly volatile metal.
- It is present in tobacco, leading to smokers having relatively higher background levels of polonium.
- It is used in devices designed to eliminate static electricity, and brushes to remove dust from films and camera lenses.
- It emits alpha radiation
- The physical half-life is 138 days, and the effective half-life is 50 days.

Biokinetics

- Ingested polonium is more readily absorbed than other alpha-emitters. Absorption is dependent on the chemical form of polonium. Low pH enhances solubility and significant amounts of polonium are absorbed in the stomach. In the intestine, polonium adheres to the mucosa rather than being absorbed. 10 to 50% is absorbed from the GI tract. The balance is excreted promptly in the faeces.
- Absorption of polonium via inhalation occurs relatively slowly, as a class M agent.
- Some chemical forms of polonium, such as polonium chloride, can be absorbed through intact skin, at rates of less than 2% per day.
- The metabolism of polonium has similarities to sulphur, with affinity for selected amino acids and proteins.
- Red blood cells accumulate polonium at 20 times the concentration in plasma. These then deposit in the reticuloendothelial system preferentially.
- Following absorption, polonium is distributed 30% to liver, 10% to kidneys, 10% to bone marrow, 5% to spleen and 45% to all other tissues, including mucous membranes, intestinal epithelium, hair follicles, tear and mammary glands.
- It is excreted into the bile by the liver.
- There is 33% excretion via urine, and 67% via faeces

Toxicity

- An ingestion intake of 1µg of ^{210}Po may be lethal.
- Acute radiation syndrome prodromal symptoms occurring within a few days of intake suggest a potentially lethal exposure.
- Radiation doses to liver, spleen and kidneys are significantly higher than doses to bone marrow and intestines, leading to severe injury to these organs occurring in association with features of acute radiation syndrome.

- Animal data suggests that death is due to multiple organ failure at lower intakes, compared with deterministic effects at higher intakes. See the table below.

- Characteristic changes include bone marrow failure, kidney and hepatic injury, damage to gut mucosa, erythema and epilation of the skin

- The exposure limits for 1 ALI are 2×10^4D and 1×10^4W Bq/year for inhalation, and 9×10^4 Bq/year for ingestion.

Table 2 Expected toxicity of [210]Po to humans, based on animal data and the HF model

Systemic burden range (MBq/kg- body- mass)	Central estimate of the risk (%) of death from deterministic effects	Expected survival time (days)	Expected histopathology	Expected haematological effects
> 1	100	1–28	Massive, rapidly occurring damage to the kidney and other organs, including bone marrow	Severe loss of lymphocytes, WBC, RBC and haemoglobin
0.4–1	100	50–250	Rapidly occurring damage to the kidney and likely damage to other organs including bone marrow	Moderate to severe loss of lymphocytes, WBC; declines in RBC and haemoglobin at time of death
0.03–0.3	1–100	300–500	Slowly occurring damage to kidney and likely damage to other organs including bone marrow	Early WBC reduction followed by recovery; possibly delayed recovery since high- LET radiation is involved
0–0.2	< 1	Normal lifespan for most	Mild lesions in kidney and possibly other organs; cancers and life-shortening possible	Minor effects if any

Reference: Scott BR. Health risk evaluations for ingestion exposure of humans to polonium-210. Dose-Response 2007; 5:94-122

Assay techniques

- Analysis of 24 hour urine and faeces samples requires chemical separation and alpha spectrometry.
  - Owing to naturally occurring polonium in the diet, background levels of 5 to 15 mBq will be found in most people.

Treatment

- Aluminium hydroxide 100 mL orally may result in minor reduction of gastrointestinal absorption.
- There are a number of alternative decorporation therapies suggested.
  - DMSA (Succimer). The effective dose for polonium is unknown. The following is the dosage schedule for lead poisoning.
    - 10 mg/kg (or 350 mg/m^2) 8 hourly orally for 5 days, then 12 hourly for 14 days
    - 2 week intervals between courses
    - Adverse effects are generally mild and self-limiting: gastrointestinal discomfort, rash, eosinophilia and elevated transaminases. Haemolysis has been reported in a patient with glucose-6-phosphate dehydrogenase (G6PD) deficiency.
    - Monitor liver function tests at least weekly
  - DMPS is a water soluble analogue of dimercaprol. It is intermediate in efficacy and toxicity between DMSA and dimercaprol. It has been demonstrated to increase excretion of polonium.
    - 300 mg orally, or intravenously by slow push, every 3 to 5 hours, reducing to 8 to 12 hourly
    - Hypotension may be seen with an intravenous bolus. Rash, fever and elevation of transaminases may occur. Bodily fluids may develop a sulphur-like odour. Erythema multiforme has been reported to occur rarely.
  - Dimercaprol (BAL, British Anti Lewisite) is the most toxic of currently available chelating agents. It may be necessary to begin therapy with this parenteral agent, if the patient is vomiting.
    - 2.5 to 5.0 mg/kg intramuscularly 4 hourly for 48 hours, then reduce to 2.5 to 3.0 mg/kg
    - 6 hourly for days 3 & 4, and 2.5 to 3.0 mg/kg 12 hourly from days 5 to 10.
    - 50% of patients experience adverse effects including hypertension, tachycardia, oral burning sensation, nausea, vomiting, abdominal pain, chest pain, headache, sweating, lacrimation, rhinorrhoea, salivation, myalgia, and pain and sterile abscess at the injection site. Fever, convulsions and coma have occurred. Toxicity is dose dependent. Therapy should be undertaken in an intensive care setting because of the toxicity of dimercaprol.
    - Nephrotoxicity is seen due to dissociation of the dimercaprol-metal complex in acid urine. Alkalinise urine prior to commencing therapy in order to minimise this risk.
    - Monitor for signs of allergy: hypotension, urticaria, hyperpyrexia
    - It is formulated in peanut oil, and therefore contraindicated in nut allergy.
    - It is contraindicated in liver disease, and may cause haemolysis in patients with glucose-6-phosphate dehydrogenase (G6PD) deficiency
  - Penicillamine is estimated to increase urinary elimination of radionuclides by one third.

- The adult dose is 250 mg 6 hourly, orally. This may be increased to 2 gm daily, in divided doses.
- The paediatric dose is 20 to 30 mg/kg/day in divided doses.
- Therapy needs to be administered promptly because the effectiveness of treatment decreases rapidly with increasing time post exposure.
- Adverse effects occur in 25 to 63% of patients. These include leucopaenia, thrombocytopaenia, haemolytic anaemia, agranulocytosis, aplastic anaemia, thrombotic thrombocytopaenic purpura, cholestatic hepatitis, nausea, vomiting, abdominal pain, pancreatitis, myasthenia gravis, sensory and motor neuropathy, breast enlargement in males and females, nephrotic syndrome, Goodpasture's syndrome and obliterative bronchiolitis. Death has occurred. The risk of toxicity is increased at higher doses and with prolonged therapy.
- Hypersensitivity effects include urticaria, rash, pruritis, fever, haematuria, proteinuria, eosinophilia, erythema multiforme, and autoimmune bullous formations.
- Contraindications: renal failure, lupus erythematosus, penicillin allergy and pregnancy. Developmental connective tissue anomalies were noted in 8 out of 100 pregnancies.
- Monitor blood cell counts and urinalysis closely during therapy.

References

88. Centers for Disease Control and Prevention. Guidance for public health departments and clinicians caring for individuals who may have been recently exposed to polonium 210 (Po-210). Department of Health and Human Services, Centers for Disease Control and Prevention; 2006.
89. Dart RC, editor. Medical toxicology. 3rd ed. Lippincott, Williams & Wilkins; 2004.
90. Harrison J, Leggett R, Lloyd D, Phipps A, Scott B. Polonium-210 as a poison. J Radiol Prot 2007; 27: 17-40
91. Health Physics Society. Polonium-210 information sheet. McLean, VA: Health Physics Society. Available from: http://www/hps.org
92. Health Protection Agency. Method for the assessment of polonium-210 in urine being used by HPA for the UK Po-210 incident. Po-210 in urine method. Version 1.2. U.K. Health Protection Agency; 2006. Available from: http://www.hpa.org.uk/polonium/measurement_Po210_in_urine.pdf
93. International Atomic Energy Agency. Methods for assessing occupational radiation doses due to intakes of radionuclides, safety reports series, no. 37. Vienna: IAEA 2004
94. Marcus CS, California Disaster Medical Assistance Team-9, Western National Medical Response Team, Los Angeles County Department of Health Services Emergency Medical Services Agency. Administration of decorporation drugs to treat internal radionuclide contamination: medical emergency response to radiologic incidents. UCLA and Los Angeles County Department of Health Services
95. Marcus CS, Siegel JA, Sparks RB. Medical management of internally radiocontaminated patients. Los Angeles County Department of Health Services, Emergency Medical Services Agency; 2006
96. MEDECOR PC: Medical decorporation PC [computer program]. Version 1.0. Ottawa: RadSci Research Inc., Defence R&D Canada; 2006. Available from: http://www.radsci.ca

97. Murray L, Daly F, Little M, Cadogan M, editors. Toxicology handbook. Elsevier Australia. 2007 104.National Council on Radiation Protection and Measurements. Management of persons accidentally

98. contaminated with radionuclides, NCRP Report No. 65. Bethesda: National Council on Radiation Protection and Measurements; 1980.

99. Peterson J, MacDonell M, Haroun L, Monette F, Hildebrand RD, Taboas A. Radiological and chemical fact sheets to support health risk analyses for contaminated areas. Argonne National Laboratory Environmental Science Division and U.S. Department of Energy. 2007.

100. Radioaction Info. In: POISINDEX® System [internet database]. Greenwood Village, Colo: Thomson Healthcare. 2008; 137

101. Scott BR. Health risk evaluations for ingestion exposure of humans to polonium-210. Dose-Response 2007; 5:94-122.

102. United States Nuclear Regulatory Commission. Fact sheet polonium-210. United States Nuclear Regulatory Commission; 2006

Radium

Properties

- The isotope of concern is ^{226}Ra.
- It is a naturally occurring silvery-white radioactive metal formed from decay of uranium and thorium, found in all soil, water, plants and animals.
- It may be found in equipment from the former Soviet Union, on instrument dials, and in older medical equipment, as well as in uranium processing wastes.
- Radium emits alpha radiation. Daughter products emit beta and gamma radiation.
- The physical half-life is 1600 years and the effective half-life is 44 years.

Biokinetics

- Inhaled radium can remain in the lungs for several months, prior to gradual absorption.
- 20 to 30% is absorbed from the gastrointestinal tract.
- It is metabolised as a calcium analogue and widely distributed throughout the body.
- Radium is preferentially deposited in bones and teeth.
- Of deposited radium, 90% will be cleared from bone within a few months, and 99% within a few years. However a portion will remain in the skeleton throughout an individual's lifetime.

Toxicity

- The target organ is bone.
- Long-term exposure is associated with leukaemia, aplastic anaemia and sarcomas. Breast and liver cancers are also seen.
- The minimum latent period for sarcoma development is 7 years.
- The exposure limits for radium are 9000 Bq/year for inhalation, and 9×10^4 for ingestion.

Assay techniques

- Nasal swabs, and urine & faeces samples are the best way to detect radium.
- Whole body counts will detect associated daughter products.
- Breath tests measuring exhaled radon can be used.

Treatment

- No therapy has proven useful once absorption has occurred.
- Alginates (Gaviscon®) may reduce absorption.
  - 100 ml single dose orally
- Oral calcium may provide competitive inhibition for uptake from the GI tract and deposition to bone.
  - 1 to 2 gm 6 hourly

- Ammonium chloride and intravenous calcium gluconate may increase urinary excretion slightly.
  – Ammonium chloride 1 to 2 gm 6 hourly orally for up to six days
  – Adverse effects include nausea, vomiting and gastric irritation
  – Contraindications: severe liver disease, metabolic acidosis, uric lithiasis, or renal failure
- Calcium gluconate
  – 2.5 gm in 500mL 5% dextrose solution intravenously, over 4 hours, repeated for 6 days
  – Contraindications: bradycardia, digoxin or quinidine therapy

References

103. Agency for Toxic Substances and Disease Registry. Radium ToxFAQs. US Department of Health and Human Services. 1999.
104. Armed Forces Radiobiology Research Institute. Medical management of radiological casualties handbook, military medical operations. 2nd ed. Bethesda: Armed Forces Radiobiology Research Institute; 2003
105. International Atomic Energy Agency. Methods for assessing occupational radiation doses due to intakes of radionuclides, safety reports series, no. 37. Vienna: IAEA 2004
106. Marcus CS, California Disaster Medical Assistance Team-9, Western National Medical Response Team, Los Angeles County Department of Health Services Emergency Medical Services Agency. Administration of decorporation drugs to treat internal radionuclide contamination: medical emergency response to radiologic incidents. UCLA and Los Angeles County Department of Health Services.
107. Marcus CS, Siegel JA, Sparks RB. Medical management of internally radiocontaminated patients. Los Angeles County Department of Health Services, Emergency Medical Services Agency; 2006
108. MEDECOR PC: Medical decorporation PC [computer program]. Version 1.0. Ottawa: RadSci Research Inc., Defence R&D Canada; 2006. Available from: http://www.radsci.ca
109. Medical Preparedness and Response Sub-Group, Department of Homeland Security Working Group on Radiological Dispersal Device (RDD) Preparedness. Medical guidelines. United States Department of Homeland Security; 2003
110. National Council on Radiation Protection and Measurements. Management of persons accidentally contaminated with radionuclides, NCRP Report No. 65. Bethesda: National Council on Radiation Protection and Measurements; 1980.
111. Pacific Northwest National Laboratory. Methods and models of the Hanford internal dosimetry program, radiation and health technology. Richland, Washington: Pacific Northwest National Laboratory; 2003. Available from: http://www.pnl.gov/eshs/pub/pnnl552.html
112. Peterson J, MacDonell M, Haroun L, Monette F, Hildebrand RD, Taboas A. Radiological and chemical fact sheets to support health risk analyses for contaminated areas. Argonne National Laboratory Environmental Science Division and U.S. Department of Energy. 2007.

Strontium

Properties

- The isotope of concern is ^{90}Sr.
- It is a soft silvery gray metal, which yellows on exposure to air.
- It is used in power generation, industrial gauges, and cancer therapy. It is also a nuclear waste product.
- Emits beta irradiation
- The daughter product of ^{90}Sr is ^{90}Y (Yttrium-90, half-life 64 hours), with which it is in equilibrium, however this does not meaningfully interfere with assays or treatment.
- Environmental ^{90}Sr, from natural sources and above-ground weapons testing, is present in food. Hence, extremely low levels of ^{90}Sr can be detected routinely on bioassay.
- The physical half-life is 28 years, and the effective half-life is 15 years

Biokinetics

- 100% absorbed from the respiratory tract within days
- 30% absorbed from the gastrointestinal tract. The amount absorbed in children less than 1 year of age is 60%. Fasting and low calcium diets increase gastrointestinal absorption.
- 100% is absorbed via open wounds
- Metabolised as a calcium analogue
- Up to 50% of an absorbed dose deposits in bone. It is assumed to be evenly distributed across the total bone mass, where it is retained and internally recycled
- Of the excreted portion of ^{90}Sr, 80% is excreted by the urinary system, and 20% via the faeces

Toxicity

- Incorporation of strontium into bones and teeth can result in tumours of bone, bone marrow and soft tissues surrounding bone.
- The exposure limits for 1 ALI are 4 x 10^5D & 6 x 10^4Y Bq/year for inhalation, and 6 x 10^5D & 5 x 10^6Y Bq/year for ingestion.

Assay techniques

- standard bioassay technique for ^{90}Sr is 24 hour urine excretion. In general a sample within the first two days is less reliable than a sample collected after several days or weeks.
- The lack of any readily detectable gamma emissions makes in vivo detection using whole body counting somewhat ineffective.
- Faecal samples are not warranted because of the high degree of absorption, and the ease of urine assays.

Treatment

- Immediately following ingestion, use of aluminium phosphate gel (or aluminium containing antacids) or sodium alginate (Gaviscon®) can reduce absorption by up to 85%.
  - The dose is 100 mL orally stat, and 40 mL 2 hourly.
- Administration of oral calcium supplementation 1 to 2 gm 6 hourly will compete with the ^{90}Sr for deposition in bone.
- Use of ammonium chloride to acidify urine will increase excretion, especially combined with intravenous calcium gluconate. If used promptly, radiostrontium levels can diminish by up to 40 to 75%. Some benefit is still obtained for up to 2 weeks following exposure to radiostrontium.
  - Ammonium chloride 1 to 2 gm 6 hourly orally for up to six days
  - Adverse effects include nausea, vomiting and gastric irritation
  - Contraindication: severe liver disease, metabolic acidosis, uric lithiasis, or renal failure
- Calcium gluconate
  - 2.5 gm in 500mL 5% dextrose solution intravenously, over 4 hours, repeated for 6 days
  - Adverse effects such as transient hypercalcaemia, vasodilation, hypotension, dysrhythmias, syncope or cardiac arrest due to rapid over-administration are unlikely to be seen if the infusion rate above is followed.
  - Contraindications: bradycardia, digoxin or quinidine therapy.
  - Monitor the ECG during administration of intravenous calcium.

References

113. Armed Forces Radiobiology Research Institute. Medical management of radiological casualties handbook, military medical operations. 2nd ed. Bethesda: Armed Forces Radiobiology Research Institute; 2003

114. Centers for Disease Control and Prevention. Radiation emergencies radioisotope brief: strontium.

115. Department of Health and Human Services, Centers for Disease Control and Prevention; 2004. 121.International Atomic Energy Agency. Methods for assessing occupational radiation doses due to intakes of radionuclides, safety reports series, no. 37. Vienna: IAEA; 2004.

116. Marcus CS, California Disaster Medical Assistance Team-9, Western National Medical Response Team, Los Angeles County Department of Health Services Emergency Medical Services Agency. Administration of decorporation drugs to treat internal radionuclide contamination: medical emergency response to radiologic incidents. UCLA and Los Angeles County Department of Health Services.

117. Marcus CS, Siegel JA, Sparks RB. Medical management of internally radiocontaminated patients. Los Angeles County Department of Health Services, Emergency Medical Services Agency; 2006.

118. MEDECOR PC: Medical decorporation PC [computer program]. Version 1.0. Ottawa: RadSci Research Inc., Defence R&D Canada; 2006. Available from: http://www.radsci.ca

119. Medical Preparedness and Response Sub-Group, Department of Homeland Security Working Group on Radiological Dispersal Device (RDD) Preparedness. Medical guidelines. United States Department of Homeland Security; 2003.

120. Murray L, Daly F, Little M, Cadogan M, editors. Toxicology handbook. Elsevier Australia; 2007. 127.National Council on Radiation Protection and Measurements. Management of persons accidentally

121. contaminated with radionuclides, NCRP Report No. 65. Bethesda: National Council on Radiation Protection and Measurements; 1980.

122. Pacific Northwest National Laboratory. Methods and models of the Hanford internal dosimetry program, radiation and health technology. Richland, Washington: Pacific Northwest National Laboratory; 2003. Available from: http://www.pnl.gov/eshs/pub/pnnl552.html

123. Peterson J, MacDonell M, Haroun L, Monette F, Hildebrand RD, Taboas A. Radiological and chemical fact sheets to support health risk analyses for contaminated areas. Argonne National Laboratory Environmental Science Division and U.S. Department of Energy; 2007.

Uranium

Properties

- Isotopes of uranium include ^{233}U, ^{234}U, ^{235}U, ^{236}U, ^{238}U, and ^{239}U
- Uranium is a weakly radioactive, extremely dense, silver-coloured metal
- Uranium is found as depleted uranium, natural uranium, fuel rods and weapons-grade material.
- Depleted uranium and natural uranium do not represent any significant irradiation hazard
- Uranium and its daughters emit alpha, beta and gamma radiation
- If sufficient enriched uranium is placed together, a criticality event may occur emitting lethal amounts of radiation.
- Natural uranium is widespread in the environment, occurring in rocks, soil, water, air, plants and animals. Hence, extremely low levels can be detected routinely on bioassay (urine 0.05 to 0.5µg/day, faeces 1.4 to 1.8µg/day)
- The physical half-life is 4.5 x 10^9 years for ^{238}U and 7.1 x 10^8 years for ^{235}U. The effective half-life is 14 days.

Biokinetics

- Absorption of uranium is low by all exposure routes, but relatively more is absorbed via inhalation than from the gastrointestinal tract.
- Several compounds of uranium are also rapidly absorbed via the eyes.
- Uranium deposited in the alveoli can persist for years.
- Fasting enhances gastrointestinal absorption. However the rate of absorption is low, from 0.1 to 6%. Soluble salts of uranium are more readily absorbed. The metal is not.
- Following absorption 20% is distributed to bone, 12% to kidneys and 12% to all other tissues.
- The remaining 56% is excreted via urine.
- The clearance half-life is up to 5000 days for bone, and 1500 days for kidneys.

Toxicity

- The chemical toxicity of soluble forms of uranium is a greater concern than the radiation dose. The renal toxicity of uranium varies with the chemical form, and increases with the solubility.
- Uranium damages the renal proximal convoluted tubules. Urinary levels > 0.1mg/L are nephrotoxic, and 20mg/L is potentially life-threatening
- Urinary function should be monitored at levels > 2mg/L
- Symptoms of exposure may include nausea, vomiting, abdominal cramping and diarrhoea. Renal failure, anaemia, rhabdomyolysis, myocarditis, liver impairment, coagulopathy and ileus have been described following uranium acetate ingestion.
- Pulmonary injury may occur following exposure to insoluble reactive forms of uranium compounds.
- Osteosarcoma is known to occur.

- The exposure limits for 1 ALI for ^{238}U are 9 x 10^{4}D Bq/year, 1 x 10^{4}W & 600Y Bq/year for inhalation and 8 x 10^{5}D Bq/year & 3 x 10^6 Bq/year for ingestion. The exposure limits for ^{233}U and ^{235}U are of the same order of magnitude.

Assay techniques

- The selection of assay techniques is dependent on the chemical form of uranium and the route of exposure.
  - For soluble forms, assay urine to determine renal burden
  - For less soluble forms, assay faeces early and perform lung counts
  - If there is a mixture, or the form is unknown, assay urine and faeces, as well as perform lung counts.
- Urine analysis is an indicator of systemically deposited uranium.
  - Urine samples can be analysed using elemental mass or alpha radioactivity measurements.
  - Samples collected after the first 24 hours have elapsed, best reflect the systemically deposited uranium.
- In vivo measurement of lung counts correlates with respiratory system deposition following inhalation, by measurement of photon emissions from chest counting with a low-energy planar germanium detector.
  - For depleted and natural uranium, the measurement of ^{234}Th (Thorium-234), a daughter product, will confirm the deposition of uranium in the respiratory system.
- Faecal assay is an indicator of uranium being cleared from the lung, and as a measure of insoluble forms that have been ingested.

Treatment

- If either the threshold for toxicity or a committed effective dose of 1mSv is exceeded the following should be considered:
  - GI tract absorbents
  - Chelation with Ca or Zn DTPA is only effective if administered in the initial 4 hours. As this is realistically unlikely, dosage will not be discussed here.
  - Oral or intravenous administration of sodium bicarbonate converts uranium to uranyl bicarbonate in alkaline urine, which is more readily excreted.
  - Oral therapy with 4 g initially, then 2 g every 4 hours (paediatric dosage 84–840 mg/kg/day in divided doses); or
    - Intravenous therapy: Commence with a bolus of 1–2 mmol/kg, then infuse 100mmol in 1 litre 5% dextrose @ 250 ml/hour until a urine pH of 8 is achieved and maintained. 20 mmol of potassium chloride may be added to the infusion to maintain normokalaemia.
    - Paediatric infusion rate is twice maintenance fluid rates.
    - Titrate the dose to alkalinize the urine.
    - Beware of fluid overload, hypernatraemia, hyperosmolality, and hypokalaemia.
    - Significant alkalosis will depress cardiac function.

- Contraindications: renal failure, severe hypernatraemia, hypokalaemia, metabolic or respiratory alkalosis, poorly controlled cardiac failure, acute pulmonary oedema.
- Monitor serum bicarbonate and potassium at least 4 hourly.

    - Tubular diuretics may be helpful

References

124. Armed Forces Radiobiology Research Institute. Medical management of radiological casualties handbook, military medical operations. 2nd ed. Bethesda: Armed Forces Radiobiology Research Institute; 2003.
125. Centers for Disease Control and Prevention. Radiation emergencies radioisotope brief: uranium. Department of Health and Human Services, Centers for Disease Control and Prevention; 2004.
126. Dart RC, editor. Medical toxicology. 3rd ed. Lippincott, Williams & Wilkins; 2004. 133.International Atomic Energy Agency. Methods for assessing occupational radiation doses due to intakes of radionuclides, safety reports series, no. 37. Vienna: IAEA; 2004.
127. Marcus CS, California Disaster Medical Assistance Team-9, Western National Medical Response Team, Los Angeles County Department of Health Services Emergency Medical Services Agency. Administration of decorporation drugs to treat internal radionuclide contamination: medical emergency response to radiologic incidents. UCLA and Los Angeles County Department of Health Services.
128. Marcus CS, Siegel JA, Sparks RB. Medical management of internally radiocontaminated patients. Los Angeles County Department of Health Services, Emergency Medical Services Agency; 2006.
129. MEDECOR PC: Medical decorporation PC [computer program]. Version 1.0. Ottawa: RadSci Research Inc., Defence R&D Canada; 2006. Available from: http://www.radsci.ca
130. Medical Preparedness and Response Sub-Group, Department of Homeland Security Working Group on Radiological Dispersal Device (RDD) Preparedness. Medical guidelines. United States Department of Homeland Security; 2003.
131. Murray L, Daly F, Little M, Cadogan M. Toxicology Handbook. Elsevier Australia; 2007. 139.National Council on Radiation Protection and Measurements. Management of persons accidentally contaminated with radionuclides, NCRP Report No. 65. Bethesda: National Council on Radiation Protection and Measurements; 1980.
132. Pacific Northwest National Laboratory. Methods and models of the Hanford internal dosimetry program, radiation and health technology. Richland, Washington: Pacific Northwest National Laboratory; 2003. Available from: http://www.pnl.gov/eshs/pub/pnnl552.html
133. Peterson J, MacDonell M, Haroun L, Monette F, Hildebrand RD, Taboas A. Radiological and chemical fact sheets to support health risk analyses for contaminated areas. Argonne National Laboratory Environmental Science Division and U.S. Department of Energy. 2007.

Acute radiation syndrome

Exposure to high levels of penetrating radiation can involve the whole body (uniformly or non-uniformly), a significant portion of the body, or a small, localised part. The exposure can be acute, protracted, or fractionated (in divided doses) over time.

Acute radiation syndrome (ARS) is an acute illness caused by irradiation of the whole body (or a significant portion of it). It follows a somewhat predictable course and is characterised by signs and symptoms that are manifestations of cellular deficiencies and the reactions of various cells, tissues, and organ systems to ionising radiation.

Immediate, overt manifestations of the acute radiation syndrome require a large (i.e., at least a few grays (Gy), usually whole-body) dose of penetrating radiation delivered over a short period of time. Penetrating radiation comes from a radioactive source or machine that emits gamma rays, X-rays, or neutrons. Acute radiation syndrome may also be rarely seen with extremely high levels of internal contamination. The signs and symptoms of this syndrome are non-specific and may be indistinguishable from those of other injuries or illness.

The ARS is characterised by four distinct phases: a prodromal period, a latent period, a period of illness, and one of recovery or death. During the prodromal period patients might experience loss of appetite, nausea, vomiting, fatigue, and diarrhoea; after extremely high doses, additional symptoms such as fever, prostration, respiratory distress, and hyperexcitability can occur. However, all of these symptoms usually disappear in a day or two, and a symptom-free, latent period follows, varying in length depending upon the size of the radiation dose. A period of overt illness follows, and can be characterised by infection, electrolyte imbalance, diarrhoea, bleeding, cardiovascular collapse, and sometimes short periods of unconsciousness. Death or a period of recovery follows the period of overt illness.

In general, the higher the dose the greater the severity of early effects and the greater the possibility of late effects.

Depending on dose, the following syndromes can be manifest:

- **Haematopoietic syndrome** – characterised by deficiencies of leucocytes, especially lymphocytes, and platelets, with immunodeficiency, increased infectious complications, bleeding, anaemia, and impaired wound healing.

- **Gastrointestinal syndrome** – characterised by loss of cells lining intestinal crypts and loss of mucosal barrier, with alterations in intestinal motility, causing vomiting and diarrhoea, fluid and electrolyte loss. There is loss of normal intestinal bacteria, and damage to the intestinal microcirculation resulting in sepsis; in addition to the haematopoietic syndrome.

- **Cerebrovascular/Cardiovascular syndrome** – primarily associated with effects on the vasculature and resultant fluid shifts. Signs and symptoms include vomiting and diarrhoea within minutes of exposure, confusion, disorientation, cerebral oedema, hypotension, and hyperpyrexia. Fatal in a short time.

- **Skin syndrome** – can occur with other syndromes; characterised by loss of epidermis (and possibly dermis) with 'radiation burns'.

Diagnosis

Consider acute radiation syndrome in the differential diagnosis if any of the following are present:

- history of a known or possible radiation exposure (for example, entering an irradiation chamber when the source is unshielded);

- history of proximity to an unknown (usually metallic) object with a history of nausea and vomiting, especially if nausea and vomiting are unexplained by other causes;

- tendency to bleed (epistaxis, gingival bleeding, ptechiae) and/or respiratory infection with neutropaenia, lymphopaenia, and thrombocytopenia, with history of nausea and vomiting two to three weeks previously; or

- epilation, with a history of nausea and vomiting two to three weeks previously.

Note the type of symptoms, time of onset, severity, and frequency.

Obtain an immediate FBE with differential. Repeat in 4–6 hours, then every 6 to 8 hours for 24 to 48 hours. Look for a drop in the absolute lymphocyte count if the exposure was recent (see diagram). If the initial WBC and platelet counts are abnormally low, consider the possibility of exposure a few days to weeks earlier.

Figure
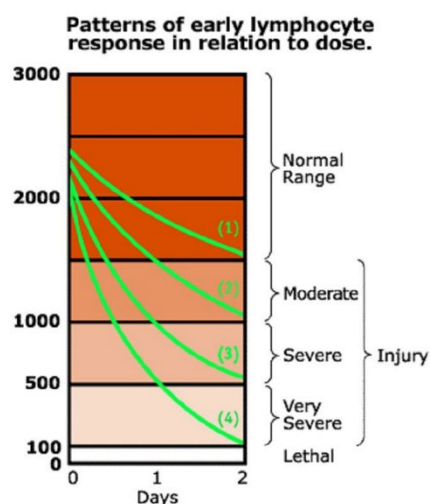
Curves 1–4 correspond roughly to the following whole-body doses: curve 1–3.1 Gy; curve 2–4.4 Gy; curve 3–5.6 Gy; curve 4–7.1 Gy. From Goans, Ronald E., Holloway, Elizabeth C., Berger, Mary Ellen, and Ricks, Robert C. "Early Dose Assessment Following Severe Radiation Accidents," *Health Physics* 72(4): 1997.

Acute radiation syndrome: dose less than 2 gray

Nausea and vomiting due to radiation are seldom experienced unless the exposure has been at least 0.75 to 1 gray of penetrating gamma or X-rays and exposure occurred within a matter of a few hours or less. The prospective patient who has been asymptomatic within the past 24 hours will most certainly have had less than

0.75 gray of whole-body exposure. Hospitalisation generally will be unnecessary if the dose has been less than 2 gray.

Management of ARS (dose <2 gray)

- Close observation and frequent FBE with differential
- Outpatient management may be appropriate
- Provide instructions regarding home care

Acute radiation syndrome: dose greater than 2 gray

Signs and symptoms become increasingly severe with dose.

Haematopoietic syndrome

- In the prodromal phase nausea, vomiting and anorexia occur within a few hours at higher radiation dose levels or after 6 to 12 hours at lower dose levels. The prodrome lasts 24 to 48 hours, after which time the patient is asymptomatic and may feel well. The absolute lymphocyte count will fall; however a stress response may be present with a transient neutrophilia.
- The latent phase lasts a few days to as long as 2 to 3 weeks at the lower radiation dose levels. The patient is asymptomatic but full blood examination will show characteristic changes, with lymphocyte depression and gradual decrease in neutrophil and platelet counts.
- The bone marrow depression phase requires sophisticated treatment. Infection and haemorrhage could occur when white cell and platelet counts become critically low.
- At 2 to 10 gray stem cells in the bone marrow are never completely eradicated; some may replicate and eventually produce sufficient blood elements. Supportive therapy is required during the recovery phase.

Gastrointestinal syndrome

Occurring with radiation doses over 10 gray, this syndrome is distinguishable from the haematopoietic syndrome by the prompt onset of nausea, vomiting and profuse diarrhoea, followed by a short latent period.

Gastrointestinal (GI) symptoms recur and lead to marked dehydration, and vascular effects. The GI mucosa becomes increasingly atrophic, and massive amounts of plasma are lost to the intestine. Massive denuding of the GI tract and accompanying septicaemia and dehydration can occur. If the patient survives long enough, depression of the haematopoietic system occurs and complicates the clinical course.

Cerebrovascular/Cardiovascular syndrome

This syndrome occurs with radiation exposure greater than 30 gray, an extremely high dose, to the whole-body. Always fatal, there is very early nausea, vomiting, anorexia and prostration, and irreversible hypotension. Blood pressure will be markedly unstable. Within hours after exposure the victim will be listless, drowsy, tremulous, convulsive, and ataxic. Death most likely will occur within a matter of days.

Appendix E: Treatment of acute radiation syndrome

Acute radiation syndrome (ARS) is classically described as having three sub-syndromes: the haemopoietic (>1 Gy), the gastro-intestinal (>3 Gy) and the neurological (>15 Gy). Case studies over the last twenty years, however, show that ARS is much a more complex condition, with appreciable damage occurring to the cardiovascular system and all internal organs at levels over 3 Gy.

Several cases of acute and sub-acute exposure to very high doses of radiation have demonstrated that, given optimal treatment, the haemopoietic syndrome can be survived, even when the dose is very high. Damage to the cardiovascular system and internal organs, however, is much more difficult to overcome, and most deaths in this group have come from Radiation-induced Multi-Organ Dysfunction (RiMOD).

Various publications give post-exposure outcomes in terms of LD50/60, and with modern treatment, this limit is approaching 8 Gy. However, longer-term survival figures are much less impressive. In spite of optimal treatment, the twelve-month survival rate from acute whole-body doses greater than 6 Gy appears to be zero. [Note that final whole-body dose assessments are generally lower than initial assessments, so it is proper to provide cytokines and supportive treatment to those where the initial estimate is up to 10 Gy].

For partial body, fractionated or chronic doses, it is much harder to predict outcomes, for several reasons:

- it is much more difficult to calculate equivalent whole-body doses.
- damage is much more variable among organ systems; and
- the body's self-repair mechanisms can mitigate against much of the impact.

ARS is much more likely following a criticality accident or nuclear detonation than a radiation dispersal device. In accident or terrorist scenarios exposure will rarely be even, and most patients will have sustained other injuries, such as burns or blast. These injuries should be given priority, as specific intervention for radiation injury (apart from an initial dose of cytokines) is not required for the first 48 hours.

Initial emergency management

If trauma is present, treat. If external contaminants are present, decontaminate.

Modalities for treating acute radiation syndrome include:

- Symptomatic relief (analgesia, anti-emetics)
- Reverse isolation in a positive-pressure room
- Enteral feeding with well-cooked, low-residue food
- Anti-microbials
- Blood products (irradiated whole blood, red cells and platelets)
- Colony stimulating factors (G-CSF, GM-CSF, epoietin)
- Stem cell transplants (including umbilical cord blood and bone marrow transplants)

It is difficult to ascertain in advance which patients will require the higher levels of treatment; but these modalities are not often required in the first 24–28 hours, allowing for preliminary biodosimetry and a more thorough secondary triage.

The following guidelines illustrate which treatments are available for components of ARS. They are general guidelines only, and treatment for individual patients should be based on the best available dose assessment and their clinical and haematological status. In a mass casualty event, it may be necessary to withhold intensive treatment from some of the more highly-exposed patients who have little chance of survival, which roughly corresponds to those who vomit within the first hour after an acute exposure (see triage chapter).

Symptomatic relief

Patients with ARS may experience severe pain from irradiated skin, even if they do not exhibit the classic 'cutaneous' syndrome. Pain is often fleeting and not easily controlled -high doses of opioids may be required.

Nausea and vomiting may be amenable to common anti-emetics if the dose was low (< 3Gy), but most patients will require ondansetron or granisitron to control their symptoms. Note that another serotonin receptor antagonist, alosetron, is contra-indicated in ARS due to the risks of constipation and ischaemic colitis.

Reverse isolation

Ideally, patients who have been exposed to high doses should be placed in reverse (positive-pressure) isolation and started on cytokines and prophylactic antibiotics as soon as feasible. Realistically, there is no imperative for isolation to be imposed immediately, as the immune system will remain functional for a few days or weeks post-exposure.

The same precautions are required as for immuno-suppressed patients on chemo- or radiotherapy. Measures are taken to protect the patient from infectious organisms carried by people and the environment.

Fluids

Where the gut or kidneys have been affected, patients may experience difficulty in maintaining fluid balance. However, care should be taken not to over-hydrate patients, as radiation burns do not require the same level of fluid support as thermal burns per unit surface area.

Enteral feeding

Enteral feeding is an important modality for maintaining gut function and stimulating the crypt cells. Food must, however, be as free as possible from any source of infection. All foods must be well-cooked and no fresh food (for example, fruit or cheese) is allowed. High-calorie preparations, such as Sustagen, may be useful, but it is important to include some solid foods as well. A good multi-vitamin and mineral preparation may be required.

Anti-microbials

Anti-virals

For patients with a known history of Herpes simplex, Herpes/Varicella zoster, or Cytomegalovirus, recrudescence can be expected as the immune system fails. These patients will require prophylactic or therapeutic anti-viral treatment. Carriers of Human Immunodeficiency virus (HIV), hepatitis B (HBV) or hepatitis C (HCV) may also experience a resurgence of their disease.

Anti-bacterials

Antibiotics should be administered to all patients with a neutrophil count of less than 0.5×10^9 cells/L. Gram-negative gut disinfection using an absorbable fluoroquinolone (such as norfloxacin or ciprofloxacin) is recommended for all patients, but other antibacterials should be administered only as required on clinical grounds.

Anti-fungals

Fungi and parasites are a significant hazard, and a high index of suspicion must be maintained for the duration of the patient's stay. Confirmation of infection is very difficult, but a persistent fever in the presence of adequate antibiotic cover is generally in an indication of candida, aspergillus or pneumocystis infection. Amphotericin B is the drug of choice.

Blood products

Blood products should be administered as required. Most patients who have suffered a high enough exposure to cause vomiting in the first two hours will experience severe marrow dysplasia and will require platelets (to prevent haemorrhage) and red cells (to combat anaemia). All blood products must be irradiated to 25 Gy to inactivate white cells and prevent GvHD. If it is possible, apheretic products are preferred to pooled products, but this is unlikely to be practical for mass casualty situations.

Colony-stimulating factors

There are several colony-stimulating factors available in Australia which may be helpful in treating irradiated patients. All are 'authority' drugs and are not currently licensed for use in acute radiation syndrome; however, obtaining permission for off-license use in ARS is not expected to be difficult.

White cells

Both G-CSF (filgrastim, pegfilgrastim) and GM-CSF (sargramostim) are available, and may reduce the level and duration of neutropaenia. Pegfilgrastim has the advantage of being given once every 3-5 days rather than daily, making it more suitable for mass casualty use. Note that G-CSF may be inhibitory to megakaryocytes and can prolong thrombocytopaenia.

Red cells

Epoietin and darbepoietin act on erythrocyte precursors and may reduce the requirement for packed red cell transfusions. They can cause rapid splenic enlargement and even rupture, and can exhaust the body's iron stores.

Platelets

A megakaryocyte-stimulating factor (PEG-rHuMGDF) is available in the US.

The most important point to make for all the colony-stimulating factors is that they work best when given early prior to the development of the manifest illness. If it is clear that a patient has received a potentially lethal dose (3-10 Gy) on symptomatology, then CSFs should be administered as soon as possible. For this purpose, pegylated preparations are preferred, as they do not need to be given daily.

If sufficient supplies are available, cytokines should be provided to ambulant patients in the 1-3 Gy exposure group as well, as they will reduce the need for intensive supportive care.

The provision of cytokines does not remove the need for optimal supportive care, as the cytokines will not produce adequate levels of circulating cells for some days or weeks.

Stem cell transplants

Stem cell transplants may be required when the whole-body dose has been high enough to ablate all the stem cells in the bone marrow (where the patient is classed as H4). At doses this high, however, there will be considerable damage to other tissues, and the chance of long-term survival is not high. Further complications arise from the fact that these patients require additional immunosuppression to ensure that the graft will 'take', since bone marrow ablation is rarely as complete as in radiotherapy.

Stem cells from adults can be obtained through apheresis of peripheral blood following stimulation by G-CSF, but this procedure requires at least five days' preparation and is painful. There is also a theoretical risk of leukaemia for the donor due to the effects of G-CSF on the marrow.

Umbilical cord blood cells are a good source of stem cells with a low risk of graft versus host disease (GvHD), but the small quantities obtained from each cord, and the small number of samples stored, mean that the supply is limited, and a match may not be obtained.

Bone marrow cells can be obtained from adults more easily than apheretic stem cells, but the uptake is variable, and the risk of GvHD is high.

Table 3 Summary of treatment options

Scenario	Presentation	Dose range for treatment (Gy)		
		Antibiotics	**Cytokines**	**Stem Cells**
Small numbers	Healthy, no other injuries	2–10	3–10	7–10[*]
	Multiple injuries or burns	2–6	2–6	N/A
Mass Casualties	Healthy, no other injuries	2–7	3–7	7–10[*]
	Multiple injuries or burns	2–6	2–6	N/A

* 4-10 Gy if there is prior autologous marrow stored, or the patient has a syngeneic donor

Reference: Wasalenko JK, et al. Medical management of the acute radiation syndrome: recommendations of the strategic national stockpile radiation working group. Ann Int Med. 2004; 140: 1037-1051

Follow-up and counselling

Because of the diffuse radiation damage to body tissues, patients who have suffered ARS are at a higher risk of developing cardiovascular or respiratory complaints later in life. There is also a risk of cancer in general and haemopoietic cancer in particular. These risks are stochastic and cannot be predicted with any accuracy on an individual level.

Patients who have suffered supralethal exposures (> 6 Gy acute whole body) should be given the opportunity to discuss end-of-life matters with their families and appropriate counsellors.

References

134. Waselenko et al. Medical Management of the Acute Radiation Syndrome: Recommendations from the Strategic National Stockpile Radiation Working Group. Ann Intern Med 2004; 140:1037-1051.

Cutaneous radiation injury

Cutaneous radiation injury (CRI) occurs when the skin absorbs an appreciable amount of ionising radiation. It may occur in isolation, but in accidental exposures it is often found in conjunction with some degree of acute radiation syndrome (ARS). In a terrorist incident or nuclear explosion, CRI would be found in combination with thermal burns and other injuries.

Consider local radiation injury in the differential diagnosis if the patient presents with a skin lesion without a history of chemical or thermal burn, insect bite, or history of skin disease or allergy. If the patient gives a history of possible radiation exposure (such as from a radiography source, X-ray device, or accelerator) or a history of finding and handling an unknown metallic object, note the presence of any of the following: erythema, blistering, dry or wet desquamation, epilation, ulceration. Local injuries to the skin evolve very slowly over time and symptoms may not manifest for days to weeks after exposure.

CRI is never just 'skin-deep'. The underlying connective tissue, muscle and even bone can be affected without any obvious sign in the early stages. Initial evaluation of the injury is complicated by the many variables that can affect CRI, including the type, energy and total energy deposition of the

radiation, the total area exposed and the depth of penetration. ARS, concomitant injuries and underlying medical conditions are added complicating factors.

CRI is notoriously difficult to treat, and suspected cases should be referred for specialist assessment by radiation oncologists wherever possible. Treatment is largely symptomatic, though skin stem cells and colony-stimulating factors are available. Lifelong follow-up is required for severe cases, since damage to deeper tissues may become manifest many years or even decades after the original injury.

Mode of injury

CRI can occur by any modality of radiation, though damage from alpha sources is rare because of the protective effect of the keratin layer. Beta radiation, low-energy X-rays and slow neutrons will penetrate a few centimetres and so deposit most or all of their energy into the skin and connective tissues. For high-energy X-rays, gamma rays and fast neutrons, energy deposition in the skin will only be a small percentage of the total tissue dose. It follows that for any given external dose in grays, the skin will suffer proportionately more damage from beta particles, low-energy X-rays and slow neutrons. It also follows that an external dose of gamma rays or neutrons sufficient to cause CRI will have severe effects on the underlying tissue.

External contamination is rarely active enough to cause acute CRI. Prompt decontamination (removal of clothing and washing of exposed skin and hair) is generally all that is required. If the contaminant was particularly active the patient should be advised of the risk of skin cancer in later years.

External exposure may be localised (partial body) or general (whole body). Local exposure is usually from a beam source or a misplaced radiotherapy or industrial source; these exposures are often unnoticed at the time and may present with established or recurrent ulcers. Whole-body exposure may occur in criticality accidents or as the result of a nuclear detonation, and such cases may be complicated by thermal or blast injuries.

Mechanism of injury

As for all other radiation injuries, cellular damage occurs as a result of energy transfer. DNA strands are broken, proteins are disrupted and free radicals are formed. Pro-inflammatory genes and cytokines are up regulated, antioxidant capacity is reduced and a cascade of cell damage follows.

Extensive damage leads to cell necrosis, tissue breakdown and visible signs such as epilation, blisters, sloughing and ulcers. Lesser damage may cause little in the way of acute signs, but can contribute to apoptosis (early cell death) with subsequent atrophy, fibrosis and/or late ulceration.

The most sensitive cells are the dividing cells in the basal layer of the dermis, but all levels can be affected.

Presentation

The threshold for deterministic skin effects is approximately 6 Gy, though there is some variation in sensitivity among individuals. The majority of cutaneous radiation injuries are not diagnosed at the time of irradiation, but weeks or months later, after symptoms and signs have developed.

Erythema immediately following an exposure indicates that the patient has suffered a thermal or chemical burn in addition to radiation exposure, which constitutes a combined injury. Pure radiation damage causing erythema within 2 hours indicates a severe injury (>60 Gy). Extremely high doses of radiation (>100Gy) may produce a tingling or burning sensation in the skin.

Table 15.1 shows the typical response and time of onset of skin reactions to gamma irradiation. Exposure to beta or neutron irradiation results in an earlier and more severe skin response per gray, but there may be less damage to underlying tissues.

Table 15.1 Skin response to gamma irradiation.

Signs	Dose range (grays)	Time of onset (days)
Erythema	3–10	14–21
Epilation	>3	14–18
Dry desquamation	8–12	25–30
Moist desquamation	15–20	20–28
Blister formation	15–25	15–25
Ulceration	>20	14–21
Necrosis	>25	>21

Reference: IAEA SRS-02 – Diagnosis and Treatment of Radiation Injuries, Vienna 1998

Assessment

Although CRI, like other forms of acute radiation damage, is dose-dependent, cutaneous signs are difficult to incorporate into dosimetry because of the individual variability and the relatively late manifestation of injury. Assessment is largely clinical. The extent of inflammation (in the early stages) and tissue fibrosis/atrophy (in the later stages) may be mapped by ultrasound, thermography, CT/MRI, and/or radio-isotope scans.

CRI is assessed against eight criteria (comprising symptoms and signs) and divided into four degrees which have some relation to the body's capacity for self-repair.

Table 15.2 -Assessment of acute CRI.

Symptoms/signs[1]	Degree 1	Degree 2	Degree 3	Degree 4
erythema[2]	minimal, transient	moderate; isolated patches; <10% BSA	marked; isolated or confluent patches; 10–40% BSA	severe >40% BSA
sensation	pruritis	slight, intermittent pain	moderate and persistent pain	severe and persistent pain

Symptoms/signs[1]	Degree 1	Degree 2	Degree 3	Degree 4
swelling/oedema	present but asymptomatic	symptomatic, with tension	secondary dysfunction	total dysfunction
blistering	rare, sterile fluid	rare, haemorrhage	bullae, sterile fluid	bullae, haemorrhage
desquamation	absent	patchy, dry	patchy, moist	confluent, moist
necrosis	epidermal only	dermal	subcutaneous	muscle or bone
hair loss	thinning	patchy, visible	complete, reversible	complete, irreversible
onycholysis	absent	partial	variable	complete

(1) Symptoms and signs usually appear in this order
(2) Erythema should be mapped and documented frequently

Reference: Fliedner et al: Medical Management of Radiation Accidents - Manual on the Acute Radiation Syndrome, London, 2001

As with ARS, there are five chronological stages of CRI: prodrome (first wave of erythema), latent period, manifest illness (including the second wave of erythema), recovery and late effects. The duration of each stage varies with the total exposure. In cases of non-uniform exposure (such as local injuries or criticality accidents) two or more stages may be present simultaneously in different parts of the body.

Treatment

As with any extensive skin injury, general supportive measures are essential. The skin is a vitally important organ, with roles in controlling hydration, infection, temperature regulation and nutrition. It follows that patients with moderate or extensive skin injuries are susceptible to dehydration, recurrent and systemic infection, hypothermia and nutritional deficiencies. In addition to that, radiation damage causes a cascade of inflammatory effects that can have deleterious effects on the surrounding tissue and other organs.

If acute radiation exposure has been identified, immediate treatment with cool water may reduce the development of inflammation. For severe cases, antihistamines, non-steroidal anti-inflammatory drugs (excluding aspirin) and gluco-corticosteroids are useful (although care must be taken not to impair clotting or the immune system any further).

KGF (keratinocyte growth factor) may help to stimulate regeneration of damaged skin but will not have any macroscopic effect for some weeks and must be used in addition to all other modalities, not instead of them.

Pain is a prominent feature of CRI and is difficult to treat. Mild cases may obtain adequate analgesia with NSAIDS and mild opiates such as codeine, but severe cases will require a strong opiate, plus corticosteroids and/or neuroleptics such as promethazine and haloperidol. In the most severe cases surgical sympathectomy may be required.

Fluid replacement will be needed for extensive or deep cutaneous injuries, but the total fluid requirement in the first 24 hours will be less than that for the equivalent thermal burn. After the first

24 hours, fluid replacement should be tailored to the patient's condition. Severe CRI, with extensive skin loss, may require up to 10 litres/day fluid replacement.

Temperature regulation is impaired. In the first few days the inflammatory reaction causes a rise in body temperature. After that, evaporative losses from denuded skin are likely to cause hypothermia, and a fever is a sign of infection.

Infection is a major complication where the skin's integrity has been compromised and is more likely when the body's haematopoietic system has also been affected. The body's own commensal bacteria are a major source of infection, and efforts should be made to reduce the bacterial load of the skin and the gut, with antiseptic washes and non-absorbable antimicrobials.

Severely affected skin (degree 4) will not heal, and consideration should be given to debridement. It is difficult to apply the surgical '48-hour rule' in skin injuries, because it is almost impossible to delineate the boundary between viable and non-viable skin the first few days. Imaging techniques, as described above, may assist in planning skin and tissue debridement. Autologous skin grafts are the preferred replacement wherever possible, but in extensive CRI there may be insufficient unaffected skin to use as donor sites. Graft take-up rates may be adversely affected by damage to underlying tissue.

Current research into post-exposure anti-inflammatory and antioxidant treatments may prove of use. Mesenchymal stem cells may be able to regenerate denuded skin but are not yet widely available.

Should stem cells or bone marrow transplant be considered for the treatment of severe ARS, bear in mind that irradiated skin is much more sensitive to graft-versus-host disease (GvHD) than normal skin, and skin changes will be seen at very mild levels of systemic GvHD.

Follow-up

CRI requires life-long follow-up.

Even where skin has been repaired or grafted, there will be some damage to the adjacent and/or underlying tissues that may become manifest many years or even decades after the original injury. Pigment changes, keratosis and telangiectasia are very common. Recurrent ulceration, vasculitis and deep tissue fibrosis are common sequelae, and may be accompanied by chronic pain. Skin cancer (particularly basal cell carcinoma) is also common.

Prevention

In some cases, such as planned radiotherapy, it may be feasible to use prophylactic measures to reduce cutaneous and mucous membrane damage. There are only two preparations currently available in Australia:

a) amifostine, an organic thiophosphate pro-drug, which must be given 15-30 minutes prior to radiotherapy, and often requires the use of a 5HT3-antagonist such as ondansetron; and

b) palifermin, a keratinocyte growth factor.

* Sunburn may be considered as a very mild form of CRI. Because the causative radiation is primarily in the UV range, which does not penetrate below the dermis, effects are localised to the skin and rarely exceed Degree 1 in the Fliedner, et al classification.

Combined injury

Combined injury is defined as any wound, infection or exposure to other noxious agent occurring at or around the same time as a radiation injury. Combined injuries have a much worse prognosis than single-modality injuries, and, when mass casualties have occurred, should be triaged accordingly (see Table 16.1).

Table 16.1 Triage categories without and with radiation exposure

Triage category without radiation exposure	Triage category adjusted for radiation exposure		
	< 1.5 Gy	1.5–4.5 Gy	4.5–10 Gy
Immediate	Immediate	Immediate	Expectant
Delayed	Delayed	Variable[1]	Expectant
Minimal	Minimal	Minimal[2]	Minimal[2]
Expectant	Expectant	Expectant	Expectant
No injury	Ambulatory monitoring	monitor; treat as needed	monitor; treat as needed

(1) May be delayed or expectant depending on the nature and extent of the concomitant injury.
(2) Although the concomitant injury may require no or minimal treatment, the patient will need monitoring and eventual treatment for ARS. Colony-Stimulating Factors, if available, should be administered as soon as possible to those with significant exposures.

Adapted from: Waselenko et al. Medical Management of the Acute Radiation Syndrome: Recommendations from the Strategic National Stockpile Radiation Working Group. Ann Intern Med 2004; 140:1037-1051

Radiation and wounds

Radiation injury impairs wound healing. Open wounds are prone to infection and increase the mortality rate by a considerable margin, so wound repair should be undertaken where possible. Where not possible, such as in extensive blast injuries or heavily-contaminated wounds, the survival rate will be appreciably lower.

Debridement and primary closure of wounds should occur in the first 24–48 hours after exposure. After 48 hours the body's capacity for repair is severely reduced, and no further surgical intervention should be carried out for approximately 8–10 weeks.

Radiation and burns

The combination of thermal burns and radiation exposure has a synergistic effect on mortality, and even a small dose of radiation can transform a survivable burn into a lethal burn. In mass casualty incidents, a patient with greater than 30% BSA burn and any amount of radiation exposure should be triaged to the 'expectant' category.

Initial treatment should proceed as for thermal burns, but the prognosis is much worse, firstly, because the radiation-induced damage affects the basal cell layer (from which new skin growth originates) and secondly, because of systemic inhibition of wound healing. Unfortunately, the

difficulty in assessing skin dose and the delay in manifestation of cutaneous radiation injury makes it difficult to formulate a definitive treatment plan in the early stages.

If a thermal burn is contaminated with radioactive material, decontamination should be attempted in a very gentle way so as not to further damage the burnt skin. Blisters should be left intact if possible, but open blisters should be trimmed and irrigated. Any residual material will be sloughed off in the normal way over the succeeding days or weeks, thus reducing the body burden.

Early administration of keratinocyte growth factor may enhance recovery in damaged and grafted skin. Radiation-damaged skin is not suitable for harvest for grafting, and if skin damage is extensive then allografts, xenografts or artificial substrates must be considered.

Radiation and chemical agents

Although there are very few data on the combined effects of chemical agents and radiation exposure, it is known that radiation decreases the ability of the body to respond to chemical insult. For those patients who survive the initial exposure, the mortality rate for combined chemical and radiation exposure over the next few weeks will be higher than for chemical or radiological exposure alone.

Mustard agents and T2 mycotoxins (both strong alkylating agents) have a radio-mimetic effect and can produce a syndrome that resembles ARS. A patient with combined mustard/T2 and radiation exposure will develop a more severe radiation-like syndrome than would be expected from the initial assessment.

Radiation and infection

Because radiation has a profoundly inhibiting effect on the body's immune system, patients are exquisitely susceptible to infection. Care must be taken to disinfect the skin and gut (the two most common sources of infection in the irradiated patient), and to debride and close wounds wherever possible.

Apart from non-absorbable oral antibiotics for the gut, antibiotics should not be given prophylactically, but should be administered for specific infections, preferably after blood/swab cultures and sensitivity results are known. Anti-virals and anti-fungals may be required.

Prenatal radiation exposure

Most radiation exposure events are unlikely to expose the foetus to levels causing health effects.

Foetal sensitivity to radiation is dependent on the radiation dose to the foetus. The effect of radiation is reduced with fractionation (division of the dose into units administered at different times) or protraction (lengthening the time to give a dose) of the dose compared with an acute exposure of equivalent magnitude. Consequently, there is a lessening of the incidence or severity of foetal health effects seen as a result of irradiation when the dose is fractionated or protracted.

Additionally, the foetal age determines health consequences for the foetus.

Foetal development

Foetal age may be defined in two different ways. In clinical settings, foetal age is usually referred to in terms of gestational age, the time since the onset of the last menstrual period. However, individual menstrual cycles may be quite variable in length. Foetal age may also be described as the time elapsed post-conception. This is generally two weeks less than gestational age.

Nevertheless, determining exact foetal age is relatively imprecise and the following is meant only as a guide. In this document foetal age is described in relation to time post-conception.

Development of the foetus can be considered in three phases:

- pre-implantation, from conception to implantation (blastogenesis) (days 0–14)
- major organogenesis, extending from the third to the eighth week post-conception (days 15–55), and
- foetal development from the ninth week post-conception until birth. This includes the period of central nervous system development from the 8th to the 25th weeks.

Risks of non-cancer health effects due to radiation are greatest during organogenesis and the early foetal period, less in the second trimester, and least in the third trimester.

Health effects of foetal irradiation

Health effects are due to cell killing or DNA damage. DNA damage may result in leukaemia, cancer or potential hereditary effects. Damage from cell killing may result in a number of effects:

- failure of embryo implantation
- increased incidence of miscarriage
- central nervous system abnormalities
- cataracts
- growth retardation
- malformations

The distribution of these potential health effects is determined by the foetal age at exposure. See table 17.1.

During blastogenesis, when the number of cells in the conceptus is small, the effect of damage to these cells results in failure to implant. At this stage malformations are very rare and surviving embryos appear to be unaffected, essentially an all or nothing effect. From animal studies, the threshold for failure of implantation is 50 mGy. In a human population this would be difficult to detect, as the spontaneous failure rate for implantation is estimated to be as high as 30-50%.

During organogenesis, malformations may be caused in the organ systems under development at the time of exposure. The threshold for malformations is 100–200 mGy or higher. At 100–200 mGy, the risk of malformation is low, but increases with increasing dose.

Central nervous system effects

As the period of foetal neurological development is long and because it is the most radiation-sensitive system, radiation-induced abnormalities are usually accompanied by neuropathology.

From 8 to 25 weeks, the CNS is particularly sensitive to radiation. Foetal doses in excess of 100 mGy are associated with decreased IQ. Below this level, there is no detectable decrease in IQ.

Doses in excess of 1 Gy result in a high probability (40%) of severe intellectual impairment, especially if the dose occurs during the 8th to 15th weeks when the measured effect is a reduction of IQ of 30 points. The effect increases with increasing dose. The decrease in IQ is smaller from the 16th to 25th weeks. The effect of reduced IQ has not been observed for other periods in foetal development.

Heterotopic grey matter and microcephaly are suggestive of radiation as a cause. Similar features are also seen in foetal alcohol syndrome.

Table 17.1 Potential non-cancer health effects of prenatal radiation exposure

| Acute radiation dose to foetus | Time post-conception | | | | |
	Blastogenesis 0–14 days	Organogenesis 15–55 days	Fetogenesis 8–15 weeks	16–25 weeks	26–38 weeks
< 50 mGy	Threshold for non-cancer health effects				
50-500 mGy	Slightly increased incidence of failure to implant. Surviving embryos have no significant non-cancer health effect.	Increased incidence of major malformations. (Not seen at < 100 mGy)	Reduction in IQ up to 15 points. Incidence of severe intellectual impairment up to 20%. (CNS effects not seen at < 100 mGy)	Non-cancer health effects unlikely	
> 500 mGy*	High incidence of failure to implant. Surviving embryos have no significant non-cancer health effect.	Increased incidence of miscarriage. Substantial risk of major malformations. Growth retardation likely.	Increasing incidence of miscarriage. Incidence of severe intellectual impairment > 20%. Growth retardation likely. Probable increase in major malformations	Possible increased incidence of miscarriage. Growth retardation possible. Reduction in IQ possible. Severe intellectual impairment possible. Possible increase in major malformations.	Possible increased incidence of neonatal death
> 1 Gy*	50% of embryos killed	Increased incidence of miscarriage.	Reduction in IQ up to 30 points. Incidence of		

Acute radiation dose to foetus	Time post-conception				
	Blastogenesis 0–14 days	Organogenesis 15–55 days	Fetogenesis		
			8–15 weeks	16–25 weeks	26–38 weeks
		Substantial risk of major malformations. Severe permanent growth retardation.	severe intellectual impairment up to 40%. Severe permanent growth retardation.		

* The mother may have acute radiation syndrome in this range, depending on her whole-body dose.

Adapted from CDC. Prenatal radiation exposure: a fact sheet for physicians. Department of Health and Human Services, Centers for Disease Control and Prevention, 2005.

Childhood cancer

Increased risk of childhood cancer and leukaemia is associated with foetal radiation exposure, based on epidemiological studies of children who were prenatally exposed during diagnostic radiology procedures.

Animal studies have not demonstrated an increase in cancer incidence from prenatal radiation exposures occurring during blastogenesis or early organogenesis. Susceptibility increases gradually up to the neonatal period. Increased incidence of tumours is seen at the following sites: breast, ovary, brain, liver and lung.

In a population exposed only to background radiation, the spontaneous incidence of childhood cancer and leukaemia from ages 0–15 years, is 2–3 per 1000 (0.2–0.3%). At low doses of radiation it is difficult to detect a change in incidence in human populations. The absolute cancer risk in ages 0–15 after foetal irradiation has been estimated as 600 per 10,000 persons each exposed to 1 Gy, or 0.06% per 10 mGy.

Excess cancers as a result of in utero exposure have not been demonstrated among Japanese atomic bomb survivors.

Pre-conception irradiation of either parent's gonads has not been shown to cause increased cancer or malformations amongst their children. Studies of the descendants of atomic bomb survivors have not demonstrated any hereditary effects, nor have studies on the offspring of survivors of childhood cancer treated with radiation therapy.

Evaluation of risk to the foetus

The foetus may be exposed during external irradiation of the mother, but also by any radionuclide absorbed by the mother, or transferred across the placenta. The estimation of foetal dose requires consideration of all potential sources of exposure.

External irradiation

There are a number of considerations in estimating foetal dose from external radiation sources. The uterus shields the foetus from radiation sources external to the mother. Foetal dose is affected by maternal anatomy, including uterine position and bladder distension. The irradiation of the foetus may not be uniform as the foetus grows larger. And, finally, the mother may have had more than one exposure.

Most diagnostic procedures, performed correctly, do not increase risk of prenatal death, malformation or intellectual impairment. See tables 17.2 and 17.3 for estimated foetal doses from common radiological and nuclear medicine procedures. Dosimetry surveys of medical procedures demonstrate that the delivered dose varies considerably between countries. It may be especially difficult to estimate exposures from fluoroscopy procedures, as the precise duration of the procedure and location of the beam may not be recorded. Therapeutic uses of radiation can result in significant harm to the foetus because of the higher doses delivered to the mother.

Table 17.2 Estimated foetal doses from common diagnostic procedures in the UK.

Examination	Mean (mGy)	Maximum (mGy)
Conventional X-ray examinations		
Abdomen	1.4	4.2
Chest	< 0.01	< 0.01
Intravenous pyelogram	1.7	**10**
Lumbar spine	1.7	**10**
Pelvis	1.1	4
Skull	< 0.01	< 0.01
Thoracic spine	< 0.01	< 0.01
Fluoroscopic examinations		
Barium meal	1.1	5.8
Barium enema	6.8	**24**
Computed tomography		
Abdomen	8.0	**49**
Chest	0.06	0.96
Head	< 0.005	< 0.005
Lumbar spine	2.4	8.6
Pelvis	**25**	**79**

Doses > 10 mGy are highlighted.

Adapted from ICRP. Pregnancy and medical radiation; publication 84. Oxford, United Kingdom: Elsevier Science; 2000.

Table 17.3 Foetal whole-body dose from common nuclear medicine procedures in early pregnancy and at term

Radiopharmaceutical	Procedure	Maternal administered activity (MBq)	Foetal whole body dose	
			Early (mGy)	At term (mGy)
^{99m}Tc	Bone scan (phosphate)	750	4.6–4.7	1.8
^{99m}Tc	Lung perfusion (MAA)	200	0.4–0.6	0.8
^{99m}Tc	Lung ventilation (aerosol)	40	0.1–0.3	0.1
^{99m}Tc	Thyroid scan (pertechnetate)	400	3.2–4.4	3.7
^{99m}Tc	Red blood cell	930	3.6–6.0	2.5
^{99m}Tc	Liver colloid	300	0.5–0.6	1.1
^{99m}Tc	Renal DTPA	750	5.9–9.0	3.5
^{67}Ga	Abscess/tumour	190	14–18	25
^{123}I	Thyroid uptake*	30	0.4–0.6	0.3
^{131}I	Thyroid uptake*	0.55	0.03–0.04	0.15
^{131}I	Metastases imaging*	40	2.0–2.9	11.0

*Foetal thyroid doses are much higher than whole body dose, viz. 5–15 mGy/MBq for ^{123}I and 0.5–1.1 Gy/Bq for ^{131}I.

Adapted from ICRP. Pregnancy and medical radiation; publication 84. Oxford, United Kingdom: Elsevier Science; 2000

The difficulties of dose estimation may be compounded where exposure is accidental or a result of deliberate misuse. A realistic estimate that includes an assessment of the uncertainty regarding the dose should be provided to the patient.

Internal contamination

Maternal biokinetics, the physical, chemical and biological properties of radionuclides and the effect of gestational age on placental structure and function are essential influences on placental transfer of maternally absorbed radionuclides.

For radionuclides that do not cross the placenta, foetal dose is derived from the energetic beta, gamma and X-ray radiation from radionuclides in maternal tissues. However, the risk from maternally absorbed radionuclides may be increased if the substance accumulates within the maternal bladder. Adequate maternal hydration and frequent voiding will reduce the risk to the foetus from renally excreted radionuclides.

Radionuclides that cross the placenta are generally in ionic form and may localise within specific tissues or organs or disseminate throughout the foeto-placental unit. Some radionuclides are selectively concentrated in specific foetal tissues, resulting in higher tissue concentrations relative to the mother. See Table 17.4.

Many of the radionuclides capable of crossing the placenta are alpha and beta emitters. The concentrated emissions from these radionuclides may not be confined to the organ or tissue of localisation because of the extremely small size of the tissue or its transient nature in foetal development. This further complicates dose estimation and the prediction of potential health effects.

Studies of animals that were exposed to radionuclides as foetuses, have demonstrated dose-related increases in the incidence of tumours. Only a few radionuclides have been studied in this way (iodine, phosphorus, plutonium, tritium & strontium). However, a decrease in breast tumours was also found after chronic exposures to tritiated water caused ovarian dysfunction.

Many radionuclides also transfer to breast milk. Breast-feeding may have to be suspended for a period from several hours to several weeks dependent on the specific radionuclide.

Table 17.4 Selected radionuclides and the foeto-maternal circulation*

Element (& form)	Crosses the placenta	Tissue distribution	Foetal tissue concentration > maternal tissue concentration	Consequence
^{241}Am	Yes	Villus yolk sac, mostly, then placenta. Some distributed to skeleton, liver, soft tissues		Potential effects on haemopoietic stem cell lines (which migrate from the yolk sac) No effect on the maternal blood supply to the placenta (unlike Pu)
Cobalt radioisotopes	Yes	Endocrine organs, renal cortex, gastric mucosa, liver, skeleton	Yes	Not stated
^{137}Cs	Yes	Uniform distribution throughout the body. Some concentration in muscle & bone		Not stated

Element (& form)	Crosses the placenta	Tissue distribution	Foetal tissue concentration > maternal tissue concentration	Consequence
^{3}H as tritiated water	Yes	Uniform distribution throughout total body water	Yes, because of the relatively greater total body water	Growth retardation, microcephaly, vascular pathology, sterility. Embryotoxic & teratogenic at high dose
^{3}H, organic forms	Yes	Selective incorporation into tissues & metabolic pathways		Embryotoxic & teratogenic at high dose
Iodine radioisotopes	Yes	Selective concentration in thyroid, especially after the thyroid forms at 8 weeks post conception. Maximum concentrations from 20-28 weeks.	Yes	Hypothyroidism, thyroid tumours in later life
Iridium radioisotopes#	Yes		Yes	Growth retardation, altered postnatal development
^{32}P	Yes	Influenced by development of ossification sites		Skeletal malformations Embryotoxic & teratogenic at high dose
Plutonium radioisotopes	Yes	Villus yolk sac, mostly, then placenta. Some distributed to skeleton, liver, soft tissues		Potential effects on germ & haemopoietic stem cell lines (which migrate from the yolk sac). Foetal death. Embryotoxic & teratogenic at high dose. Interruption to the maternal blood supply to the placenta at the highest doses.
^{210}Po	Minimal	Some deposition in the visceral yolk sac and placenta		Foetal dose derived from maternal and placental sources

Element (& form)	Crosses the placenta	Tissue distribution	Foetal tissue concentration > maternal tissue concentration	Consequence
Radium radioisotopes	Yes	Skeleton		Not stated
90Sr	Yes	Skeleton, liver & kidney. Influenced by development of ossification sites	Yes	Skeletal malformations. Bone & pituitary tumours. Embryotoxic & teratogenic at high dose.
Uranium radioisotopes		Skeleton, liver, kidney, placenta & foetal membranes		Foetal death, growth retardation, major malformations

Data based on gestational studies on Platinum, which has similar chemical properties and biological behaviour to Iridium.

Further information on other radionuclides which have been studied in relation to the foeto-maternal circulation is obtainable from National Council on Radiation Protection and Measurements. Radionuclide exposure of the embryo/fetus, NCRP Report No. 128. Bethesda: National Council on Radiation Protection and Measurements; 1998.

Counselling

Irradiation of the pregnant patient can lead to apprehension regarding potential foetal effects. Lack of understanding about the risks of prenatal radiation exposure may lead to unnecessary anxiety. Individual foetal dose estimations should be made by a qualified dosimetry expert who should be involved in advising the patient.

The following considerations are useful in preparing advice for exposed pregnant persons.

In a population exposed only to background radiation, the background incidence of

- miscarriage, post-implantation, is 15%
- major malformations 2–4%
- intrauterine growth retardation 4%
- genetic diseases 8–10%
- intellectual impairment (IQ < 70) 3%
- severe intellectual impairment (IQ < 50) 0.5%
- the lifetime risk of cancer is 1 in 3, with fatal cancer at 1 in 5
- childhood cancer is 2–3 per 1000 (0.2-0.3%).

For exposures occurring prior to implantation, surviving embryos are unlikely to be affected. However, there is always considerable uncertainty around the precise gestational age.

Up to radiation doses of 100 mGy, major malformations or neurological impairment probably do not occur. At doses above 100 mGy, there is dose-dependent increasing risk of major malformations, growth retardation and miscarriage. The risk of a measurable reduction in IQ is of particular concern if the foetus was between 8 and 15 weeks post-conception age at doses above 100 mGy, or 16 and 25 weeks at doses above 500 mGy.

The lifetime risk for radiogenic induction of childhood cancer or leukaemia is 1 in 170 (or 0.6%) per 100 mGy.

Foetal doses below 100 mGy should not be considered a medical reason for termination. At foetal doses greater than this, the magnitude of foetal damage is a function of the dose and the stage of pregnancy.

References

1. International Commission on Radiological Protection. Pregnancy and medical radiation; publication 84. Oxford, United Kingdom: Elsevier Science; 2000.
2. Centers for Disease Control and Prevention. Prenatal radiation exposure: a fact sheet for physicians. Department of Health and Human Services, Centers for Disease Control and Prevention, 2005
3. National Council on Radiation Protection and Measurements. Radionuclide exposure of the embryo/fetus, NCRP Report No. 128. Bethesda: National Council on Radiation Protection and Measurements; 1998.
4. Mettler FA. Accidental radiation exposure during pregnancy. In: Gusev IA, Guskova AK, Mettler FA, editors. Medical management of radiation accidents, 2nd ed. CRC Press; 2001: 527-539.

Health.gov.au

All information in this publication is correct as at September 2012