

Review article

Radiation accidents and their management: emphasis on the role of nuclear medicine professionals

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Large-scale radiation accidents are few in number, but those that have occurred have subsequently led to strict regulation in most countries. Here, different accident scenarios involving exposure to radiation have been reviewed. A triage of injured persons has been summarized and guidance on management has been provided in accordance with the early symptoms. Types of casualty to be expected in atomic blasts have been discussed. Management at the scene of an accident has been described, with explanation of the role of the radiation protection officer, the nature of contaminants, and monitoring for surface contamination. Methods for early diagnosis of radiation injuries have been then described. The need for individualization of treatment according to the nature and grade of the combined injuries has been emphasized, and different approaches to the treatment of internal contamination have been presented. The role of nuclear medicine professionals, including physicians and physicists, has been reviewed. It has been concluded that

the management of radiation accidents is a very challenging process and that nuclear medicine physicians have to be well organized in order to deliver suitable management in any type of radiation accident. *Nucl Med Commun* 35:995–1002 © 2014 Wolters Kluwer Health | Lippincott Williams & Wilkins.

Nuclear Medicine Communications 2014, 35:995–1002

Keywords: diagnosis of radiation injuries, internal contamination, radiation exposure, radiation protection, surface contamination, treatment of radiation injuries

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Received 29 January 2014 Revised 19 May 2014 Accepted 23 May 2014

Introduction

This manuscript is directed at medical professionals who may be involved in the management of radiation injuries, starting from the first few hours or days after an exposure of undefined severity. Experience has shown that, in addition to occupational physicians, the complete management of an emergency case involves other professionals such as haematologists, oncologists, plastic surgeons, dermatologists, vascular surgeons, psychiatrists and consultants in other medical specialities including nuclear medicine.

Management of radiation exposure is difficult, partly because of misinformation on the part of the exposed persons and partly because of current perceptions of medical staff about the effects of exposure.

While radiation accidents are rare, sufficient data were considered available from incidents over preceding decades for the International Atomic Energy Agency (IAEA) and WHO to publish guidelines on the health management of radiation accidents in their Safety Reports Series in 1998 [1]. What is meant, precisely, by a ‘radiation accident’? According to the International Basic Safety

Standards, an accident is ‘any unintended event, including operating errors, equipment failures or other mishaps, the consequences or potential consequences of which are not negligible from the point of view of protection or safety’ [2].

Possible accident scenarios

In some respects, terrorist-mediated exposure to radiation from sources other than a nuclear weapon should be relatively manageable, as it is difficult to mass expose people to large doses of radiation from other sources. This is assuming that the terrorists use only radiation. A combination of radiation with chemical and biological agents is possible, but synergism between radiation and these agents is unlikely. Furthermore, in such an eventuality, management of the immediate effects of chemical and biological exposure would take priority over management of the effects of radiation exposure. Dispersal of radioactive substances could be mediated with and without the use of explosives (Table 1).

Dispersal with explosives

The purpose of including radioactive material along with explosives would be to cause additional fear and panic over and above the explosive-associated traumatic injuries. It is well known that mass hysteria such as that induced by fear of radiation ‘bombs’ can lead to more nonradiation or nontraumatic effects such as chaos in

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Table 1 Sources of radiation exposure

Source of accident	Radioactive substance	Common body parts exposed
Industrial		
Sterilization	^{60}Co , ^{137}Cs	Whole body, hands
Radiography	^{192}Ir , ^{137}Cs	Hands and other parts
Gauging	^{192}Ir , ^{137}Cs	Hands and other parts
Medical practice		
Diagnostics	X-ray generators	Hands, face
Therapy	^{60}Co , ^{137}Cs	Whole body, hands and other parts
Spent sources	Accelerators ^{60}Co , ^{137}Cs and others	Whole body, hands and other parts
Nuclear reactors	^{137}Cs , ^{90}Sr ^{131}I ^{210}Pu	Whole body Thyroid Lung
Others		
Research	Spectrum of sources including reactors	Hands, face and other parts
Depleted uranium ammunition	^{238}U , ^{235}U , ^{234}U	

public transport systems, chaos in the shopping patterns of citizens and depletion of food stocks. The extent of dispersal of radioactivity would depend on the strength of the explosives, the physical form of the radiation source used, the site of the event, and the atmospheric conditions. Major health hazards would probably be restricted to a radius of 1 km. The aim of the emergency response would be to calm down and control the mass hysteria as well as monitor and control the contamination area.

Dispersal without explosives

Low-level radioactive sources such as those in smoke detectors, radiopharmaceuticals (used in nuclear medicine) and isotopes used in research may be used to cause fear and panic. No immediate health effects would be expected and the probability of any long-term effects would be very low. Highly radioactive sources such as cobalt-60, caesium-137 (used in radiotherapy machines) and iridium-192 (used in industrial radiographic devices) can cause serious exposure. However, sources are usually metallic and easily detectable at check-points. Serious exposure would probably involve those who have handled the sources or those with local radiation-induced skin injuries, who are at risk for acute radiation syndrome requiring medical attention [3,4].

Power plants/reactors

An attack on a commercial nuclear power plant is a possibility; however, at all these sites security is high. Furthermore, the reactor core is encased in a thick stainless steel jacket embedded within concrete. If an accident occurs, the reactor is designed to slow down and stop the reaction. The coolant system of a reactor does contain some radioactivity and if damaged would release radioactive iodine and noble gases. The explosion in 1986 at the Chernobyl nuclear power plant, which had been constructed without a containment vessel, resulted in 237

persons being overexposed [5–7]. The natural disaster that affected Fukushima also needs to be considered.

Nuclear weapons

The detonation of a nuclear weapon requires more technical expertise and funding and is therefore a less likely scenario. However, a low-level nuclear weapon detonation that fails could have a substantial explosive impact, even though the yield might be only of the order of 0.01 kt. For reference, the bomb used in Hiroshima had an approximate yield of 13 kt. It should be noted that the destructive effects of nuclear weapons are due to air blast and thermal radiation.

Uranium enriched with the ^{235}U isotope is used in the nuclear industry as fuel for nuclear reactors and nuclear bombs. Depleted uranium (DU) is useful for non-nuclear applications including radiation shields in medical equipment used for radiotherapy, containers for transport of radioactive materials and ballast for aircraft. It is about half as radioactive as natural uranium, but denser. It is mainly used militarily in armour-piercing ammunition. The radiation emitted from a DU penetrator consists of α , β and γ radiation. Ammunition produced from DU, primarily in the form of cartridges, was used in the Balkans and in the 1991 Gulf War. The main radiation hazard from DU is from contact with bare skin, although the dose limit to skin is exceeded only if the skin is in contact with DU for more than 250 h/year. Uranium is highly toxic when personnel are subjected to acute exposure, which may cause kidney damage. According to current occupational exposure standards, a concentration of 3 μg uranium/g of kidney tissue should not be exceeded, and to this end legislation restricts long-term (8 h) workplace air concentrations of soluble uranium to 0.2 mg/m^3 and short-term air concentrations (15 min) to 0.6 mg/m^3 [2].

Medical cyclotrons

The cyclotron is the most widely used particle accelerator for producing medically important radionuclides. Cyclotron radiation surveys are an integral part of the overall radiation safety in the cyclotron facility [8]. Individuals who work in cyclotron facilities should be guided by the IAEA recommendations (Table 2) regarding dose limits [9].

Table 2 IAEA-recommended absorbed dose limits for radiological workers and members of the public

Type of exposure	mSv/year
Radiological worker: effective dose (internal + external), averaged over 5 years ^a	20
Radiological worker: equivalent dose to the lens of the eye	20
Radiological worker: equivalent dose to the extremities (hands and arms below the elbow, feet and legs below the knees) and skin	500
Visitors and public: effective dose (internal + external)	1

IAEA, International Atomic Energy Agency.

^aWith the caveat that effective dose in any single year shall not exceed 50 mSv/year.

Types of casualty

The types of casualty expected of any blast include injuries due to flying fragments and collapsing buildings. However, two types are peculiar to atomic blasts: flash burns and radiation effects. Statistics from the blasts in Japan show that 85% of injuries sustained were due to trauma and burns: radiation accounted for only 15%.

Trauma may be direct, due to blast, or indirect, due to falling or flying objects.

Burns may be classified as flash burns and thermal burns. Flash burns occur at the precise time of atomic explosion and are peculiar to this event, being caused by infrared and ultraviolet rays of very high intensity over a short period. The range of flash burns is up to about 3650 m. In an unwarranted and unprotected populace, flash burns would produce numerous casualties. Ordinary thermal burns are common among survivors as the number of fires started by an explosion is high.

Radiation sickness occurs as a result of radiation released at the time of explosion or from radioactive contamination of the ground.

Psychological trauma is also to be expected in the case of an explosion and may include disorientation, hallucination, confusion, panic, apprehension and claustrophobia.

Triage of injured persons

It is useful to classify radiation accidents according to their severity (in the size of reading), the number of individuals affected (e.g. more than five is considered a major accident) and their radiological effects.

Three main categories of exposure can be delineated:

- (1) Individuals who have been overexposed or are suspected of overexposure, and who present with signs of injuries such as trauma, burn and chemical contamination. These individuals should be managed as in any medical emergency. They should undergo specific emergency tests (blood cell counts, blood sampling for cytogenetic studies and HLA typing) in order to assess the severity of the exposure and the required treatment.
- (2) Individuals who have been exposed externally and have suffered external and internal contamination or are suspected of having been exposed. These individuals should be regrouped in a treatment centre where they can undergo secondary triage into three subcategories:
 - (a) Exposure of the whole body
 - (b) Local exposure of parts of the body
 - (c) Contamination with radionuclides
- (3) Individuals who have received low doses and are free from any other injury. These individuals have to be registered and controlled as outpatients for a few days.

Medical management of individuals

Individuals contaminated either externally or internally should be identified and treatment should be started immediately and specifically. If the accident involves only a small number of casualties, medical management is easy to organize, but a large-scale accident involving hundreds of people would place serious demands on hospitals.

Medical treatment should be delivered in accordance with the type of trauma and the urgency of each case. The need for emergency treatment is determined initially by the presence of conventional injuries such as trauma, wounds and thermal or chemical burns.

In individuals who have suffered radiation exposure, the early clinical symptoms are very helpful for triage and decision making on medical care. The most important early clinical signs are nausea, vomiting, diarrhoea, and skin and mucosal erythema. The decision on hospitalization in cases of whole-body exposure or local exposure depends on the presence of particular early clinical signs, as described in Table 3.

Management at the scene

Assuming an accident has happened, the radiation protection personnel, medical physics experts and preferably nuclear medicine physicians must be informed. The radiation advisor establishes a radiation contamination control line. If initial response and fire-fighting operations are still ongoing, the control line may be the same as the evacuation line established for explosive hazards. The number of emergency personnel who are permitted to cross the radiation contamination control line should be kept to an absolute minimum. Personnel with cuts should remain outside the contaminated area. Anyone passing this line into the fire area must wear appropriate protective equipment that may include protective coveralls, gloves, rubberized boots, head protective gear and respiratory protection. Personnel assisting in the radiation survey and decontamination operations should wear full-face respirators with high-efficiency dust filters. Tape should be used to seal the clothing when there are openings to the body.

The monitoring instrument to be used must have the beta shield open. Decontamination supplies should be made available by the local military community at the request of the radiation protection advisor. Special attention must be given to the areas between the fingers and around the nails. Contaminated clothing should be removed, if feasible, at the site. Also, the injured person should be wrapped in a clean sheet to prevent the possible spread of contamination. Other than the removal of contaminated clothing, no other type of decontamination should be performed on a seriously injured person. A person should be assigned to ensure that the names, addresses and telephone numbers of those people who

Table 3 Early symptoms of radiation injuries and management guide [1]

Dose (Gy)		Clinical signs		Management	
WBE	LE	WBE	LE	WBE	LE
< 1	< 10	No vomiting	No erythema		Outpatient care with a 5-week surveillance period (skin and bloods)
1–2	8–15	Vomiting 2–3 h after exposure	Early erythema or abnormal sensation		Surveillance in a general hospital (or outpatient care for 3 weeks followed by hospitalization if necessary)
2–4	15–30	Vomiting 1–2 h after exposure	Early erythema or abnormal sensation		Hospitalization under care of a haematologist. In the case of burns, in a surgical department
> 4	> 30	Vomiting earlier than 1 h after exposure and/or severe symptoms, e.g. hypotension	Early erythema within 3–6 h or earlier after exposure of skin and/or mucosa with oedema		Hospitalization to a specialized centre for radiopathology and a fully equipped haematological and surgical unit

LE, local exposure; WBE, whole-body exposure.

cross the radiation contamination control line, whether contaminated or not, are recorded, along with results of personnel monitoring.

Monitoring for surface contamination

There are two methods of monitoring for body surface contamination, direct and indirect, and either or both may be used as conditions demand. The direct method of monitoring, which is the simplest and most convenient, entails positioning the instrument probe directly over the contaminated area. This method allows the contamination level to be calculated in Bq/cm², and the measurements can be related to the derived working limit for surface contamination. A typical contamination monitor consists of a rate meter to which various types of detecting heads can be connected. Alpha contamination is detected by means of a zinc sulfide (ZnS) scintillator coupled to a photomultiplier tube. The ZnS screen is coated with Melinex (a very thin plastic material) and aluminium to make it light tight. The aluminium coating is thin enough to allow alpha particles to penetrate through. It is important when carrying out direct surface monitoring of alpha contamination that the probe be as close to the surface as possible.

In the indirect method, which is used to measure the degree of loose contamination or to monitor contamination in an area of high radiation background, smears are taken that can be monitored outside the affected area. In this method a filter paper is wiped over a known surface area (usually 0.01 m²), placed in a polythene envelope to avoid cross-contamination and then taken to an area of low radiation background, where it is counted in a detecting system of known efficiency.

Diagnosis

The biological and possible health consequences of radioactive contamination depend on the following: mode of entry, pattern of distribution, sites of deposition of radionuclides in organs, nature of the radiation emission from the contaminating radionuclide, amount of radioactivity on/in the body, and the biological pathway of the contaminant. This information is essential for adequate evaluation, assessment and medical management of a contaminated individual.

The surface contamination falls into two categories: fixed and loose. In the case of fixed contamination, the radioactivity cannot be transmitted to personnel, and the hazard is consequently that of external radiation. Loose contamination becomes an internal radiation hazard as a result of transmission into the body through the mouth or skin or through inhalation of contaminated air. Once the radioactive substance has been taken into the body, it will continue to irradiate the body until either the activity has decayed or normal biological excretion has occurred. It should be noted that there may be a combination of fixed and loose contamination with or without injuries.

Table 4 Guidelines for protective measures [1]

For attendants	Protective clothes should be issued to all personnel involved – i.e. coverall with hood, mask and gloves. The edges of both mask and gloves should be taped. Paramedic and ambulance personnel should be surveyed for contamination before going off duty.
Room setting	An isolated room or a room away from the general emergency area should be used. Air circulation should be prevented and a tub or table with a drainage system provided. Other useful items include containers for waste water and any contaminated materials, and plastic bags.
Survey meter	A well-maintained Geiger-Müller counter with beta and gamma detection capability is usually sufficient. The survey should be conducted at a distance of about 25 mm from the person's body, moving the detector no faster than 50 mm/s.
Personal dosimeter	A film badge or thermoluminescence dosimeter should be regarded as a minimum requirement, although a direct reading personal dosimeter is preferable. Exposures should be kept as low as reasonably achievable, but in any case should be within the limits set by the national competent authorities.

In most cases the contaminants are difficult to remove. They can be classified under three headings: soluble (ionic), particulate and colloidal. The soluble (ionic) contaminants are normally associated with the surface of the substrate by physical absorption or by ion exchange with the reactive groups (usually acidic) present on the surface of most nonmetallic materials. Anionic contaminants are repelled from these surfaces by the mutual repulsion of the negatively charged species and hence little absorption is detectable. However, cations are attracted to the acidic surface, and in favourable conditions, particularly at low concentrations, polyvalent cations are absorbed almost completely. Unfortunately, most fission products and all the heavy natural radioactive elements fall into this category [10].

Uranium is reabsorbed as uranyl ion and in the blood is bound as a complex compound with protein and bicarbonates in the cell wall, and, instead of cylindrical cells, cubic cells are created, which are not capable of normal function. Many cases of lung cancer and kidney disorder have been reported in uranium workers. Uranium is deposited in the following manner in the body: 22% is deposited in the skeleton, 12.5% in kidneys and 12.2% in other soft tissue. For uranium there are two retention components in the bone: (a) 20% of uranium entering the body is retained in bone with a half-time of 20 days; and (b) 2% is retained with a half-time of 5000 days. Soft tissue retention of uranium is assessed in the same way as kidney retention; 12% of uranium is assumed to be deposited in soft tissue with a 6-day half-time and 0.5% with a 1500-day half-time.

Following accidental internal contamination with uranium (inhalation or ingestion), 93.97% is eliminated from the body within 7 months of exposure; the remaining 6.02% is 'buried' in bones, kidney and soft tissues (for up to 41 years in soft tissues and up to 137 years in bones) and cannot be removed from the body by any means.

In the case of external contamination, physical measuring equipment such as surface contamination monitors (Geiger-Müller detectors, etc.) can be used (Table 4) [1]. Swab samples have to be taken from body surfaces and orifices and measured. In the case of internal contamination, through inhalation, ingestion or wounded or apparently undamaged skin, physical measurement includes thyroid monitoring, whole-body counting,

gamma camera measurement, and analysis of blood and excreta. For the latter, all blood, urine and faecal samples have to be collected and labelled to record the time of sampling.

The purpose of contamination diagnosis is to obtain information on the time of intake, the nature of the radionuclides involved and the distribution of the radionuclides on the surface of and within the organism. In the event of simple contamination with one or several radionuclides, there will be no clinical manifestations initially.

The severity of the injury depends on the dose level incurred, the dose rate, the radiosensitivity of the tissues involved, the area of the body exposed and the extent of exposure suffered by the organ system. The severity of the injury is greater when the whole body is exposed; partial body exposure to the same dose has less impact on health. An absorbed radiation dose of about 3.5 Gy is generally expected to result in the death of 50% of the exposed population group within 2 months if there is no medical treatment. This LD_{50/60} value can be increased to about 5.0–6.0 Gy with sufficient medical treatment [1].

A very early classification will be based on clinical symptoms such as nausea, vomiting, diarrhoea, erythema and fever. These signs, as well as the time of their appearance, their frequency and their severity, should be carefully recorded (Table 5). This permits the classification of victims into two categories according to whether the absorbed dose is greater or less than 2 Gy. Confirmation and more precise classification will be based on haematological counts, including, in particular, tests to observe the decline of lymphocytes within the first 2 days, allowing a more detailed classification within the category when the dose exceeds 2 Gy.

Data provided by MRI, computerized tomography, vascular scintigraphy, histochemical and immunocytochemical studies of biopsy material, as well as topographic dosimetry, including in-depth distribution of the doses, and clinical evolution should all be taken into consideration by a multidisciplinary team to identify the stage and extent of radiation injury by the end of the first week.

Skin reaction should be monitored daily with the aid of colour photographs.

Table 5 Methods for early diagnosis of radiation injuries

Procedure	Clinical findings	Time of onset	Minimum exposure (Gy)
Assessment of acute clinical findings	Nausea and vomiting	Within 48 h	~ 1
Assessment of delayed signs of skin injury	Erythema	Within hours to days	~ 3
	Epilation	Within 2–3 weeks	~ 3
	Erythema	14–21 days	3–10
	Epilation	14–18 days	> 3
	Dry desquamation	25–30 days	8–12
	Moist desquamation	20–28 days	15–20
	Blister formation	15–25 days	15–25
	Ulceration (within skin)	14–21 days	> 20
	Necrosis (deeper penetration)	> 21 days	> 25
Laboratory examinations			
Blood count	Lymphocyte count < 1×10^9 cells/l	Within 24–72 h 6 days since exposure	~ 0.5
			0.1–1.0
			1–2
			2–4
			4–6
			6–8
			> 8
Cytogenetics	Dicentric, rings, fragments	Within hours	~ 0.2

Skin reaction should be monitored daily with the aid of colour photographs. Modified from International Atomic Energy Agency and World Health Organization [1]. Adaptations are themselves works protected by copyright. So in order to publish this adaptation, authorization must be obtained both from the owner of the copyright in the original work and from the owner of copyright in the translation or adaptation.

Treatment

A multidisciplinary team approach is required, involving medical physicians, nuclear medicine physicians, radiation protection officers, plastic and reconstructive surgeons, medical oncologists and haematologists. Treatment has to be individualized according to the nature and grade of the combined injuries. Expert advice from external organizations such as IAEA, Public Health England or a similar body in individual countries should be sought.

As radiation injury is characterized by a latent period, all important treatments of the nonradiation components of combined radiation injury should be carried out during the first 2–3 weeks. Later efforts will be necessary for the treatment of bone marrow and skin radiation injuries.

Skin contamination

Generally, a soap wash should suffice. However, for heavier contamination, care should be taken not to cause skin abrasion due to excessive washing, and other decontamination agents should be used. In the radiopharmaceutical industry a freshly reconstituted mixture of 250 ml water with a powder containing 1.25 g natrii laurysulfas (soap and chelating agent), 1.25 g amyllum tritici (chelating agent for iodine, not iodide), 1.25 g natrii edetas (a strong chelating agent for dissolved metals) and

8.75 g sodium bicarbonate (regulation of pH) is used. This is effective if used soon (within few hours) after contamination for the decontamination of most regular radiopharmaceuticals (^{99m}Tc based) and similar agents (e.g. ^{131}I). Commercial decontaminants such as Radiacwash Toweletts (Biodex Medical Systems Inc., Shirley, NY, USA) are used extensively in hospitals, laboratories and reactor facilities as first-line general-purpose decontaminants. Radiacwash sequesters metallic ions and lifts up and firmly suspends the contaminating particles, allowing the contamination to be rinsed away with hard, soft or salt water.

Respiratory tract contamination

Deposition of radioactive particles in the sinuses and lungs is one of the more common types of accidental exposures. Insoluble particles, once inhaled into the lungs, may be mobilized and translocated to other organs at a low rate over many months or years. Irrigation of the nasal passage gently with saline solution or water using a catheter or syringe is required. The subject's head should be bent over a basin with mouth open during this process. In rare cases, trachea-bronchial lavage may be required.

Internal contamination

Internal contamination can occur from the dispersal of powdered, liquid or gaseous radioactive material. The material may enter the body by inhalation or ingestion, through intact skin or through wounds or burns. Unless treatment is instituted quickly, its effectiveness will be limited; furthermore, knowledge of both the radionuclide and the chemical form is required.

There are several general approaches to the treatment of internal contamination (Table 6):

- (1) Mobilization as a means of elimination from tissue
- (2) Chelating
- (3) Reduction of absorption
- (4) Dilution, blockage
- (5) Displacement by nonradioactive materials

Mobilizing agents

These agents are more effective if they are given soon after exposure, but some still produce an effect if given within 2 weeks. If radioiodine has been deposited in the thyroid and no KI is given, propylthiouracil and carbimazole might be considered. Ammonium chloride given orally is effective in mobilizing radiostrontium deposited in the body. Its effectiveness can be enhanced by simultaneous use of intravenous calcium gluconate. Diuretics would be logical in the case of accidents with Na-22, Na-24, Cl-38 and K-42.

Table 6 Specific therapy for internal contaminants

Tritium (^3H)	Dilution [force fluids (~4 l/day) for at least 1 week], diuresis
Iodine-125 or iodine-131	Blockage (potassium iodide 120 mg given up to 2 h after exposure); beyond ~4 h use mobilization (antithyroid drugs) and sodium perchlorate (400 mg)
Caesium-134 or caesium-137 Thallium and rubidium	Reduction of GI absorption using ferric ferrocyanide (Prussian blue) (optimum adult dose 3 g/day; paediatrics 1 g/day), administered at regular intervals, i.e. in doses of 1 g (two capsules) every 8 h, in order to maintain its gastrointestinal availability throughout the day. The drug can be used over long periods, for months if necessary. Very effective for ^{134}Cs and ^{137}Cs
Strontium-89 or strontium-90	Reduction of GI absorption (aluminium phosphate gel antacids, 100 ml, will reduce Sr-89/90 absorption by 87% if given prior to Sr-89/90, and by 57 and 43%, respectively, if given 30 and 60 min after oral ingestion of Sr) Blockage (strontium lactate) Displacement (oral phosphate) Mobilization (ammonium chloride orally + intravenous Ca gluconate to enhance its effect) Barium sulfate for ingested strontium and radium Intravenous calcium gluconate for urinary excretion
Plutonium and other transuranic elements (americium, curium)	Chelation: Ca-DTPA for the first chelation dose (adults: 1 g slow intravenously with 100–250 ml of 5% dextrose and normal saline over 60 min; paediatric: 14 mg/kg intravenously not to exceed 1 g. For inhalational exposure only give in nebulized inhalation at a ratio of 1 : 1 with sterile water or saline.
Yttrium-90	Zn-DTPA after 24 h and for repeated daily use: dosage same as for Ca-DTPA. In pregnant patients use this exclusively.
Lutetium-177 Uranium	Zn-DTPA should not be used as a chelator for uranium or neptunium. Sodium bicarbonate to increase excretion and prevent kidney damage, which is likely with acidic urine. Alkalinization of urine: reduces chances of acute tubular necrosis Dose: 4 g orally initial dose, then 2 g every 4 h until urine pH of 8–9 is obtained and maintained or 2–3 amps (44.3 mEq each; 7.5%) in 1000 cc normal saline at 125 cc/h. Bicarbonate is potassium-wasting, so replacement therapy will be needed. Paediatrics: 84–840 mg orally in divided doses every 4–6 h Monitor response by measuring 24-h urine and stool collection for uranium content Reduction of absorption (emetics, lavage, charcoal or laxatives) in case of ingestion
Source unknown	

DTPA, diethylene triamine penta-acetic acid; GI, gastrointestinal.

Chelating agents

Therapy with a chelating agent is most effective when it is begun immediately after exposure while the radionuclide is still in circulation and before incorporation within cells or deposition in bone.

The powerful chelating agent diethylene triamine penta-acetic acid (DTPA) is effective in removing many of the transuranium metals (plutonium, americium, californium, curium, and neptunium), rare earths (cerium, yttrium, lanthanum, promethium and scandium) and some transition metals (zirconium and niobium). The clinical use of Ca and Zn-DTPA is primarily for the treatment of plutonium and americium exposures. Zn-DTPA is less toxic than Ca-DTPA and therefore is advantageous for longer-term treatments and especially for fractionated treatments. Animal studies have shown that Ca-DTPA is more effective than Zn-DTPA when given promptly after exposure to ^{239}Pu , ^{252}Cf or ^{241}Am . This finding has led to the general recommendation that Ca-DTPA should be used within the first 24–48 h after exposure, followed by Zn-DTPA for continuing treatments.

A note of caution is needed in the case of plutonium. The effectiveness of DTPA in enhancing the excretion of plutonium depends on the chemical form. For both wounds and inhaled particles, uptake of the insoluble form, for example plutonium oxide, into the circulation occurs over many days and weeks, and DTPA is therefore not effective in these cases. However, the soluble form, such as plutonium nitrate, shows relatively rapid uptake and translocation and therefore is more available in the circulation for chelation. Data from individuals

treated with Ca-DTPA soon after exposure (within 24 h) indicate that about 60–70% of the soluble form is removed.

In the case of uranium exposure, chelating agents should not be given as the kidneys may then be subjected to uranium overload. Treatment to remove uranium intake is not particularly successful, but sodium bicarbonate in saline may be given by slow intravenous infusion.

Elimination by extracorporeal treatment

These methods are effective while the radionuclides are circulating in the bloodstream. Depending on the chemical properties and metabolism of the radionuclide compound, haemodialysis may be effective. Haemoperfusion can also be used, in which blood is passed through a column of activated charcoal or resin.

Lavage

Lavage of the tracheobronchial tree has proved to be an effective form of treatment on inhalation of relatively soluble radionuclides in a very limited number of cases. The procedure should be considered only in patients exposed to high doses, in whom a reduction in the dose could be expected to prevent acute or subacute effects such as radiation pneumonitis or fibrosis.

Thyroid blocking

When gaseous contamination occurs, no therapy is available except in the case of gaseous radioiodine, when immediate blocking of the thyroid with iodine may be indicated.

Bone marrow transplantation

Bone marrow transplantation (BMT) as a form of treatment may be used for victims of accidental whole-body irradiation when the dose is sufficiently high to make spontaneous bone marrow recovery impossible [3,11,12]. It is necessary to observe the HLA compatibility for allogenic BMT. This therapy may be recommended for patients exposed to whole-body doses exceeding 9 Gy [13,14].

Haematopoietic growth factors

Use of haematopoietic growth factors such as granulocyte-colony stimulating factors and granulocyte macrophage colony stimulating factors increase the rate of haematopoietic recovery in patients after radiation exposure and may obviate the need for BMT when stem cells are still viable [15–17]. Interleukins (IL-1 and IL-3) act in synergy with granulocyte macrophage colony stimulating factors. During the past decade, these factors have been suggested as having the potential to accelerate bone marrow recovery after radiation exposure in the lethal range. They have been used successfully for radiation victims of the Goiânia, San Salvador, Soreq and Nesvizh accidents [3,4,18,19].

Criteria for choice of therapy

Appropriate criteria are as follows:

- (1) If the lymphocyte count during the first week is within the range of 0.2–0.5 g/l (200–500 cells/ μ l), spontaneous recovery is possible. Therapy comprises isolation, antibiotics and supportive treatment, including platelet infusion. Growth factors can be used.
- (2) If the lymphocyte count in the first week is lower than 0.2 g/l, the stem cells are probably irreversibly damaged. Treatments are as above. Additional growth factor therapy is a method of choice.
- (3) If the lymphocyte count within the first week is less than 0.1 g/l, treatment with growth factors and BMT has to be considered.

Conclusion

The management of radiation accidents is a very challenging process. Nuclear medicine physicians have to be well organized in order to deliver suitable management in any kind of radiation accident, which includes fast triage of injured persons, prompt diagnosis of radiation

casualties and urgent initiation of specific treatment procedures.

Acknowledgements

Extensive guidance and text from IAEA documentation was sought for this review.

Conflicts of interest

There are no conflicts of interest.

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