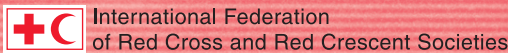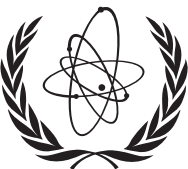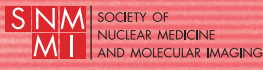# Medical Management of Persons Internally Contaminated with Radionuclides in a Nuclear or Radiological Emergency

A Manual for Medical Personnel

Jointly sponsored by the

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MEDICAL MANAGEMENT OF PERSONS INTERNALLY CONTAMINATED WITH RADIONUCLIDES IN A NUCLEAR OR RADIOLOGICAL EMERGENCY

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MEDICAL MANAGEMENT OF PERSONS INTERNALLY CONTAMINATED WITH RADIONUCLIDES IN A NUCLEAR OR RADIOLOGICAL EMERGENCY

A MANUAL FOR MEDICAL PERSONNEL

INTERNATIONAL ATOMIC ENERGY AGENCY
VIENNA, 2018

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FOREWORD

This manual covers the specific measures to be taken in the medical management of individuals who have been internally contaminated through inhalation, ingestion or absorption of radionuclides in a nuclear or radiological emergency. It includes a number of exposure scenarios, risk models and dosimetric data which can be used during the response to a nuclear or radiological emergency or for other purposes. However, it may be necessary to adapt some of the concepts discussed in this manual to reflect the prevailing national, regional or local medical conditions and capabilities.

The manual is published as part of the IAEA's Emergency Preparedness and Response (EPR) series. It supports several other publications issued on this overall topic, including IAEA Safety Standards Series No. GSR Part 7, Preparedness and Response for a Nuclear or Radiological Emergency, and EPR-Medical 2005, Generic Procedures for Medical Response during a Nuclear or Radiological Emergency.

This publication has been co-sponsored by the International Federation of Red Cross and Red Crescent Societies and the Pan American Health Organization, and endorsed by the American Association of Physicists in Medicine (AAPM), the American Society for Radiation Oncology (ASTRO), the European Association of Nuclear Medicine (EANM), the Latin American Association of Societies of Nuclear Medicine and Biology (ALASBIMN), and the Society of Nuclear Medicine and Molecular Imaging (SNMMI). The IAEA wishes to acknowledge the boards of all the organizations that have co-sponsored and endorsed this publication.

CONTENTS

1. INTRODUCTION

1.1. BACKGROUND

An emergency is a non-routine situation that necessitates prompt action, primarily to mitigate a hazard or adverse consequences for human health and safety, quality of life, property or the environment. This definition encompasses nuclear and radiological emergencies and conventional emergencies such as fires, release of hazardous chemicals and natural disasters. It includes situations for which prompt action is warranted to mitigate the effects of a perceived hazard. A nuclear or radiological emergency is one in which there is, or is perceived to be, a hazard due to the energy resulting from a nuclear chain reaction or from the decay of the products of a chain reaction, or due to radiation exposure [1, 2, 3]. In this manual, the term 'radiation emergency' will be used indistinctly for both cases.

IAEA Safety Standards Series No. SF-1, Fundamental Safety Principles [4], states that:

"The primary goals of preparedness and response for a nuclear or radiation emergency are:

— To ensure that arrangements are in place for an effective response at the scene and, as appropriate, at the local, regional, national and international levels, to a nuclear or radiation emergency;

— To ensure that, for reasonably foreseeable incidents, radiation risks would be minor;

— For any incidents that do occur, to take practical measures to mitigate any consequences for human life and health and the environment."

During a radiation emergency, radiation workers, first responders or the public in general may be subjected to external irradiation, to internal/external contamination with radionuclides or to both conditions, which may be combined with conventional injuries such as trauma. External irradiation (or external exposure) may originate from a radiation source, or, in the eventuality of a nuclear accident (as at the Chernobyl and Fukushima Daiichi nuclear power plants), from airborne radionuclides (cloud shine), radionuclides deposited on clothing and skin or radionuclides deposited on the ground (ground shine). Internal contamination may originate from inhalation or ingestion of radionuclides or from radioactive material deposited on wounds, and, exceptionally, from absorption through the intact skin.

The IAEA has issued a number of publications on planning and preparedness for and overall response to radiation emergencies, which cover a wide spectrum of emergency scenarios as well as the respective medical interventions [2, 4, 5, 6]. This manual discusses the specific measures for the medical handling of individuals who have been internally contaminated with radionuclides; it complements or supplements previous publications on the subject issued by the IAEA alone or in cooperation or association with other relevant organizations.

Radiation emergencies may involve, for example, the following facilities, activities or applications [7]:

— Irradiation facilities (sterilization of food and medical supplies);

— Nuclear reactors (power generation and research);

— Radioisotope production facilities;

— Industrial radiography facilities (or industrial radiography on other sites);

— X ray and radiotherapy (medicine, research);

— Unsealed radionuclides (medicine, research);

— Transport of radioactive materials;

— Malicious acts involving radioactive materials.

Independently of its application, in general terms, any activity with open radioactive sources implies a risk of internal contamination with radionuclides.

1.2. OBJECTIVE

This manual focuses on the medical management of internal contamination with radionuclides. Its primary objective is to provide practical information, to be used for treatment decisions by medical personnel during a radiation emergency. It seeks to present this information in a clear and straightforward way that can be easily understood and followed even by someone who does not have any background knowledge or experience in this specific area. It may also be used by policy makers and health authorities in charge of planning the general as well as the medical response to radiation emergencies.

Guidance provided here, describing good practices, represents expert opinion but does not constitute recommendations made on the basis of a consensus of Member States.

1.3. SCOPE

This manual deals primarily with the medical management of internal radiation contamination during a radiation emergency. It does not address external contamination. It supplements, from the medical perspective, EPR-Medical 2005 [2], a publication that presents the generic procedures for the medical response during a radiation emergency.

1.4. STRUCTURE

The structure of this manual follows in a logical way the progression of the response to a radiation emergency and covers the various issues that need to be taken into account. It starts by providing information on the first response to, and medical management of, internal contamination and discusses a number of concepts involving triage criteria and initial treatment decisions. The manual then considers the issue of dose assessment and its relevance for treatment decisions, followed by a description of the most common methods for the treatment of internally contaminated patients.

Section 2 provides information and guidance on the general medical management of persons internally contaminated, and Section 3 provides information on the assessment of internal doses. Section 4 discusses contamination pathways, metabolic phases and methods for treatment of internally contaminated persons.

Section 5 provides information on the treatment of persons internally contaminated with specific radionuclides. The radionuclides, which are covered in some detail, have been selected either because of the high probability that they will be present in emergencies that involve internal contamination or because of their radiotoxicity and their consequent

potential for severe health impact. The information provided is based on studies issued in international publications; it is not intended to serve as a medical protocol, since the different regulations of individual Member States will need to be taken into account in each case.

Various issues with regard to the screening of a large number of people after a radiation emergency with a high number of individuals involved, including the establishment of radiation monitoring units, are discussed in Section 6. The safe handling of deceased bodies with radiation contamination during procedures such as autopsies, embalming, funeral services, burials and cremation is discussed in Section 7. Section 8 contains brief descriptions of clinical cases involving internal radiation contamination. These case studies, which present a variety of typical contamination scenarios, were selected to serve as examples for medical management in different situations.

The three appendices include further information on: drugs that can be used for the treatment of internally contaminated patients (I), the protection of health care providers and the preparation of hospital facilities and equipment (II), and the differences between radioactive and chemical or biological hazards (III).

2. CONSIDERATIONS IN THE MEDICAL MANAGEMENT OF INTERNALLY CONTAMINATED PATIENTS

2.1. GENERAL CONSIDERATIONS IN THE MEDICAL MANAGEMENT OF INTERNAL CONTAMINATION

During a radiation emergency, workers, first responders and members of the public may become internally contaminated with radionuclides. The possible shortage of medical resources, such as personnel and facilities, the lack of therapeutic strategies and the insufficiency of countermeasures to avoid or minimize radiation exposure may compromise the overall response. Careful planning and allocation of medical resources are essential for an efficient response that addresses the possible health consequences of a radiation emergency. In this respect, radiation contamination poses logistical and technical challenges.

In radiation emergencies, as in other emergency situations, individuals may arrive at hospitals by self-referral and hospitals need to be prepared to receive people with little or no warning and to enact planned measures to protect personnel, conventional hospital patients, visitors, volunteers, facilities and equipment from radiation contamination. In addition, essential procedures need to be available in order to avoid disruption of ordinary activities.

As part of planning and preparedness, the risks associated with treating patients with internal radiation contamination need to be well communicated to health personnel in hospitals, especially to those who have little knowledge of radiation or limited experience in treating patients with radiation exposure or contamination. It is important to emphasize that, in most cases, universal biosafety precautions are adequate for the safe handling of patients contaminated with radionuclides.

Hospitals in general, and especially those within a system designed to respond to radiation emergencies, need their personnel to be well informed of the actual risks related to assisting patients contaminated with radionuclides, and a hospital plan has to be established and periodically updated for proper management. Periodical and systematic drills involving all health personnel (including medical doctors, nurses, technicians and other professionals) that could take part in the medical response to a radiation emergency are paramount in order to: (a) avoid an exaggerated perception of the risks and (b) instil good practices, including those of radiation protection.

Specific decorporating drugs need to be available, and the stockpile has to be kept under strict control by the appropriate national and local public health authorities. It is important that medical protocols for the management of internal contamination with radionuclides be available and periodically updated.

> *A fundamental conceptual aspect that will be mentioned frequently in this manual is that treatment of any concomitant life threatening condition always takes precedence over radiological assessment and external or internal radiological decontamination.*

Children, pregnant women, the elderly, people on continuous medication, people with physical or mental disabilities and minority cultural or linguistic groups are considered populations that need special attention in emergencies, including radiation emergencies. For

each group, special considerations may be necessary and need to be considered in the planning of the medical response.

2.2. MEDICAL MANAGEMENT AT THE SCENE AND TRANSPORTATION

In radiation emergencies, the first priorities at the scene are conventional medical evaluation and the stabilization of patients. Internal contamination by itself does not cause immediate acute manifestations or life threatening health conditions. An appropriate response to a radiation emergency will reduce the risk of internal contamination and external exposure for individuals in general (the public) as well as for responders.

Detailed information for planning and delivering the generic and first response to a radiation emergency is found in various publications issued by the IAEA, the World Health Organization (WHO) and other international organizations [2, 8, 9, 10].

> *Goals of emergency medical response (IAEA EPR-Medical 2005 [2]):*
> 1. *Save lives and perform required emergency medical procedures;*
> 2. *Treat radiation injuries and injuries resulting from an emergency situation;*
> 3. *Perform required public health actions, including public advice and counselling, and long term medical follow-up.*

In general terms, the main objectives of the on-site medical response include [11]:

— Triage of victims: identification of individuals with life-threating conditions, medical stabilization for as long as necessary (or possible) and transfer to emergency medical care facilities;

— Identification and assistance of other individuals with non-life-threating injuries;

— Identification of those who may be externally and/or internally contaminated and prevention of the spread of contamination.

Radiological contamination can be either external (clothes, skin) or internal (presence of radionuclides inside the body), or both. External contamination is out of the primary scope of this manual and will not be covered in detail. However, external and internal contamination are inherently related, and, from the medical perspective, some concepts can be applied to both circumstances.

Decontamination efforts at the scene will normally be limited to the removal of external clothes and shoes and the protection of body areas and wounds suspected to be contaminated. With a few limited exceptions, no other decontamination procedures are advisable or feasible on the scene of a radiation emergency.

Internal contamination with radionuclides does not by itself cause early clinical signs and symptoms. If these occur, two situations need to be considered:
— Association of the radioactive material with a chemical that is responsible for the manifestations, in accordance with its characteristic toxicity [11].
— The very rare event of a massive internal burden (as happened in the Goiânia accident with caesium-137 [12]), or a case of internal contamination with a very

radiotoxic nuclide such as polonium-210 [13], when acute radiation syndrome (ARS) may develop within days. In such an instance, the clinical and laboratory findings would be pertinent to the diagnosis of ARS.

Therefore, in practical terms, no clinical manifestations are caused by internal contamination with radionuclides. Nevertheless, it is worth mentioning that, once an individual is aware that he or she is 'contaminated with a radioactive material', he or she can present unspecific manifestations such as nausea and vomiting of psychological aetiology, which are not to be taken unequivocally as prodromal manifestations of ARS [14].

The main health concern with internal contamination with radionuclides is the stochastic late effect of cancer development. The probability for this development depends on a number of factors, such as the radiotoxicity of the contaminant, route of entry, radiosensitivity of the target organ or tissue, and age of the person at the time of the contamination. The International Commission on Radiological Protection (ICRP) and other organizations have derived nominal dose coefficients for cancer risk development [15].

Any emergency personnel who notice signs or symbols indicating radiation hazard in areas where an injured person is located have to be aware of the possibility of contamination or exposure and act in accordance with these potential conditions [16]. The first priority at the scene of a radiation emergency is the medical evaluation and stabilization of victims, as already outlined. In many instances, removal of external clothes will not jeopardize the medical evaluation and consequent stabilization. It is important that the transport of seriously injured victims not be delayed because of radiological monitoring or decontamination efforts [16].

Wounds will need to be protected with impermeable dressing to avoid contamination or intake of radionuclides if contamination is actually present. It is not advisable to attempt to decontaminate the wounds at the scene.

It will need to be assumed that those patients who have been considered as externally contaminated could be also internally contaminated [11].

Transportation of patients contaminated with radioactive materials from the emergency scene to the hospital will follow pre-established radiation protection protocols, as long as this does not cause any delay in the medical assistance of individuals with life threatening conditions [9].

All materials that were used to handle and treat the patient or that may have come in contact with the patient during transport, including gloves, pads, bandages, splints, oxygen masks, blood pressure cuffs etc., and any waste remaining in the ambulance will need to be considered contaminated [16].

When dispersion of radioactive material (dust/smoke/liquid) is suspected or confirmed, the victim(s) will need to be removed from the contaminated scene as soon as possible to avoid or minimize intake of radioactive materials to the body by inhalation or ingestion.

Normally, first responders are protected against radiological contamination by standard biosafety procedures. The use of respiratory protective equipment may be indicated in special conditions in which air dispersion of radioactive material is or could be present and in case of fire and smoke [9].

As a basic safety measure, members of the medical transport team will not eat, drink or smoke at the emergency scene, in the transport vehicle or at the hospital facilities, until they have been surveyed and released by the appropriate service of the hospital (Radiation Protection Support Group).

> ***Unstable patients have priority for medical evaluation, and the stabilization of the patient should occur before any decontamination or dosimetric procedure is attempted.***

After medical triage, if there is no need for urgent removal to the hospital, contamination monitoring may be performed by qualified personnel on the scene or in a reception centre on victims with no serious or life threatening conditions or on those that have already been stabilized. In the following situations, it is possible that victims incurred internal contamination, and confirmatory evaluation is needed:

— In a radiation emergency with dispersion of radioactive material (dust, smoke, liquid);

— If contamination is detected, especially on the head, hair, face or hands.

Measuring and identifying radionuclides at the scene is not normally possible, nor is it strictly necessary from the medical point of view. Therefore, if victims or patients are potentially internally contaminated, they need to be transferred to a hospital or facility where measuring and identification of radionuclides can be performed by in vivo counting (whole body counting, thyroid counting, lung counting) and/or by in vitro analyses (faeces and urine bioassays) [16].

Decorporation treatment is not recommended at the scene of a radiation emergency; transport of injured victims is not to be delayed because of decontamination procedures [9]. Non-specific decorporation measures, such as gastric lavage, could be indicated in some special conditions as an early initial countermeasure for internal contamination with radionuclides, but contraindications and complications that might occur during this procedure have to be taken into account. Complications associated with gastric lavage have been well described in the medical literature, and they include aspiration pneumonia, laryngospasm, arrhythmia, oesophageal or stomach perforation, fluid and electrolyte imbalance, and small conjunctival haemorrhages [17, 18]. Therefore, this or similar measures should not be considered for management on the scene.

2.3. MEDICAL MANAGEMENT AT THE HOSPITAL

The most important factor to be analysed and taken into immediate consideration is the health status of the patient. The management of life threatening conditions needs to have absolute priority and be handled under traditional medical and surgical protocols. Dose estimations, decontamination procedures and decorporation therapy are secondary priorities in these cases. Therefore, initially, hospital emergency personnel have to triage individuals by using conventional medical and trauma criteria [11].

There are no specific clinical manifestations caused by internal contamination with radionuclides as such, unless a toxic chemical agent is associated [2].

No matter how internally or externally contaminated an unstable patient may be, this will never be a significant health risk for the medical personnel and staff in charge, as long as standard biosafety and basic radiation protection precautions are adopted. Unless absolutely necessary, female personnel with confirmed or possible pregnancy should avoid working directly in contact with patients contaminated with radionuclides, even though the occupational risk for accidental incorporation would be minimal.

By way of comparison, the radiological risk to health care personnel assisting such a patient is similar to or lower than the biological hazard from normal medical practice [14].

Depending on the condition of the patient, when contamination has been detected in areas not covered by clothing, washing those parts of the body, especially the hands, head and neck, under running water reduces the risk of accidental intake (in stable patients). Initial nasal, oral and/or wound swabs can be considered before the washing [19].

The hospital management of patients involved in radiation emergencies includes [11]:

— Evaluation of patients for evidence of ARS and initiation of treatment as necessary;

— Evaluation for emergency treatment of patients with local radiation injuries (such as cutaneous radiation syndrome), contaminated wounds and radionuclide intakes;

— Confirmation (or non-confirmation) of suspected intakes;

— Evaluation and treatment of patients with injuries and psychological distress.

Once the medical condition of the patient(s) is stable, and internal and/or external contamination is suspected, the following actions are considered good practice [16]:

— To restrict access to the treatment area.

— To survey the treatment area to determine the 'background' radiation level present, prior to the patient's arrival (a Geiger–Müller detector from nuclear medicine department could be useful).

— To adhere to the radiation protection standards and procedures, including the use of protective clothing to diminish the risk of contamination, and ideally to assist patients in the designated area of the emergency department in order not to disrupt the routine of the hospital.

— To have a quick head-to-toe radiological survey performed by a radiation protection officer (or by another trained professional) with the appropriate equipment, including a judicious survey of wounds. The wounds may be counted with a Geiger–Müller detector, and the count rate may be used to estimate the intake initially (based on the activity in the wound). This will normally provide sufficient evidence of the presence or absence of gross contamination.

— To remove the patient's clothes very carefully (if this was not done previously), and place them in plastic bags adequately labelled with the patient's name and the day and hour of the procedure. Clothes are excellent samples for the identification of the contaminant radionuclides if radiological analysis is available. This procedure could be performed by other organizations in the country; close collaboration with the national competent authority is necessary.

— To notify the national competent authority, if this was not done previously.

If the clinical condition of the patient has been stabilized, the next priority is to treat wounds that might be contaminated. Wound dressings are removed and saved for further evaluation. After irrigating the wound gently with sterile saline, adequate monitoring equipment with a suitable probe can be used to evaluate the effectiveness of the decontamination process. The intact skin immediately adjacent to the wound has to be careful and quickly decontaminated, and drapes applied in the area to prevent the spread of radioactive materials. Irrigation and decontamination of wounds may be optimized by using a tepid saline or water jet under mild pressure.

> *It is estimated that removing external clothing reduces external contamination (if present) by about 80 to 90 per cent.*

In stable individuals with no wounds, the external decontamination will start on the face (if contamination is present) and then move to the other most contaminated areas. The next priority is to decontaminate body orifices. If contamination is found around the nose or mouth, or if high concentrations of airborne radioactive material are known or suspected to have occurred, there is the potential for internal deposition, and samples (swabs) can be collected [11].

Biological samples, depending on the condition of the patient, could also be obtained at this stage. Urine and faeces are most commonly used for the estimation of intakes, but breath, blood or other samples are used in special cases. The choice of bioassay sample will depend not only on the major route of excretion, as determined from the physicochemical form of the intake and the biokinetic model for the element(s) involved, but also on such factors as ease of collection, analysis and interpretation [20]. Some of the biological samples that could be obtained are the following:

— Nasal (from each nostril separately) and oral swabs: These could initially be counted with handheld instrumentation to provide limited results that, when positive, might help in the early medical management. In case of negative results, internal contamination may not be excluded, and samples will be sent for further radiological measurements.

— Urine samples: Following the entry of radionuclides into the blood and systemic circulation, clearance from the body will generally be via the urine. Urine contains waste and other materials, including water, extracted by the kidneys from the blood, and collected for up to several hours or more in the bladder before voiding. Because of this mixing in the bladder, radionuclide levels in samples of urine obtained soon after an acute intake need to be interpreted with caution. The bladder will normally be cleared soon after the intake. All samples will need to be analysed. After the first few days, 24-hour samples of urine normally provide the best basis for assessing intake [20].

— Faecal samples: Intakes of insoluble material can often be assessed by this kind of sample. The mass and composition of individual faecal voidings can be quite variable and depend strongly on the diet. For this reason, reliable estimates of daily faecal excretion rates of radioactive materials can usually be based only on total collections over 3–4 days. Single samples will, in most cases, only be used for screening purposes [20].

— Blood samples: These samples provide the most direct means for estimating levels of radionuclides present in the systemic circulation, but they are not often used because of medical constraints on the sampling process. With only a few exceptions (e.g. iron-59 and chromium-51 in labelled erythrocytes), blood samples provide very limited information on the total systemic activity following an intake owing to the rapid clearance from the bloodstream and deposition in tissues [20].

— Tissue samples: For localized deposits of radionuclides with high radiotoxicity (e.g. transuranic elements) in a wound, it is usually advisable, subject to medical advice, to excise the contamination soon after the intake [20].

— Other biological samples, such as hair and teeth: These can be used to assess intakes, although, in general, they cannot be used for quantitative dose assessments. Tissue samples taken at autopsy may also be used to assess the body content of radionuclides [20].

Urine, faeces and other biological samples need be collected in uncontaminated areas, in order to ensure that activity measured in the sample is representative of body clearance. Special care needs to be taken in the handling of samples to be used for the assessment of internal exposure. With respect to the potential hazard from contamination, both biological and radioactive contaminants need to be considered [20].

Many large hospitals have nuclear medicine departments that employ physicians and technical personnel who are trained in the use of radiation detection and measurement instruments. At other hospitals, radiology departments may have trained staff who could also assist [13]. It is important to define a clear process for notifying the national authorities, who can provide assessment and support to the medical teams.

2.4. INITIAL DECISIONS FOR THE TREATMENT OF PATIENTS

The vast majority of radiation emergencies do not involve potentially hazardous levels of external radiation exposure or radionuclide intake. Considering only internal contamination, the route of intake plays an important role in the severity of the expected outcome and in treatment decisions [11].

The diagnosis of internal contamination may be just presumptive, based on the emergency circumstances and/or preliminary measurement results. A whole body counter is not normally useful for the measurement of accidental contamination, because it is set up and calibrated at a very low level of detection for the occupational monitoring of radiation workers. In addition, there are limited whole body counter facilities.

> *Treatment for internal contamination is in the vast majority of cases intended to reduce the risk of long term effects and not for the treatment of an acute radiation related injury.*

Bioanalyses for the identification and quantification of radionuclides in the body (urine, faeces and blood samples) are time consuming (24 to 48 h), so there might be instances when the physician needs to decide whether or not to begin treatment exclusively on the basis of presumptive evidence. The following aspects are helpful in making the clinical judgement as to whether or not to initiate treatment even without the confirmatory test results being available [11, 14]:

— History of the accident, including time of occurrence, radionuclide(s) involved (if the information is available), circumstances and results of the dose estimations;

— Probable pathways of contamination (especially through wounds);

— Solubility of the contaminant radioactive material (if known);

— Radiotoxicity of the contaminant (if known);

— Patient's age and his/her specific clinical conditions (pregnancy, liver function, kidney function);

— Toxicity of the drug to be used for decorporation.

Initial analyses from the nasal or oral swabs and wound counts will also help to guide the medical decision, particularly when the samples are taken during the first hour of the accident [21]. They could be also useful to the internal dosimetry laboratory in deciding what amount and type of bioassay sampling may be advisable in order to obtain sufficient data for a better subsequent dose assessment [22].

Appropriate specialized treatment should be given to any person who receives a radiation dose that could potentially result in severe deterministic health effects [22]. At a given level of intake, some individuals may not need any kind of treatment, while others, depending on multiple factors, could be subject to significant health risks and require pharmacological or other treatments. Since no treatment is completely free of risk, a benefit-to-risk decision has to be made before initiating any course of treatment. It also needs to be taken into account that, for individuals with significant internal intakes, prompt actions are most effective.

When a wound is contaminated and the radionuclide is not removed, the radionuclide may be absorbed and metabolized into the body. Therefore, copious irrigation with physiological saline solution or with diethylenetriamine-pentaacetate (DTPA) (depending on the case) is indicated. Depending on the radionuclide involved in the contamination of a wound, a systemic therapy will need to be considered; for example, for contamination with plutonium or other actinides, treatment with chelation therapy (DTPA) is indicated [23].

When nasal or oral swabs indicate the inhalation of radionuclides, additional studies may be required to determine the intake and the need for decorporation treatment. However, some situations, such as intake of plutonium or americium, may require the prompt administration of DTPA before a substantial deposition in organs can occur [11].

In the case of ingestion of radionuclides, there will be a transit time through the gastrointestinal (GI) tract prior to absorption (uptake) into the bloodstream. Some actions, such as the administration of alginates and aluminium-containing compounds, can reduce the amount of radionuclides absorbed. These drugs bind some chemical elements (such as strontium), reducing their uptake [11].

Lessons learned from accidents indicate that the psychological impact of the treatment of radiation induced injuries needs to be minimized. Therefore, the treatment is provided as close to the individual's home as possible, or in a region where the patient's language and culture are common. Provisions for family members to accompany the patient have to be evaluated when treatment is offered in another country [24].

Each case needs to be analysed by itself by the healthcare and health physics teams. The patient will be fully briefed on the risks and benefits associated with the treatment method.

As mentioned, the kind of treatment may vary from case to case depending on several factors.

3. DOSIMETRIC CONSIDERATIONS IN THE ASSESSMENT OF INTERNALLY CONTAMINATED PATIENTS

3.1. ASSESSMENT OF INTERNAL CONTAMINATION WITH RADIONUCLIDES

The aim of the assessment of internal contamination for purposes of radiation safety is to quantify the incorporation of the radioactive material into the body and to estimate the committed effective dose and, where appropriate, the committed equivalent dose to demonstrate compliance with dose limits. The ICRP, in Publication 103 [15], warned against the use of effective dose for evaluating the medical consequences of an individual's exposure. Therefore, the assessment of committed effective dose will not assist in evaluating the risk of severe deterministic and stochastic effects associated with internal contamination, such as late cancer development in a certain organ or tissue.

Once a decision is taken to initiate a 'definitive' specific decorporation treatment, the physician needs to bear in mind that, for some radionuclides, owing to the lack of direct knowledge or experience, the recommended treatment is based on experience with a stable isotope or element that shares an identical or similar metabolic behaviour with the radionuclide concerned.

For an assessment based and long term treatment decision, it is essential that physicians, physicists and other professionals employ a multidisciplinary approach to provide medical support, dose estimations, psychological support and follow-up.

3.2. BASIS FOR DECORPORATION DECISIONS

Dispersion of radioactive material may lead to contamination of the environment and individuals. Depending on a number of factors, if a radioactive material is incorporated into the human body (intake), as with any other contaminant, a deleterious health effect might occur. The use of specific drugs for impeding the deposition of radionuclides in organs or tissues could avoid accumulation and retention of radionuclides in the body. For instance, timely administration of stable iodine may block the uptake of radioiodine by the thyroid gland.

Natural processes of radionuclide excretion from the body can be accelerated by means of decorporation therapies. Decorporation itself is the action of biological processes that may be facilitated or enhanced by chemical or biological agents, by means of which incorporated radionuclides are removed from the human body [22]. The process of treatment for persons with internally deposited radionuclides is aimed at reducing the internal dose and hence the risk of health effects. It can be accomplished by reducing absorption, preventing incorporation and internal deposition of radionuclides within organs, and promoting elimination or excretion of absorbed nuclides [2]. The main decorporation methods include blocking and isotopic dilution, displacement, use of ion exchange resins, mobilization and chelation.

Decorporation agents and procedures are not completely free of possible untoward side effects. Therefore, indications for long term decorporation therapies need to be based on risk criteria. Reasonable decorporation actions are expected to be undertaken, as promptly as possible, if there is a risk of severe deterministic effects [25–27].

The generic criteria for decorporation are established and expressed in terms of the individual risk for human health to be averted by decorporation, as shown in Table 1.

TABLE 1. GENERIC CRITERIA FOR DECORPORATION IN EMERGENCY EXPOSURE SITUATIONS TO REDUCE THE RISK OF HEALTH EFFECTS DUE TO INTAKE OF RADIOACTIVE MATERIAL

Risk	Value	Actions
Risk of development of severe deterministic effect	>0.5%	All reasonable decorporation actions are expected to be undertaken, as promptly as possible, and under any circumstances, to avoid the risk of severe deterministic effects in any organ or tissue due to the intake of a radioactive material
Risk of development of radiation induced cancer	≥1%	Reasonable decorporation actions should be undertaken to minimize absolute lifespan risk of radiation induced cancer in any organ or tissue due to the intake of radioactive material
Risk of development of radiation induced cancer	<1%	No decorporation action should be undertaken

Reasonable decorporation actions to minimize the risk of radiation induced cancer in any organ or tissue due to the intake of radioactive material should be undertaken in accordance with the appropriate operational intervention level (OIL).

In some instances, the medical decision to begin immediate decorporation treatment will be based solely on the strength of evidence, preliminary or early assessments and/or clinical judgement. For the long term use of decorporating drugs, it is essential to have a comprehensive evaluation of the intake. In this manual, OILs are the parameters to be considered to assist in decisions regarding decorporation treatment.

3.3. BASIS FOR THE USE OF OILs FOR DECORPORATION

IAEA Safety Standards Series No. GSR Part 7, Preparedness and Response for a Nuclear or Radiological Emergency [1], defines an OIL as "A set level of a measurable quantity that corresponds to a generic criterion". In addition, IAEA Safety Standards Series No. GS-G-2.1, Arrangements for Preparedness for a Nuclear or Radiological Emergency [7], defines an OIL as follows:

> "A calculated level, measured by instruments or determined by laboratory analysis, that corresponds to an intervention level or action level. OILs are typically expressed in terms of dose rates or of activity of radioactive material released, time integrated air concentrations, ground or surface concentrations, or activity concentrations of radionuclides in environmental, food or water samples. An OIL is a type of action level that is used immediately and directly (without further assessment) to determine the appropriate protective actions on the basis of an environmental measurement."

The risk for the development of a severe deterministic or stochastic effect in an organ or tissue T after intake of a radionuclide R is a function of the intake. Table 2 provides a list of some radionuclides with their minimum values of reference level of intake (RLI), which correspond to the generic risk criteria for use of decorporation treatment presented in

Table 1. They have been calculated on the basis of information provided in various IAEA publications.

TABLE 2. MINIMUM VALUE OF REFERENCE LEVEL OF INTAKE CORRESPONDING TO THE GENERIC RISK CRITERIA FOR DECORPORATION

Radionuclide	RLI_{Min}, Bq	Radionuclide	RLI_{Min}, Bq	Radionuclide	RLI_{Min}, Bq
H-3	2.6×10^9	Ru-106	1.7×10^6	Ra-228	7.1×10^4
P-32	3.0×10^7	Ag-110m	8.2×10^6	Th-228	2.8×10^3
Cr-51	1.4×10^9	Sb-124	1.5×10^7	Th-232	8.5×10^3
Mn-54	6.3×10^7	Sb-125	2.2×10^7	Th-234	1.1×10^7
Fe-59	2.8×10^7	I-125	5.8×10^6	U-234	1.3×10^4
Co-57	9.9×10^7	I-129	8.8×10^5	U-235	1.5×10^4
Co-58	4.7×10^7	I-131	4.5×10^6	U-238	1.6×10^4
Co-60	3.7×10^6	Cs-134	7.2×10^6	Np-237	2.1×10^4
Zn-65	2.4×10^7	Cs-137	9.9×10^6	Pu-238	1.0×10^4
Rb-86	2.8×10^7	Ba-140	1.7×10^7	Pu-239	1.1×10^4
Sr-85	1.1×10^8	Ce-141	2.7×10^7	Pu-240	1.1×10^4
Sr-89	1.2×10^7	Ce-144	2.1×10^6	Am-241	1.3×10^4
Sr-90	8.7×10^5	Hg-203	4.3×10^7	Cm-242	2.5×10^4
Zr-95	1.8×10^7	Ra-226	3.2×10^4	Cm-244	1.5×10^4

The amount of radioactive material incorporated by an individual can be measured through the retention of radionuclides in some organs or tissues and the excretion rates characteristic of internal exposures (using biokinetic models). This relationship is the basis for the use of OILs for decorporation. Thus, OILs may be calculated and established for decorporation treatment by internal dose assessment through in vivo bioassays (retention in the whole body, BRt; retention in the lung, LRt; retention in the thyroid, TRt) and by in vitro bioassays (daily urinary excretion, UEx; daily faecal excretion, FEx).

During a radiation emergency, persons may be both externally and internally contaminated with radionuclides. A radiation meter does not always discriminate between contamination that is inside the body and contamination that is outside the body (depending on the emissions). Checking a patient for contamination will be done prior to decontamination so that the presence of contamination on the face and hands can be confirmed; this serves as a good indication of possible internal contamination.

As a rule of thumb, if contamination is detected around the nose and mouth within the first hour after exposure, a swab of both nostrils and the mouth will need to be obtained and counted using a contamination meter. If samples obtained from both nostrils have approximately the same count rates, it is likely that the patient inhaled homogeneously

distributed radioactive material. A gross estimate of intake following inhalation can be made by evaluating the nasal swabs. The summed counts from both nostrils are converted to activity, which represents roughly 5% to 10% of the deposition in the alveolar–interstitial gas exchange region of small, insoluble particles 1 to 5 μm in diameter [21]. If one nostril demonstrates markedly higher counts than the other, and the individual does not have unilateral nostril breathing, this suggests mechanical contamination of the nostril (e.g. from a contaminated finger), and the risk of significant internal contamination via inhalation is potentially lower. As inhaled contaminants remain only a short period of time in the upper respiratory tract before being removed by the normal clearance mechanisms, a negative test (nasal or mouth swabs) does not rule out the possibility of internal contamination. Therefore, nasal swabs will need to be collected within the first hour after exposure, whenever possible [21].

It is important to note that a contamination meter can be used to screen the patient for potential radiation contamination, but this cannot identify the radionuclides involved. Other detectors, such as gamma and alpha spectrometers, portable or laboratory installed, may also be used for this purpose.

Besides the early techniques mentioned above — which must be performed within the first hour to provide accurate results — other techniques are also useful for screening patients for potential internal contamination. If a radiation emergency occurs at a nuclear facility, data from workplace air monitoring can provide a good indication for potential internal exposure to workers and responders. During a mass casualty emergency, portal monitors could be used to screen a large number of people for internal contamination involving gamma emitter radionuclides (as long as no life threatening condition is present, which would make medical stabilization a priority). In addition, gamma cameras in nuclear medicine departments in hospitals could also be used for screening individuals for radioactive contamination. However, appropriate training for hospital personnel is needed [28].

Quantitative and qualitative assessment of internal radiation contamination is achieved through bioassay techniques for the identification and measurement of radionuclides in urine, blood or faecal samples (in vitro bioassay) and/or through lung, thyroid, wound or whole body counting (in vivo bioassay). Bioassays need specialized instrumentation and expertise. It is important to identify specialized bioassay laboratories during the emergency planning process, as hospital laboratories usually do not have the required instrumentation and expertise [2].

Whole body counting is the most accurate bioassay method for assessing internal contamination with radionuclides that emit penetrating gamma radiation. However, such counting systems are not always available. It is important to consider that large intakes of radionuclides may exceed the capacity of detectors. In addition, external contamination can strongly interfere with the measurements, resulting in inaccurate readings. Generally, urine and faeces bioassays are the most feasible methods for assessing intake. Because of their convenience, urine samples are the preferred type for bioassay measurements of internal contamination with soluble compounds. Urine bioassays can be used to measure a wide range of radionuclides. In general, 24-hour samples are preferred, because biokinetic models used to interpret data are based on daily excretion rates. However, in a mass casualty emergency, spot samples are more practical. Measurements of spot samples can be normalized by using specific gravity or creatinine methods to reflect the daily excretion [20, 29]. In general, the first sample will be taken as soon as possible after exposure. Sequential samples will initially be

necessary to assess the intake and will be used later to monitor the effectiveness of the treatment.

As previously mentioned, OILs for decorporation decisions are calculated levels of quantities that can be measured by instruments (in vivo bioassay) or determined by laboratory analyses (in vitro bioassay). They correspond to RLIs, for example the RLI that makes decorporation necessary to avoid severe deterministic effects or the RLI for decorporation to minimize the future occurrence of stochastic effects, especially cancer development.

The following OILs are used in individual monitoring in cases of internal exposure:

For in vivo bioassay:

- BRt — Retention in whole body, Bq;

- LRt — Retention in the lung (thoracic region of respiratory system), Bq;

- TRt — Retention in thyroid, Bq.

For in vitro bioassay:

- UEx — Daily urinary excretion, Bq/d;

- FEx — Daily faecal excretion, Bq/d.

The OIL is the radionuclide specific time (t) dependent function of corresponding RLI:

$$\text{OIL}_R(t) = \text{RLI}_R \times f_{T,R}(t) \tag{1}$$

where $f_{T,R}(t)$ is the radionuclide specific retention function for in vivo bioassay or the radionuclide specific excretion function for in vitro bioassay. Decorporation agents and procedures are not free of possible untoward side effects. To limit harmful effects of decorporation, the decorporation therapy ought not be used if the intake of radioactive material is one tenth the minimum value of RLI given in Table 2, or less. Applicable bioassay methods for individual monitoring of some selected radionuclides, which have been adapted from Ref. [2], are presented in Table 3.

TABLE 3. BIOASSAY METHODS FOR SELECTED RADIONUCLIDES [2]

Element and radionuclide		Compounds and absorption type (F) = fast; (M) = medium; (S) = slow	In vivo			In vitro	
			BRt	LRt	TRt	UEx	FEx
Hydrogen	H-3	All compounds				▪	
Iron	Fe-59	Oxides, hydroxides and halides — (F)	▪			▪	
		All unspecified compounds — (M)	▪	▪		▪	
Cobalt	Co-57, Co-58,	Oxides, hydroxides, halides and nitrates — (S)	▪	▪		▪	▪

Element and radionuclide		Compounds and absorption type (F) = fast; (M) = medium; (S) = slow	In vivo			In vitro	
			BRt	LRt	TRt	UEx	FEx
	Co-60	All unspecified compounds — (M)	■	■		■	■
Strontium	Sr-85	Strontium titanate (SrTiO$_3$) — (S)	■	■		■	
		All unspecified compounds — (F)	■			■	
	Sr-89, Sr-90	Strontium titanate (SrTiO$_3$) — (S)				■	
		All unspecified compounds — (F)				■	
Ruthenium	Ru-106	Halides — (M)	■	■		■	
		Oxides and hydroxides — (S)	■	■		■	
		All unspecified compounds — (F)	■	■		■	
Iodine	I-125	All compounds — (F)			■	■	
	I-131, I-133	All compounds — (F)			■	■	
Caesium	Cs-134, Cs-137	All compounds — (F)	■			■	
Radium	Ra-226, Ra-228	All compounds — (M)	■	■		■	
Thorium	Th-228, Th-232	Oxides and hydroxides — (S)	■	■		■	■
		All unspecified compounds — (M)	■	■		■	■
Uranium	U-234	Most hexavalent compounds, e.g. UF$_6$, UO$_2$F$_2$ and UO$_2$(NO$_3$)$_2$ — (F)				■	■
		Less soluble compounds, e.g. UO$_3$, UF$_4$, UCl$_4$ and most other hexavalent compounds — (M)				■	■
		Highly insoluble compounds, e.g. UO$_2$ and U$_3$O$_8$ — (S)				■	■
	U-235	Most hexavalent compounds, e.g. UF$_6$, UO$_2$F$_2$ and UO$_2$(NO$_3$)$_2$ — (F)				■	■
		Less soluble compounds, e.g. UO$_3$, UF$_4$, UCl$_4$ and most other hexavalent compounds — (M)		■		■	■
		Highly insoluble compounds, e.g. UO$_2$ and U$_3$O$_8$ — (S)		■		■	■

Element and radionuclide		Compounds and absorption type (F) = fast; (M) = medium; (S) = slow	In vivo			In vitro	
			BRt	LRt	TRt	UEx	FEx
	U-238	Most hexavalent compounds, e.g. UF_6, UO_2F_2 and $UO_2(NO_3)_2$ — (F)				▪	▪
		Less soluble compounds, e.g. UO_3, UF_4, UCl_4 and most other hexavalent compounds — (M)				▪	▪
		Highly insoluble compounds, e.g. UO_2 and U_3O_8 — (S)				▪	▪
Neptunium	Np-237	All compounds — (M)		▪		▪	▪
Plutonium	Pu-238, Pu-239, Pu-240	Insoluble oxides — (S)				▪	▪
		All unspecified compounds — (M)				▪	▪
Americium	Am-241	Insoluble oxides — (M)		▪		▪	▪
Curium	Cm-242	All compounds — (M)				▪	▪
	Cm-244	All compounds — (M)				▪	▪
Californium	Cf-252	All compounds — (M)		▪		▪	▪

The Graphic Database on Predicted Monitoring Data for Intakes of Radionuclides [30] provides retention and excretion data for inhalation and ingestion intake by workers and members of the public of the following radionuclides:

H-3, P-32, Cr-51, Mn-54, Fe-59, Co-57, Co-58, Co-60, Zn-65, Rb-86, Sr-85, Sr-89, Sr-90, Zr-95, Ru-106, Ag-110m, Sb-124, Sb-125, I-125, I-129, I-131, Cs-134, Cs-137, Ba-140, Ce-141, Ce-144, Hg-203, Ra-226, Ra-228, Th-228, Th-232, Th-234, U-234, U-235, U-238, Np-237, Pu-238, Pu-239, Pu-240, Am-241, Cm-242, Cm-244 and Cf-252.

The biokinetic models developed by the ICRP can be used for the calculation of the effective dose arising from the soluble component once the systemic uptake has been determined. As a first approximation, data for direct uptake to blood (injection) can be used. These evaluations are very crude approximations and are only to be used with caution, as an internationally agreed recommendation on models for wounds is still lacking [31].

Some groups have combined the National Council on Radiation Protection and Measurements (NCRP) wound model describing the retention of selected radionuclides at the site of a contaminated wound with the ICRP element-specific systemic models for those radionuclides to derive dose coefficients for intakes via contaminated wounds, providing data for 35 radionuclides commonly encountered in various activities, such as those involving nuclear weapons, fuel fabrication or recycling, waste disposal, medicine, research and nuclear power [32]. These include:

H-3, C-14, P-32, S-35, Fe-59, Co-57, Co-58, Co-60, Tc-99m, Ru-106, I-125, I-129, I-131, Cs-134, Cs-137, Ir-192, Tl-201, Po-210, Ra-226, Ra-228, Th-228, Th-230, Th-232, U-234, U-235, U-238, Np-237, Pu-238, Pu-239, Pu-240, Pu-241, Am-241, Cm-242, Cm-244 and Cf-252.

In spite of logistical and technical problems, in vivo bioassay measurement provides the most rapid and reliable data for the estimation of the total activity of radionuclides in the whole body or in a specific region of the body at the time of measurement. Whole body counters (fixed or transportable) and special counters such as low energy chest counters, wound monitors, thyroid counters or screening equipment could be used to perform these measurements. In some cases, medical devices such as gamma cameras can also be calibrated for quantification of activity in the body [28].

Table 4 shows the main methods of analysis for some radionuclides. Some of these methods are not usually available in hospital facilities; it is essential that this be addressed during the response preparedness stages [2].

TABLE 4. METHOD OF ANALYSIS FOR SELECTED RADIONUCLIDES [2]

Radionuclide	Method
H-3	Liquid scintillation
Fe-59	Gamma spectrometry
Co-57, Co-58, Co-60	Gamma spectrometry
Sr-85, Sr-89, Sr-90	Liquid scintillation
Sr-85	Gamma spectrometry
Ru-106	Gamma spectrometry
I-125, I-129, I-131	Gamma spectrometry, liquid scintillation
Cs-134, Cs-137	Gamma spectrometry
Ra-226, Ra-228	Proportional counter
Uranium	Fluorimetry, alpha spectrometry, inductively coupled plasma mass spectrometry
Thorium	Spectrophotometry, alpha spectrometry, inductively coupled plasma mass spectrometry
Pu-238, Pu-239, Pu-240	Alpha spectrometry
Np-227	Gamma spectrometry

Radionuclide	Method
Am-241	Alpha spectrometry
Cm-242, Cm-244	Alpha spectrometry
Cf-252	Gamma spectrometry, alpha spectrometry

4. CONTAMINATION PATHWAYS, METABOLIC PHASES AND METHODS FOR THE TREATMENT OF INTERNALLY CONTAMINATED PATIENTS (DECORPORATION METHODS)

Several factors influence the possible medical consequences of internal contamination and the need for treatment. Important ones include:

— The amount of radioactive material that enters the body (intake);

— Its chemical form (influences solubility and hence uptake);

— The kind of emissions and half-life of the contaminant radionuclide (alpha emitters have greater internal radiotoxicity);

— The radiosensitivity of the organ or tissue where, after uptake, the radionuclide is incorporated (target organ or tissue);

— The age of the person (young people have a longer life expectancy, so the probability of cancer is greater);

— Individual physiological factors that make excretion more difficult (e.g. kidney failure);

— The contamination pathway (contamination by soluble materials through wounds would lead to direct uptake).

Once a decision has been taken to initiate a specific decorporation treatment, the physician has to bear in mind that, for some radionuclides, owing to the lack of direct knowledge or experience, the recommended treatment is based on the treatment for contamination with a stable isotope or element that shares an identical or similar metabolic behaviour with the radionuclide concerned. Prompt intervention can reduce dose, which in turn may be enough to make a significant impact on health consequences. The medical team involved has to remember that treatment is usually intended to reduce the risk of long term effects rather than to ease the effects of an acute radiation related injury. Detailed information on specific therapies for different radionuclides is found in Appendix I.

An initial and highly important consideration is the route of entry of the radioactive material into the body. There are five potential pathways through which persons may become internally contaminated with radionuclides. These include inhalation of radioactive particles or gases, ingestion of radioactive dust and/or contaminated food or water, absorption of radioactive material through open wounds, absorption of radioactive material through intact skin and injection of radioactive materials into the body [11]. Once it enters the body, the radioactive material undergoes a series of physiological processes. The way radioactive material is retained in and/or released from organs and tissues depends on factors such as its physical and chemical forms, the intake pathway and physiological conditions [5].

Inhalation of radioactive materials may occur during radiation emergencies. Approximately 25% of inhaled radionuclides are immediately exhaled [33]. The fate of the remaining 75% of inhaled radionuclides depends on their physicochemical properties, especially the particle sizes and their solubility in the lungs or GI tract. Particles with an aerodynamic diameter greater than 10 μm tend to stay in the upper respiratory tract and are further cleared to the GI tract by the mucociliary route. Smaller particles can be deposited in the lower respiratory tract, where they may irradiate the lung tissue or be absorbed into the body and later deposited in other organs. Soluble particles such as caesium chloride can be absorbed

directly into the circulatory system, while insoluble particles such as plutonium oxides enter the lymphatic system or may be cleared by the mucociliary action to the GI tract. Special attention will need to be given to patients with respiratory disease, especially chronic airflow limitation. These patients present slow 'lavage', because the mucociliary action is impaired by their condition [31].

Ingestion may be another important internal contamination pathway. For example, as a consequence of accidental releases from nuclear facilities, as in Chernobyl and Fukushima, food and drinking water supplies may be contaminated with radioactive material [5]. Absorption from the GI tract also depends on the chemical properties, and particularly the solubility, of the radioactive material. Depending on the chemical form, certain easily soluble radionuclides such as some caesium compounds are absorbed, while other radionuclides may pass through the GI tract with minimal absorption. Absorption of radionuclides is usually assumed to occur from the small intestine. The contents of the small intestine are alkaline, so elements that hydrolyse readily, such as rare earths and the actinides, are poorly absorbed [31].

Open wounds and absorption through intact skin are additional routes by which radionuclides can enter the body. During some types of radiation emergencies, people may get injured by blast materials or sharp edges. As a precautionary measure, wounds should be considered contaminated until proven otherwise, and need to be evaluated for the presence of radioactive materials as long as it does not interfere with the treatment of life-threating conditions. Mechanical damage has to be avoided during skin decontamination in order to avoid internal contamination [2, 5]. Skin wounds, including acid burns, create a portal for any particulate contamination to come into direct contact with the subcutaneous tissue, bypassing the epithelial barrier.

Factors that determine the rate of absorption of the radionuclide from intact skin or a wound include chemical compounds that interfere with the integrity of the skin, the solubility of the radioactive material, pH, tissue reactivity and the size of the contaminant particles. Particles with higher solubility are absorbed more quickly. While much of the material may be retained at the wound site, soluble material can be transferred to the blood and hence to other parts of the body. Insoluble material will be slowly translocated to regional lymphatic tissue, where it will gradually dissolve and eventually enter the blood. A variable fraction of insoluble material can be retained at the wound site or in lymphatic tissue for the life of the contaminated individual [31].

Few radioactive materials can enter the body via intact skin. In this case, the skin absorption occurs primarily through passive diffusion. The physical barrier of the epithelium is resistant to particulate matter. Therefore, very few radionuclides can penetrate the intact skin to any appreciable degree. Tritium (H-3) in the form of tritiated water can pass readily through the skin like other water molecules.

Another very relevant aspect concerns the four metabolic phases to be taken into account in internal contamination with radionuclides: intake, uptake, deposition and decorporation [11, 22]:

— **Intake** refers to the act or the processes involved in taking radionuclides into the body by inhalation or ingestion or through the skin. The word 'intake' also denotes the activity of the radionuclides incorporated into the body in a given time period or as a result of a given event. In some publications, the term 'incorporation' is used to

denote this phase of internal contamination with radionuclides. Much less frequently, the word 'internalization' is employed for the same purpose.

— **Uptake** refers to the processes by which radionuclides enter the systemic circulation (body fluids) from the respiratory tract, from the GI tract or directly through the skin, especially through wounds. In other words, the fraction of an intake entering the systemic circulation is referred to as the uptake.

— **Deposition** is the ingress of the radionuclide into the cells of its target organ or tissue (e.g. the thyroid for radioiodines) after uptake or the contact of radioactive materials with regions of the respiratory tract in the case of inhalation as an intake process.

— **Decorporation** is the action, mediated by biological processes and facilitated by chemical or biological agents, by means of which incorporated radionuclides are removed from the human body [22].

Of course, the best therapeutic approach after intake has occurred is to avoid or minimize as much as possible the radionuclide uptake.

The solubility (transportability) of a compound containing radionuclides is an important factor for deciding on the appropriate kind of treatment. In principle, systemic therapy would not be indicated if contamination occurred with a non-soluble material. However, caution is needed, because no material is completely insoluble and, conversely, some material reported as highly soluble may contain a relatively insoluble fraction. Besides, other factors such as the size of the particles (especially if contamination resulted from inhalation) influence the degree of absorption of a radioactive material. Another aspect to be considered is that information on solubility will not be readily available for the initial medical decision on the therapeutic approach.

The immediate treatment goals for internal contamination are:

— To impede or reduce uptake of the radionuclide into the blood and deposition into target organs or tissues;

— To accelerate the excretion of radionuclides from the body;

— To minimize the absorbed dose by the most effective method.

The ultimate goal of the treatment is to reduce the long term risk of radiation induced cancer. This may be accomplished by reducing radionuclide uptake from the site of entry, stimulating excretion, diluting the radioactive material or chelating it [34]. After a radionuclide has been retained in tissues with a slow cell turnover, the effectiveness of treatment is significantly reduced. It is therefore generally accepted that treatment is most effective when administered as soon as internal contamination occurs [11].

The selection of a preferable treatment method depends on factors such as:

— Physical characteristics of the contaminant radionuclide (type of decay, half-life, etc.);

— Biokinetics of the radionuclide (solubility of the material is an important aspect);

— Radiosensitivity of the target organ or tissue targeted by the radionuclide;

— Intake pathway and activity (burden);

— Availability and efficacy of treatment and possible side effects of the prescribed therapy;

— Age and comorbidities of the contaminated person.

The concept of target organ, although important, does not take into account the total risk attributable to the exposure of all tissues irradiated (effective dose). In 1990, the ICRP, updating the existing concepts of detriment and effective dose for the purpose of radiological protection, specified a number of organs and tissues that have to be considered because of their susceptibility to radiation damage, the seriousness of such damage and the extent to which this could be treatable. In 2007, the ICRP, in Publication 103, further updated the concept of detriment [15].

Treatment procedures for internal contamination with radionuclides are generally included in the categories discussed below [35]. The duration of decorporation treatment will depend on a very judicious evaluation of its efficacy, and the involvement of both clinical and dosimetric aspects is necessary. Different professionals can be part of this assessment, such as health physicists, dosimetry personnel, radiopathologists, toxicologists and clinicians.

4.1. GENERAL PROCEDURES

These procedures aim to reduce or inhibit the absorption of radionuclides from the GI or respiratory tracts or from skin and wounds [5]. Examples of general procedures that can be used to reduce radionuclide uptake are gastric lavage, the use of emetics and laxatives, gastric alkalinization and wound irrigation. Ideally, general and specific procedures like the administration of decorporating drugs are most effective if begun within the first hour after intake. In many instances, gastric lavage and the use of laxatives or emetics are not feasible (as in a mass casualty emergency) or can even be contraindicated for clinical or toxicological reasons.

Although lung lavage could also be considered a 'general procedure', by virtue of its particularities, it will be dealt with as a specific topic.

4.2. BLOCKING

Blocking agents reduce the body's uptake of a radionuclide by saturating tissues, organs and metabolic processes with the stable isotope (an identical non-radioactive element). The most commonly known blocking agent is potassium iodide (KI), which is used to prevent the deposition of radioactive iodine isotopes in the thyroid gland. If promptly administered, KI will saturate the thyroid with non-radioactive iodine so that the radioactive iodine isotope, inhaled or ingested, will pass through the body instead of being taken up by the thyroid and subsequently irradiating it. KI is most effective if it is taken shortly before or shortly after internal contamination occurs, as illustrated by the graph in Fig. 1 [2, 11, 36].

FIG. 1. Protection of the thyroid gland by KI from inhaled iodine-131 as a function of the time of administration [36].

4.3. ISOTOPIC DILUTION

Isotopic dilution consists of the administration of large quantities of a stable isotope to accelerate the process of elimination of the radionuclide. Tritium contamination can be treated by increasing the fluid intake. Enhanced fluid intake (e.g. water, tea, milk) will increase excretion and can reduce the time tritium stays in the body [5].

4.4. DISPLACEMENT

Displacement has essentially the same principle as blocking and dilution therapies, but in this instance, a non-radioactive element with a different atomic number is used. The non-radioactive element competes for the uptake sites, displacing the radioisotope from the receptor, as calcium gluconate competes with radiostrontium for bone deposition or stable iodine displaces technetium-99m [5, 21].

4.5. ION EXCHANGE

Radioactive caesium recycles from the blood into the gut; therefore, ferric hexacyanoferrate, known as Prussian Blue, is useful to capture recycling caesium through an ion exchange mechanism even a long time after contamination has occurred. Prussian Blue was extensively and successfully used for caesium-137 decorporation in the Goiânia accident [37–39].

4.6. MOBILIZATION

Mobilization refers to increasing the natural turnover process to release radionuclides from body tissues and to enhance the elimination rate (diuretic action). For example, the use of ammonium chloride, when given orally, results in acidification of the blood and increases the elimination of internalized radiostrontium.

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4.7. CHELATION

Chelating agents are organic or inorganic compounds capable of binding metal ions to form complex ring-like structure called 'chelates'. Chelating agents possess 'ligand' binding atoms that form either two covalent linkages or, in the case of bidentate chelates, one covalent and one coordinate or two coordinate linkages, which make them easily excreted by kidneys or other organs [40].

The rate of the chelation reaction depends on the metal. It tends to be fast with most metals, and in these cases the reaction is instantaneous, but with some other ions, such as Cr(III) and Co(III), the reaction tends to be very slow.

Chelates are categorized by coordination numbers, which correspond to the number of bonds between the metal and the chelating agent. In the chain of the chelating agent, the donor atoms are separated by suitable numbers of other atoms to allow the formation of chelate rings.

The use of chelating agents is most effective when the treatment begins immediately after exposure, while the radionuclides are still in circulation and before their deposition within cells in target organs, such as bone or liver.

Chelating agents firmly bind to metals (including radioactive ones) to eliminate them from the body. The formation of radionuclide complexes that leads to greater excretion via kidney and/or intestine is proven effective for actinides and lanthanides, such as plutonium and americium. The chelating agent with the greatest potential range of use in radiotoxicology is DTPA. The drug is usually indicated by intravenous route, but an aerosol form is also available in some countries. Normally, DTPA can only be used under medical supervision in specialized centres. It is indicated, for example, for internal contamination with americium or plutonium. DTPA is often used in two formulations with calcium and zinc [41, 42].

Factors that can affect the stability of chelating agents include:

— Chemical properties of the chelating agent (number of atoms in the chelating ring; five and six atom rings are the most stable).

— Acidity or alkalinity. Chelates with a low stability constant can be dissociated in mild acidic conditions, and pH is also an important factor influencing complex formation and stability. Most chelating agents are unstable at low pH, whereas at high pH metals tend to form insoluble hydroxides, which are less accessible to chelating agents. This feature becomes significant in pathological conditions leading to acidosis or alkalosis [40].

— Selectivity of the chelating agent and concentrations of competing metals compared to that of the target metal. In the human body, several elements (calcium, iron, etc.) can compete with a target metal that needs to be removed by a chelating agent, so that essential elements may be also chelated from the body.

A properly selected and administered chelating drug will therefore enhance the excretion of some specific radionuclides and reduce their residence times in the body. Thus, it is important that a chelator satisfy criteria that allow it to:

— Transport across physiological barriers into compartments where a toxic metal ion is concentrated;

— Form a stable complex with the metal after removing it from the biological chelator, if required, at the site;

— Form a chelation complex whose properties render it non-toxic and facilitate its excretion, not only from the site of deposition, but also from the body [43].

In addition to DTPA, other important chelating agents (see Appendices) that can be used for decorporation of radioactive metals are dimercaprol (British anti-Lewisite, BAL), dimercaptosuccinic acid (DMSA) and deferoxamine (DFOA).

4.8. EXCISION

Wound debridement and excision for removal of fixed contamination may also be necessary. This demands a well-established evaluation of the condition by specialized personnel in order to provide the foundation for a sound medical decision on the basis of the benefits and risks of the surgical procedure. When surgical exploration and excision of contaminated tissue/foreign material is necessary, it should be performed with the assistance of a radiation safety professional (i.e. health physicist) using a wound probe. The excised material needs to be saved for radioanalysis. There is no contraindication to the use of standard local or systemic anaesthetic agents in managing these types of wound [44].

4.9. LUNG LAVAGE

Lung lavage is an invasive procedure that implies the same risk as that of general anaesthesia. It is indicated in a very limited number of cases. A thorough medical and dosimetric evaluation, among other parameters, is mandatory for indicating this kind of treatment for internal contamination with insoluble radioactive materials deposited in the lungs. Parameters that are used to evaluate the indication of lung lavage include clinical status, patient's age, existence of potential comorbidities, radiotoxicity of the contaminant, its burden and dose assessments. In selected cases, bronchoalveolar toileting may be performed by flexible bronchoscopy. This is a technique that is rarely used and would be expected only in a case with a very large lung burden of insoluble inhaled particles (i.e. an alpha emitter such as plutonium) [21].

Lung lavage has been indicated in cases that aim to avoid deterministic effects for lung doses above 6 gray-equivalents (Gy-Eq) anticipated within a 30 day period, and it needs to be considered carefully, on a case-by-case basis, to reduce the risk of stochastic effects at lower committed equivalent doses to the lung.

5. BASIC INFORMATION ON SELECTED RADIONUCLIDES AND POSSIBLE DECORPORATION THERAPY

There are different approaches for the medical management of internal contamination with radionuclides. The information that follows is based on the limited documented clinical experience and several publications on the treatment of internal contamination with radionuclides [2, 11, 45–51].

National health regulations of each Member State concerning the use of the drugs described in this section need also to be fully taken into account.

5.1. AMERICIUM (AM)

5.1.1. Origin

Americium is not found in nature. Americium-241 is produced in nuclear reactors; its physical characteristics are shown in Table 5. Releases to the environment may occur during the reprocessing of spent fuel [45, 46].

TABLE 5. PHYSICAL CHARACTERISTICS OF AMERICIUM-241 (Am-241)

Physical characteristics	Am-241
Physical half-life	432.7 years
Effective half-life	45 years (bone)
Main emissions	Alpha and gamma
Target organs	Liver, lung, bone, bone marrow

5.1.2. Chemical and metabolic behaviour

Americium is one of the transplutonium elements. They are actinides of valence 3+, which are all more transportable in the body than plutonium. Although incorporations are always minute, specific activities are very high. Americium-241 is the best known of the 16 main artificial isotopes of americium [45]. It is produced from the decay of plutonium-241 by beta decay, and it decays by emitting alpha and weak gamma radiation. In all cases, owing to the high specific activity, prompt treatment is required [47].

The absorption of actinides of valence 3+ is much more rapid than that of plutonium. After ingestion or inhalation, most americium is excreted from the body in few days. Less than 1% is absorbed after ingestion [45]. Diffusion may therefore be rapid; as with all the actinides, deposition is mainly in the skeleton, with very high retention, and in the liver, with moderate clearance. Compared with plutonium, the urinary excretion is high during the days after the intake. The liver is the primary soft tissue site of initial accumulation of absorbed americium in humans. Americium deposited in bone and skeletal muscle has longer retention half-times than that of americium in the liver. Therefore, at long times after exposure (years), bone and skeletal muscle will contain a larger fraction of the systemic americium burden than the liver. Americium-241 activity resides primarily in the respiratory tract, skeleton, liver and muscle. Lymph node concentration has also been described [48]. Radioactive metals are known to be excreted in the urine, faeces and breast milk [46].

The biokinetic model for americium is the same as that for plutonium: the generic actinide model. The model takes account of the initial deposition in bone, liver, gonads and other tissues; it also allows for transfer of activity from bone surfaces to bone volume and marrow, recycling of activity between tissues, as well as loss by excretion.

5.1.3. Emergency treatment

— Trisodium calcium diethylenetriamine-pentaacetate (Ca-DTPA).

Chelating agent containing monocalcium trisodium salt and DTPA [11, 41, 47, 49]. When it is not available, trisodium zinc diethylenetriamine-pentaacetate (Zn-DTPA) can be used as a second line of treatment. Zn-DTPA is also indicated for long term treatment.

5.1.4. Pharmacological information and therapy

Ca-DTPA (diethylenetriamine-pentaacetate, monocalcium trisodium salt) [11, 41, 50].

Ampoules: Each ampoule contains the equivalent of 1000 mg of pentetate calcium trisodium (1 g) Ca-DTPA/4 mL (250 mg/mL) or 1 g Ca-DTPA/5 mL (200 mg/mL), as sterile solution for intravenous use, to be stored between 15°C and 30°C.

Micronized capsules: For use in turbo-inhaler, 40 mg per capsule [50].

Ca-DTPA chelation treatment needs to be given as soon as possible after known or suspected internal contamination with transplutonium or transuranium elements [48].

Ca-DTPA and its radioactive chelates are excreted by glomerular filtration. Impaired renal function may decrease their rates of elimination and increase the serum half-life of Ca-DTPA. When possible, obtain baseline blood and urine samples.

Patients have to drink plenty of fluids and void frequently. Serum electrolytes and essential metals need to be closely monitored during Ca-DTPA treatment. Mineral supplements, or vitamin plus mineral supplements that contain zinc, are to be given as appropriate.

Dose in adults: Evidence supports doses of Ca-DTPA from 0.5 g (half an ampoule) to 1 g, given by slow intravenous injection over a period of 3–4 minutes or by intravenous infusion diluted in 100–250 mL of 5% dextrose in water (D5W), Ringer's lactate or normal saline. Only a single initial dose of Ca-DTPA is recommended.

Dose in pregnancy: Category C (United States Food and Drug Administration, FDA)[1]. Multiple doses of Ca-DTPA could result in an increased risk of adverse reproductive outcomes and thus are not recommended during pregnancy. Therefore, treatment of pregnant women needs to begin and continue with Zn-DTPA, if available, except in cases of high internal radiological contamination [42].

Dose in children: For children less than 12 years old, 14 mg/kg, not exceeding 0.5 g/day.

Contraindications: None at the recommended dosage.

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[1] Animal reproduction studies have shown an adverse effect on the fetus. There are no adequate and well-controlled studies in humans, but potential benefits may warrant use of the drug in pregnant women despite potential risks.

5.1.5. Respiratory tract contamination

For adults, a Ca-DTPA aerosol will be prepared (one ampoule in sterile or saline water, in a conventional generator producing an aerosol of suitable particle size). This procedure may be associated with exacerbation of asthma. An alternative procedure is to use a micronized Ca-DTPA capsule with a turbo-inhaler, followed by a slow intravenous injection or infusion of half an ampoule (0.5 g Ca-DTPA) in 100 cm^3 of 5% glucose.

5.1.6. Gastrointestinal tract contamination

Intravenous injection of DTPA is provided as described and complementary treatment is given to reduce the intestinal absorption with:

— Magnesium sulphate; ampoules 20 mL/3 g, 3 to 5 ampoules orally [11];

— Aluminium hydroxide; standard dose for hyperacidity: 10 mL (1.2 g) in adults; dose to reduce intestinal absorption: 60 to 100 mL orally;

— Barium sulphate; 100 to 300 g oral in a single dose in 250 mL water.

5.1.7. Control and monitoring

The patient has to be hospitalized in a specialized centre. DTPA chelation treatment will need to be followed by biological sampling (blood, urine and faeces) and assays in order to evaluate the effectiveness of the treatment. Mineral supplementation with zinc has to be appropriately considered [41].

5.2. CAESIUM (CS)

5.2.1. Origin

Natural caesium occurs as caesium-133. The elements rubidium and caesium are found together in small concentrations in silica rich rocks. Caesium has 31 isotopes, more than any other element. All are radioactive, with the exception of the stable element caesium-133. During the period 1945–1980, several hundred atmospheric nuclear tests were performed that released to the environment an estimated 1.3 × 1018 Bq of radioactive caesium-137, which was gradually deposited on the entire planet. Other sources of emissions have been releases from nuclear accidents and, in lower quantities, from nuclear facilities during normal operation [45, 46]. Uranium-235 fission in a nuclear reactor produces a large number of fission products. Radioactive isotopes of caesium produced in a nuclear reactor are either fission products (caesium-136, caesium-137 and caesium-138) or caesium-134 resulting from neutron capture by stable caesium-133. Caesium sources are used in medicine and industry. Table 6 shows the physical characteristics of the isotopes caesium-134 and caesium-137.

TABLE 6. PHYSICAL CHARACTERISTICS OF SOME RADIOISOTOPES OF CAESIUM

Physical characteristics	Cs-134	Cs-137
Physical half -life	2 years	30.1 years
Effective half-life	~96 days	~110 days
Main emissions	Beta and gamma	Beta and gamma
Target organ	Whole body	Whole body

5.2.2. Chemical and metabolic behaviour

Caesium belongs, like lithium, sodium, potassium and rubidium, to the alkali group of metals. Chemically, caesium has a single degree of oxidation corresponding to a valence of 1+. Its metabolism in the human body is very similar to that of potassium. It is very quickly absorbed and migrates into the cells. Once the caesium is absorbed, nearby cells and tissues are at high risk of damage due to the emission of beta particles [51].

Following entry into the blood, caesium is distributed uniformly through all body tissues [52]. Approximately 10% of caesium is eliminated rapidly, with a biological half-life of 2 days, and 90% is eliminated more slowly, with a biological half-life of 110 days. Less than 1% of the caesium is retained with a longer biological half-life of about 500 days. Caesium follows the movement of potassium and is excreted into the intestine, reabsorbed from the gut into the blood, then moved to the bile, where it is excreted again into the gut (entero-hepatic circulation).

Measurable amounts of caesium-137 have been found in the breast milk of women living in areas contaminated with radioactive fallout [51].

Without Prussian Blue treatment, about 80% of caesium is excreted through the kidneys and approximately 20% in the faeces [37].

As with all rapidly absorbed radionuclides, treatment is a matter of urgency. All caesium compounds are considered soluble; one reputedly insoluble compound (caesium silicoaluminate, used in caesium sources) is in fact soluble in the body after time because of the considerable radiolysis of the compound, which has a high specific activity.

5.2.3. Emergency treatment

— Prussian Blue.

5.2.4. Pharmacological information and therapy

Capsules: supplied as 0.5 g of insoluble Prussian Blue.

Prussian Blue contains insoluble ferric hexacyanoferrate (II). The drug, after oral ingestion, is not absorbed through the intact GI wall. Its clearance from the body depends on the GI tract transit time. Prussian Blue insoluble acts by ion exchange, adsorption and mechanical trapping within the crystal structure, which is very high for caesium and thallium.

Prussian Blue binds caesium isotopes in the GI tract after these isotopes have been ingested or excreted in the bile by the liver, thereby reducing GI reabsorption (entero-hepatic circulation).

In studies of rats, pigs and dogs internally contaminated with caesium and thallium, presence of the insoluble complexes in the GI lumen changed the primary elimination route from urinary tract to GI tract (faeces) and increased the rate of elimination.

Most of the experience regarding clinical treatment with Prussian Blue comes from the Goiânia radiological accident in 1987 [12].

Dose in adults: 1 g to 3 g three times a day orally in a little water. The duration of treatment after exposure is dictated by the level of contamination and by clinical judgement; it is also based on urine and faeces bioassays [47, 50].

Dose in pregnancy: Category C (FDA)[2]. Prussian Blue insoluble is not absorbed from the GI tract. Effects on the fetus have not been described.

Dose in children: 1 g orally three times a day (2 to 12 years old). By body weight, the recommended doses range from 0.32 g/kg in a 12 year old patient to 0.21 g/kg in a two to four year old patient [52]. Dosage for neonates and infants has not been established.

Contraindications: None at the recommended dosage. Prussian Blue may be less effective in patients with impaired liver function owing to decreased excretion of bile, and a resulting drop in caesium entero-hepatic circulation. Capsules may be taken with food to stimulate excretion of caesium.

This agent can cause constipation, leading to a slow transit time for caesium, thereby increasing the absorbed radiation dose. Thus, a high fibre diet and/or fibre based laxatives may be indicated.

Interactions have not been described, even with other co-administered 'decontamination' drugs.

5.2.5.   Respiratory tract, gastrointestinal tract, skin and wound contamination

Treatment will be the same as for digestive or pulmonary contamination. Such treatment will also prevent intestinal reabsorption by interrupting the entero-hepatic cycle. In the case of wound contamination, it is important that intestinal precipitation with a solution of Prussian Blue not be delayed by local decontamination. Areas will be washed with a concentrated Ca-DTPA solution (1 g = 1 ampoule) accompanied by a slow intravenous injection or infusion of half an ampoule (0.5 g) in 100 cm^3 of 5% glucose.

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[2] Animal reproduction studies have shown an adverse effect on the fetus. There are no adequate and well-controlled studies in humans, but potential benefits may warrant use of the drug in pregnant women despite potential risks.

5.2.6. Control and monitoring

Serum electrolytes need to be closely monitored during Prussian Blue treatment owing to the risk of hypokalaemia. Caution is needed when treating patients with pre-existing cardiac arrhythmias or electrolyte disorders.

Excreta sampling and bioassays are particularly important, to determine the activity in the body and to organize the follow-up of its evolution with an acceptable accuracy on the basis of the urine/faeces activity ratios.

A quantitative baseline of the incorporation of caesium can be obtained by appropriate whole body counting, whenever this is feasible.

Preferably all patients will be transferred to a specialized centre as soon as the emergency treatment has been completed and biological samples have been obtained.

Women should interrupt breast feeding; studies to determine if Prussian Blue insoluble is excreted in human milk have not been conducted. Since Prussian Blue insoluble is not absorbed from the GI tract, its excretion in breast milk is highly unlikely. However, caesium is transmitted from mother to infant in breast milk.

5.3. COBALT (CO)

5.3.1. Origin

Stable cobalt-59 is found in the environment, at a concentration of 23 ppm in the Earth's crust. In non-saline water, its concentration is 1 ppb. This element is essential for life and is present in the nucleus of cyanocobalamine (vitamin B12).

Cobalt-60 is not found in nature and is produced industrially from neutron activation of stable cobalt. Due to its specific characteristics (see Table 7), it is used in research, in medical facilities for radiotherapy and in the industrial field for gamma radiography, sterilization and food irradiation [45, 46]. Cobalt-57 has been used for nuclear medicine studies and cobalt-58 has been used as a tracer to evaluate the metabolism of vitamin B12.

TABLE 7. PHYSICAL CHARACTERISTICS OF SOME RADIOISOTOPES OF COBALT

Physical characteristics	Co-57	Co-58	Co-60
Physical half-life	271.8 days	70.8 days	5.3 years
Effective half-life	170 days	65 days	1.6 years
Main emissions	Electron and gamma	Beta+ and gamma	Beta and gamma
Target organ	Liver	Liver	Liver

5.3.2. Chemical and metabolic behaviour

Transfer pathways in humans and laboratory animals have been studied using cobalt-57 in the form of cobalt oxide. Cobalt particles deposited in the respiratory tract can be absorbed

into the blood after dissolution or mechanically transferred to the GI tract by mucociliary action and swallowing [53].

Large particles (>2 μm) tend to deposit in the upper respiratory tract, where mechanical clearance processes occur more readily than translocation. Smaller particles that deposit in the lower respiratory tract will usually remain dissolved or be phagocytosed by macrophages and then translocated [53].

Approximately 50% of the cobalt that enters the GI tract will be absorbed [53]. But the absorption of cobalt by the GI tract varies from 20% to 95% of the amount ingested according to the age of the patient and other conditions [46].

Intestinal absorption is a function of the solubility of the salt and the amount (by weight) of cobalt in it; in the case of a soluble salt such as a chloride, intestinal absorption may attain 50% [47]. Repeated intravenous injections, such that the intake is relatively constant, are followed by retention of about 75%, with urinary excretion (17%) predominating over faecal excretion.

As a component of vitamin B12, cobalt is present in most body tissues, with the highest levels found in the liver, followed by the kidney and significant bone retention [54]. Up to 50% of absorbed cobalt is directly eliminated in half a day, approximately 5% is retained by the liver and 45% is homogeneously distributed in the rest of the tissues. From this, 60% is eliminated in 6 days, 20% in 60 days and 20% in more than 800 days, predominantly by the urine (excretion ratio 6:1).

Highly concentrated stable cobalt and its compounds may cause severe poisoning (kidneys and cardiovascular and GI systems). Inhalation increases the risk of pulmonary fibrosis.

Soluble cobalt has also been shown to alter the calcium influx into cells, functioning as a blocker of inorganic calcium channels, especially in the liver and pancreas in rats.

5.3.3.   Emergency treatment

— Trisodium calcium diethylenetriamine-pentaacetate (Ca-DTPA): chelating agent, containing monocalcium trisodium salt and DTPA [11, 41, 47, 49].
— Magnesium sulphate, aluminium hydroxide or barium sulphate in GI contamination.

5.3.4.   Pharmacological information and therapy

Ca-DTPA (diethylenetriamine-pentaacetate, monocalcium trisodium salt) [11, 41, 50].

Ampoules: 1 g Ca-DTPA/4 mL (250 mg/mL) or 1 g Ca-DTPA/5 mL (200 mg/mL), as sterile solution for intravenous use. Each ampoule contains the equivalent of 1000 mg of pentetate calcium trisodium; to be stored between 15°C and 30°C.

Dose in adults: Evidence supports doses of Ca-DTPA from 0.5 g (half an ampoule) to 1 g, given by slow intravenous injection over a period of 3–4 minutes or by intravenous infusion

diluted in 100–250 mL of 5% dextrose in water (D5W), Ringer's lactate or normal saline. Only a single initial dose of Ca-DTPA is recommended.

Dose in pregnancy: Category C (FDA)[3].

Dose in children: For children less than 12 years old, 14 mg/kg and not exceeding 0.5 g/day.

Micronized capsules: For use in turbo-inhaler, 40 mg per capsule [47, 50]; adult dosage: from one to five capsules, depending on the model; 3 breaths per capsule.

Alternative treatment: Cobalt gluconate (care needs to be taken with the vasodilator action in blood vessels), dimercaptosuccinic acid (DMSA), ethylenediamine tetraacetic acid (EDTA) and N-acetyl-cysteine are considered possible alternative drugs for cobalt contamination. In cases of GI contamination, the following complementary treatments could be considered:

— Magnesium sulphate; ampoules: 20 mL/3 g, 3 to 5 ampoules orally [11];

— Aluminium hydroxide; standard dose for hyperacidity: 10 mL (1.2 g) in adults; dose to reduce intestinal absorption: 60 to 100 mL orally [11];

— Barium sulphate; 100 to 300 g oral in a single dose in 250 mL water.

5.3.5. Skin and wound contamination

The skin area will be washed with a concentrated Ca-DTPA solution (1 g = 1 ampoule) accompanied by a slow intravenous injection or infusion of Ca-DTPA. Either a conventional salt such as cobalt gluconate or a chelate such as trimethylamine hydroxy-cobalt-di-8-oxyquinoline-5-sulphonate can be used. These cobalt compounds are vasodilators and have to be used carefully.

5.3.6. Respiratory tract contamination

For adults, a Ca-DTPA aerosol will be prepared (one ampoule in sterile or saline water, in a conventional generator producing an aerosol of suitable particle size). An alternative procedure is to use a micronized inhaler of Ca-DTPA in capsule, followed by slow intravenous injection or infusion of Ca-DTPA.

5.3.7. Gastrointestinal tract contamination

As most cobalt salts are insoluble, special therapy is not necessary after ingestion to accelerate the digestive transit. Magnesium sulphate, aluminium hydroxide or barium sulphate could be used.

5.3.8. Control and monitoring

Urine and faeces bioassays and whole body counting.

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[3] Animal reproduction studies have shown an adverse effect on the fetus. There are no adequate and well-controlled studies in humans, but potential benefits may warrant use of the drug in pregnant women despite potential risks.

5.4. IODINE (I)

5.4.1. Origin

Iodine is a bluish-black, lustrous solid element that mainly occurs in nature as stable iodine-127. There are more than 14 major radioactive isotopes of iodine. These isotopes (radioiodines) are naturally produced by fission occurring in natural uranium. A small amount of iodine-129 is produced naturally in the upper atmosphere by interaction of high energy particles with xenon [45]. The artificial origin of radioiodines is due to releases to the environment from past atmospheric nuclear tests and production in nuclear reactors. Iodine volatilizes at ambient temperatures in gaseous form. Medical uses of iodine-131 include diagnosis and therapies especially related to thyroid diseases. Iodine-125 is used commonly in radioimmunoassay techniques. The physical characteristics of some radioisotopes of iodine are shown in Table 8.

TABLE 8. PHYSICAL CHARACTERISTICS OF SOME RADIOISOTOPES OF IODINE

Physical characteristics	I-125	I-129	I-131
Physical half-life	60 days	16 million years	8 days
Effective half-life	53 days	120 days	7.5 days
Main emissions	Electron and X rays	Beta, X rays and gamma	Beta and gamma
Target organ	Thyroid	Thyroid	Thyroid

5.4.2. Chemical and metabolic behaviour

The biokinetic model for iodine assumes that 30% of the intake activity is taken up by the thyroid and the remainder is excreted in urine. In fact, there are relatively large variations, depending on many parameters, such as the stable iodine content in common foods and thyroid dysfunction. For example, current uptake values for a European euthyroid adult are in the range 0.20–0.25, but in countries with iodine deficiency in food, this value is considerably higher. Pathological states of the thyroid may result in uptake values of 0–0.05 (blocked thyroid) to more than 0.5. When such cases are suspected, individual values need to be introduced in the dose calculations, especially for accidental exposure situations leading to significant doses for which a precise assessment is needed.

The iodine concentration in the thyroid is highest 24 hours after intravenous administration of iodine. Given the effective half-life of iodine-131, the fraction transferred to the thyroid is about 25–30% of the amount taken up (this transfer takes place via sodium/iodine symporters — transmembrane glycoproteins that act as a carrier, transporting the iodine across the basolateral membrane of the thyroid), 20% is quickly excreted in faeces and most of the remaining iodine is eliminated in the urine. Several tissues in humans, other than the thyroid, express sodium/iodine symporters and accumulate iodine; these include the mammary gland, salivary gland and gastric mucosa [55].

Clearance of iodine (including all the isotopes) is age dependent. It proceeds on the basis of two biological half-lives: one of six hours, representing elimination of the whole body

fraction (70%), and one of approximately 100 days, representing elimination of the thyroid fraction (30%). Urinary excretion normally accounts for more than 80% of the elimination of absorbed iodine [55].

5.4.3. Emergency treatment

— Stable iodine in the form of potassium iodide (KI);

— Alternative therapies include iodine-potassium iodide, sodium iodide or magnesium iodide.

5.4.4. Pharmacological information and therapy

Treatment consists of loading the thyroid with stable iodine as quickly as possible [45, 46]. Since the speed with which the thyroid becomes saturated with iodine is directly proportional to the intake, higher doses provide better protection; the recommended dose is 100 mg of iodine preferably given orally in the form of potassium iodide (130 mg of Kl). The promptness of therapy determines its effectiveness. Administration of stable iodine before contamination by radioiodine is the ideal scenario (see Table 9). The reduction of the radioiodine load is lower if the treatment is delayed. Treatment with stable iodine 24 hours after contamination slightly reduces the biological half-life of the radioiodine. Treatment more than 24 hours following the exposure may do more harm than good (by prolonging the biological half-life of radioactive iodine that has already accumulated in the thyroid). A single administration of stable iodine is usually sufficient [56].

TABLE 9. ADMINISTRATION OF KI IN ACCORDANCE WITH AGE
(adapted from [11, 56])

Age	Mass of iodine (mg)	Mass of KI (mg)	Fraction of a tablet containing 100 mg of iodine
Adults and adolescents (over 12 years)	100	130	1
Children (3 to 12 years)	50	65	1/2
Infants (1 month to 3 years)	25	32	1/4
Neonates (birth to 1 month)	12.5	16	1/8

Iodine thyroid blocking is an urgent protective action that is prescribed: (a) if exposure due to radioactive iodine is involved, (b) before or shortly after a release of radioactive iodine, and (c) within only a short period before or after the intake of radioactive iodine. Iodine thyroid blocking is prescribed when the projected equivalent dose to the thyroid due only to exposure to radioiodine exceeds 50 mSv in the first 7 days. This generic criterion applies only for administration of iodine thyroid blocking.

Iodine-potassium iodide solution (Lugol) 1%:

— Adults: 80 drops;

— Children 3 to 12 years old: 40 drops;

— Children less than 3 years old: 20 drops.

Stable iodine should be administered with caution, especially in persons with relative contraindication for taking stable iodine, such as persons with: thyroid disease, past or present; iodine hypersensitivity; and (as described in the literature) those with dermatitis herpetiformis and hypocomplementaemic vasculitis [2].

The highest priority groups for receiving stable iodine prophylaxis are: newborn babies, breastfeeding mothers and children [2].

Reported severe clinically relevant reactions include: sialadenitis (an inflammation of the saliva gland), gastrointestinal disturbances and minor rashes [56].

5.4.5. Skin and wound contamination

Local decontamination with plenty of warm water and neutral soap; oral treatment is not to be delayed.

5.4.6. Respiratory and gastrointestinal tract contamination

Stable iodine in available form according to the doses suggested.

5.4.7. Control and monitoring

Measurement of emitted radiation in front of the thyroid with a probe in contact with the skin; bioassays of urine samples. Whole body counting, if it is available, could also provide information.

5.5. PLUTONIUM (PU)

5.5.1. Origin

Plutonium is a heavy, silver-coloured radioactive metal. Essentially all the plutonium on earth has been created in the past six decades by human activities involving fissionable materials (nuclear reactors, atmospheric nuclear tests and nuclear accidents). Extremely small quantities of plutonium were created naturally in sustained underground nuclear reactions, which are estimated to have taken place about 1.9 billion years ago owing to the higher concentrations of uranium-235 at that time. Plutonium has 15 known isotopes [45, 46]. The physical characteristics of some plutonium isotopes are presented in Table 10.

TABLE 10. PHYSICAL CHARACTERISTICS OF SOME RADIOISOTOPES OF PLUTONIUM

Physical characteristics	Pu-238	Pu-239	Pu-240
Physical half-life	88 years	24 000 years	6563 years
Effective half-life	50 years	50 years	50 years
Main emissions	Alpha, X rays and gamma	Alpha, X rays and gamma	Alpha, X rays and gamma
Target organs	Bone and liver	Bone and liver	Bone and liver

5.5.2. Chemical and metabolic behaviour

For plutonium absorbed to blood, the main sites of deposition are the liver and skeleton. The model for plutonium is given in ICRP Publication 67 [33]. The model takes into account the initial deposition in bone, liver, gonads and other tissues, and allows for transfer of activity from bone surfaces to bone volume and marrow, recycling of activity between tissues, as well as loss by excretion.

Plutonium is the second element of the transuranium actinides and is transformed to plutonium oxide in contact with air. In solution, plutonium possesses five oxidation states. In rat models, no significant variations in the metabolic behaviour of plutonium were observed [57]. However, its behaviour is influenced by its particulate character rather than by its chemical nature [58].

The mechanism of absorption of plutonium from the GI tract is not yet fully understood [47]. However, absorption is increased in iron deficiency and is decreased in animals by co-administration of Fe^{3+} [59]. Skin absorption is very limited. When plutonium is inhaled, a significant fraction is transferred from the lungs through the blood to other organs, depending on the solubility of the compound.

Because plutonium is strongly bound to proteins in blood, it does not leave easily from the vasculature [59]. About 10% clears from the body. The rest is distributed between the liver, from which it is eliminated very slowly, and the bone, from which it is not, for practical purposes, eliminated at all; the biological half-lives for plutonium-238 and plutonium-239 are 40 years for the liver and 100 years for the bone, depending on the age of the affected individual, with fractional uptake in the liver increasing with age. The absorbed plutonium is excreted in urine and faeces.

5.5.3. Emergency treatment

— Diethylenetriamine-pentaacetate (DTPA).

Chelating agent containing trisodium calcium diethylenetriamine-pentaacetate (Ca-DTPA) [11, 47–49]. If it is not available, trisodium zinc diethylenetriamine-pentaacetate (Zn-DTPA) can be used as a second line of treatment. Zn-DTPA is also indicated for long term treatment.

5.5.4. Pharmacological information and therapy

Ca-DTPA (diethylenetriamine-pentaacetate, monocalcium trisodium salt) [11, 41, 50].

Ampoules: 1 g Ca-DTPA/4 mL (250 mg/mL) or 1 g Ca-DTPA/5 mL (200 mg/mL) as sterile solution for intravenous use. Each ampoule contains the equivalent of 1000 mg of pentetate calcium trisodium; to be stored between 15°C and 30°C.

Micronized capsules: For use in turbo-inhaler, 40 mg per capsule [50].

Ca-DTPA chelation treatment will be given as soon as possible after known or suspected internal contamination with transplutonium or transuranium elements [48]. Ca-DTPA and its radioactive chelates are excreted by glomerular filtration. Impaired renal function may decrease their rates of elimination and increase the serum half-life of Ca-DTPA. When possible, baseline blood and urine samples are to be obtained.

Patients will drink plenty of fluids and void frequently. Serum electrolytes and essential metals will need to be closely monitored during Ca-DTPA treatment. Mineral supplements, or vitamin plus mineral supplements that contain zinc, will be given as appropriate.

Dose in adults: Evidence supports doses of Ca-DTPA from 0.5 g (half an ampoule) to 1 g, given by slow intravenous injection over a period of 3–4 minutes or by intravenous infusion diluted in 100–250 mL of 5% dextrose in water (D5W), Ringer's lactate or normal saline. Only a single initial dose of Ca-DTPA is recommended.

Dose in pregnancy: Category C (FDA)[4]. Multiple doses of Ca-DTPA could result in an increased risk for adverse reproductive outcomes and thus are not recommended during pregnancy. Therefore, treatment of pregnant women should begin and continue with Zn-DTPA, if available, except in cases of high internal radioactive contamination [41].

Dose in children: For children less than 12 years old, 14 mg/kg, not exceeding 0.5 g/day.

Contraindications: None at the recommended dosage.

5.5.5. Skin and wound contamination

Wash areas with a concentrated Ca-DTPA solution (1 g = 1 ampoule) accompanied by a slow intravenous injection or infusion of half an ampoule (0.5 g) in 100 cm^3 of 5% glucose. Surgical removal of plutonium in a wound is a matter for discussion by specialists.

5.5.6. Respiratory tract contamination

For adults, a Ca-DTPA aerosol will be prepared (one ampoule in sterile or saline water, in a conventional generator producing an aerosol of suitable particle size). This procedure may be associated with exacerbation of asthma. An alternative procedure is to use a micronized inhaler of Ca-DTPA in capsule, followed by a slow intravenous injection or infusion of half an ampoule (0.5 g Ca-DTPA) in 100 cm^3 of 5% glucose.

Pulmonary lavage will be considered only in very specific situations and after a highly specialized evaluation.

5.5.7. Gastrointestinal tract contamination

Intravenous injection of DTPA is provided as described and complementary treatment is given to reduce the intestinal absorption with:

— Magnesium sulphate; ampoules: 20 mL/3 g, 3 to 5 ampoules orally [11];

— Aluminium hydroxide; standard dose for hyperacidity: 10 mL (1.2 g) in adults; dose to reduce intestinal absorption: 60 to 100 mL orally [11];

— Barium sulphate; 100 to 300 g oral in a single dose in 250 mL water.

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[4] Animal reproduction studies have shown an adverse effect on the fetus. There are no adequate and well-controlled studies in humans, but potential benefits may warrant use of the drug in pregnant women despite potential risks.

Any contamination or suspicion of contamination warrants general emergency treatment with Ca-DTPA. Since Ca-DTPA acts only in the blood and in the extracellular fluids, the promptness of treatment determines the extent of plutonium deposition in the skeleton and liver.

The quantity of plutonium mobilized by Ca-DTPA is proportional to the in vivo solubility of the radionuclide; in the extreme case, an insoluble compound such as plutonium oxide cannot be effectively treated by systemic chelation. Since the degree of solubility of the plutonium involved in contamination is not usually known, Ca-DTPA treatment is generally indicated. The form of treatment depends on the circumstances of the case.

5.5.8.   Control and monitoring

Measurement of emitted radiation (X rays) and bioassays of urine and faeces; whole body and lung counting based on detection of the americium-241 0.06 MeV gamma emissions is recommended.

5.6.   POLONIUM (PO)

5.6.1.   Origin

Polonium-210 is naturally present in environmental media at very low concentrations. It is a decay product from the natural uranium-238 decay series and one of the decay products of radon-222. It can be artificially produced in a nuclear reactor. Polonium produces high energy alpha emissions (see Table 11). It was the first element discovered by Marie and Pierre Curie in 1898 [45, 46].

TABLE 111. PHYSICAL CHARACTERISTICS OF POLONIUM-210 (PO-210)

Physical characteristics	Po-210
Radioactive half -life	138.4 days
Effective half-life	37 days
Main emissions	Alpha
Target organs	Liver, spleen, kidney

5.6.2.   Chemical and metabolic behaviour

Polonium has four oxidation states in natural conditions. It has 29 known isotopes. The most abundant of these is polonium-210.

Absorption of polonium by the digestive system is moderate (3–5%). There is considerable retention in the whole body. Excretion takes place partly in the urine and partly in the faeces, in very variable proportions. The retaining organs are the liver, the spleen and, above all, the kidneys, which concentrate approximately 10% of the metabolized activity.

5.6.3. Emergency treatment

— Dimercaprol (BAL); (2,3-dimercapto-1-propanol) 10%, benzyl benzoate 20%, in peanut oil [11, 49, 50];

— Magnesium sulphate, aluminium hydroxide and barium sulphate in cases of GI contamination [50].

5.6.4. Pharmacological information and therapy

Dimercaprol (BAL). Ampoules: 2 mL or 3 mL (100 mg/mL).

The treatment for poisoning by polonium is the administration of dimercaprol (BAL); its effectiveness varies, and treatment should not be continued for too long. Its action is limited to the blood compartment. Magnesium sulphate, aluminium hydroxide and barium sulphate are complementary treatment in those cases involving oral intake.

Dose in adults: 2–3 mg/kg body weight, given by intramuscular injection every four hours. First injection limited to 50 mg; injections should not be administered for more than three days and ideally under hospital conditions; individual sensitivity has to be tested at the time of the first injection (quarter of an ampoule).

In cases of GI contamination, the following complementary treatment could be considered:

— Magnesium sulphate; ampoules 20 mL/3 g; 3 to 5 ampoules orally.

— Aluminium hydroxide; standard dose for hyperacidity: 10 mL (1.2 g) in adults; dose to reduce intestinal absorption: 60 to 100 mL orally.

— Barium sulphate; 100 to 300 g oral in a single dose in 250 mL water.

Contraindications: Pregnancy, hepatic insufficiency and renal failure.

5.6.5. Control and monitoring

Urine and faeces bioassays.

5.7. STRONTIUM (SR)

5.7.1. Origin

Strontium is a grey metal which exists naturally in rocks as four stable isotopes; among them, strontium-88 is the most prevalent. It can also be found in calcium and barium minerals and in water. Sixteen major radioactive isotopes exist, produced by nuclear fission (Table 12 presents the physical characteristics of some radioisotopes of strontium). Strontium-90 emits a high energy beta particle. It is used in medical applications and occurs in nuclear reactors (fission products). The main sources of strontium in the environment (negligible) are previous nuclear tests, the operations of nuclear facilities and nuclear accidents [45, 46].

TABLE 12. PHYSICAL CHARACTERISTICS OF SOME RADIOISOTOPES OF STRONTIUM

Physical characteristics	Sr-85	Sr-89	Sr-90
Physical half-life	65 days	51 days	28 years
Effective half-life	62 days	50 days	4.6 years
Main emissions	Gamma	Beta	Beta
Target organ	Bone	Bone	Bone

5.7.2. Chemical and metabolic behaviour

The physiologically based recycling model for strontium is described in ICRP Publication 67 [33]. The model describes the kinetics of strontium in bone (trabecular and cortical), which is the main site of deposition and retention, and also considers retention in the liver and other soft tissues as well as the routes of excretion. It takes account of initial uptake onto bone surfaces, transfer from bone volume and recycling from bone and other tissues to plasma. The metabolism of strontium (an alkaline earth of valence 2+) is very similar to that of calcium owing to its ability to interact with ligands that normally bind calcium, including hydroxyapatite [60].

The food chain is the main route of intake in humans. Most of the salts are soluble and rapidly absorbed. It is estimated that about 25% is absorbed by the extracellular fluids after ingestion and 30% after inhalation, half of the absorbed amount being rapidly fixed in the skeleton. The absorption tends to decrease with age (it is higher in children) and to increase in persons with a low calcium diet.

Elimination is very slow, the biological half-life being many years, regardless of the metabolic models that are chosen. The renal clearance is substantially less than the product of the glomerular filtration rate in humans. It has been shown to be a substrate for Ca^{2+}-ATPase, transporting from the proximal tubular cells into the plasma [60].

5.7.3. Emergency treatment

— Ammonium chloride/calcium gluconate [50];

— Second line: sodium alginate;

— Other treatments: calcium carbonate, calcium phosphate, aluminium hydroxide, magnesium sulphate, barium sulphate, aluminium phosphate.

5.7.4. Pharmacological information and therapy

— Ammonium chloride.

Tablets: 0.5 g of ammonium chloride; oral use.

Dose in adults: 6 g per day; 4 tablets every 8 hours.

Pregnancy: Category C (FDA)[5].

Contraindications: Metabolic acidosis, severe impairment of renal or hepatic function.

— Calcium gluconate.

Ampoules of 10 mL containing 100 mg/mL (10%).

Dose in adults: 6 to 10 ampoules orally per day.

Intravenous use in adults: 2 g calcium gluconate in 500 mL 5% glucose per day, up to 6 days.

Pregnancy: Category C (FDA)[6].

Contraindications: hypercalcaemia, hypercalciuria, patient under inotropic drugs or calcium synergistic drugs.

— Sodium alginate; digestive contamination.

Tablets: 0.26 g; sachet 0.5 g. Oral suspension: 12.5 g/250 mL.

Dose in adults: 5 g orally slowly, twice a day or 10 g, single dose, per day.

Contraindications: Impaired renal function.

Independently of the route of entry of strontium and the therapeutic agent, the urgency of treatment is emphasized, since strontium is absorbed very quickly.

For most forms of strontium-89 and strontium-90, dose to bone and red marrow is the main concern following an intake.

Treatment is based on rendering strontium non-transportable, either by precipitation or by trapping so as to inhibit its absorption.

5.7.5. Skin and wound contamination

Rendering strontium non-transportable on the spot is possible and effective, especially if treatment is carried out during the first quarter of an hour; if available and easy to prepare or to obtain, 1 g of potassium rhodizonate or sodium rhodizonate can be sprinkled and dabbed on the affected area, which helps the preparation penetrate into the skin.

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[5] Animal reproduction studies have shown an adverse effect on the fetus. There are no adequate and well-controlled studies in humans, but potential benefits may warrant use of the drug in pregnant women despite potential risks.

[6] Animal reproduction studies have shown an adverse effect on the fetus. There are no adequate and well-controlled studies in humans, but potential benefits may warrant use of the drug in pregnant women despite potential risks.

5.7.6. Respiratory and digestive tract contamination

Ammonium chloride or calcium gluconate will be used as suggested. Complementary treatment may be necessary to block the intestinal absorption in both cases. The intestinal strontium can be trapped with sodium alginate or barium sulphate (300 mg orally) as soon as possible post-incident. Aluminium phosphate is effective, and 10 g of magnesium sulphate speeds up digestive transit and reduces absorption.

5.7.7. Control and monitoring

For strontium-89 and strontium-90, only bremsstrahlung can be measured. Bioassays of urine and faeces are recommended.

5.8. TRITIUM

5.8.1. Origin

Hydrogen has three isotopes: light hydrogen (H-1), which is most abundant; deuterium (H-2); and tritium (H-3). Tritium is naturally present as a very small percentage of ordinary hydrogen in water. It is produced as a result of the interaction of cosmic radiation with nitrogen, oxygen and argon gases in the upper atmosphere. It is also created artificially by human nuclear activities [45]. Its physical characteristics are presented in Table 13.

TABLE 13. PHYSICAL CHARACTERISTICS OF TRITIUM

Physical characteristics	H-3
Physical half -life	12.3 years
Effective half-life	8 days
Main emissions	Beta
Target organ	Whole body (tissue)

5.8.2. Chemical and metabolic behaviour

Tritium is a radioactive isotope. Its core consists of a proton and two neutrons, and its chemical properties are similar to those of light hydrogen. It may be incorporated in three different chemical forms:

— Tritium gas: absorption by inhalation.

— Tritiated water: slightly heavier than light water. This form is easily absorbed and behaves like ordinary water, except for a small fraction which becomes fixed to proteins. Tritiated water may be absorbed through a wound, by the lungs or through the skin.

— Labelled molecules: tritium follows the metabolic cycle of the labelled molecule or, in the case of degradation, of the fraction enclosing it.

The biokinetic models for both tritiated water and organically bound tritium are described in ICRP Publication 56 [61]. For tritiated water, it is assumed that 97% of activity equilibrates with body water and is retained with a half-life of 10 days. The remaining 3% is assumed to be incorporated into organic molecules and retained with a half-time of 40 days. For organically bound tritium, 50% of activity is taken to be retained with the 10 day half-time of water and 50% with the 40 day half-time of organic carbon.

In most monitoring programmes for tritium, urine samples are not aggregated over a whole day as they are for other radionuclides. Instead, it is assumed that the activity concentration of tritiated water in urine is equal to the activity concentration in body water. Thus, analysis of tritiated water in a single sample of urine is used to give the activity concentration in body water at the time that the sample was collected. For this reason, results for tritiated water are given in terms of activity concentration in urine (Bq/L) rather than as a daily urinary excretion. The assumption of equilibrium between tritiated water in urine and that in body water is consistent with the total volume of body water — 42 litres — recommended in ICRP Publication 23 on 'Reference Man' [62]. Using the above model, the average activity concentration in total body water on any day can be calculated.

5.8.3. Emergency treatment

— To speed up the body water turnover cycle, liquid intake has to be increased (3 to 4 L/day) to stimulate diuresis.

It is possible to reduce the effective half-life of tritium from 10 days to 2.4 days by increasing the consumption of drinking water. For large contaminations, intravenous hydration, management of fluid intake/output and the addition of diuretics may be indicated, but the risks and contraindications of this therapy have to be considered. In the exceptional event of massive contamination, there might be a need for special treatment such as peritoneal dialysis, but this needs to be provided only by a specialized centre.

5.8.4. Control and monitoring

Urine bioassays. The concentration of tritium in urine is the same as in body water and can be used to assess body content and dose rate without reference to an excretion model [20].

5.9. URANIUM (U)

5.9.1. Origin

Uranium is a radioactive element naturally found in the environment in low concentrations in soil, rock, surface water and groundwater. It is the heaviest naturally occurring element, a heavy metal nearly twice as dense as lead. Natural uranium is composed of three main isotopes, uranium-238 (99.2%), uranium-235 (0.71%) and a very small amount of uranium-234 (0.0057%), all of which are radioactive. It is used, among other things, for the nuclear fuel cycle and for military means [45, 46]. The physical characteristics of U-235 and U-238 are presented in Table 14.

TABLE 14. PHYSICAL CHARACTERISTICS OF SOME RADIOISOTOPES OF URANIUM

Physical characteristics	U-235	U-238
Physical half-life	7×10^8 years	4.5×10^9 years
Main emissions	Alpha and gamma	Alpha
Target organs	Kidney and bone	Kidney and bone

5.9.2. Chemical and metabolic behaviour

Uranium is part of the actinide family and is a pyrophoric grey metal that is very dense in its pure state. It has four possible valences, but is most common in two states: 4+ and 6+. The 4+ form is insoluble, but in a biological medium it is gradually converted to 6+ (it forms complexes), which is rapidly changed into the uranyl ion UO_2^{++}. This ion behaves like calcium or like the alkaline earths if it is not precipitated in the renal tubules. The physiologically based recycling model for uranium is described in ICRP Publication 69 [63]. The model is based on the generic alkaline earth model provided in ICRP Publication 67 [33]. The model describes in detail the kinetics of uranium in bone, which is the main site of deposition and retention, and also considers retention in the liver, kidneys and soft tissues, as well as routes of excretion. It takes account of initial uptake onto bone surfaces, transfer from surface to bone volume and recycling from bone and other tissues to plasma.

Uranium is considered a chemical or radiological hazard, depending on its isotopic composition. In uranium compounds enriched in uranium-235 to less than 5% to 8%, and not irradiated in a reactor, the chemical toxicity to the kidneys prevails. Otherwise, the radiation risk is predominant.

Two thirds of uranium intravenously injected as uranyl nitrate in humans is typically excreted in urine in the first 24 hours. In acid urine, the uranyl binds to renal tubular surface proteins. The kidney is the first organ to show chemical damage, and excessive uranium burden in the kidneys involves the risk of severe toxic nephritis. Also, ultrastructural analyses have shown damage to the endothelial cells in the glomeruli [64].

Despite the insolubility of many of its salts, uranium spreads through the organism fairly rapidly.

5.9.3. Emergency treatment

— Sodium bicarbonate;
— Acetazolamide;
— Complementary treatment: aluminium phosphate.

5.9.4. Pharmacological presentation and therapy

— Sodium bicarbonate.

Dose in adults: intravenous isotonic sodium bicarbonate 14% in 250 mL, slow intravenous injection or 2 bicarbonate tablets orally every 4 hours until urine reaches a pH 8 to 9.

— Acetazolamide.

This diuretic acts by inhibition of the enzyme carbonic anhydrase that is found in several tissues in the body and catalyses the rapid conversion of carbon dioxide to bicarbonate ions. In cases of uranium contamination, the dissociation of uranyl ions from bicarbonate in the kidneys is lessened with the administration of acetazolamide (250 mg). All classic contraindications of the drug and its side effects have to be considered.

— Aluminium phosphate in cases of digestive intake.

Sachet: 2.5 g aluminium phosphate; five sachets in a single dose.

Chelating agents are not to be used, despite their effect on uranium, since an increase in the migrant fraction might result, through precipitation in the kidneys, in a high renal tubule burden, accompanied by the risk of severe anuric nephritis. The complex formed by uranyl ions with sodium bicarbonate ($Na_4[(UO_2)(CO_3)_3]$) is stable and is excreted rapidly in the urine. Hence, treatment is based on the use of bicarbonate physiological solution [11, 48–50].

5.9.5. Skin and wound contamination

The wound will be washed immediately and a slow intravenous infusion of bicarbonated physiological solution (250 mL at 14%) needs to be administered. Evaluation at a specialized centre is mandatory.

5.9.6. Respiratory and gastrointestinal tract contamination

A slow intravenous infusion of bicarbonated physiological solution (250 mL at 14%) will be administered and the patient transferred to a specialized centre. Lung lavage would only be indicated in very specific situations, after a highly specialized evaluation. In GI intake, aluminium phosphate should be added to complement the intravenous bicarbonate treatment.

5.9.7. Control and monitoring

Clinical and laboratory follow-up for possible kidney damage and renal failure; urine bioassays.

5.10. SUMMARY OF POSSIBLE DECORPORATION THERAPIES FOR OTHER RADIONUCLIDES

Table 15 summarizes some of the possible therapeutic agents and some preferred treatments for cases of internal contamination with other radionuclides. The approach will vary depending on the local regulations in each Member State [65].

TABLE 15. DECORPORATION THERAPIES FOR OTHER RADIONUCLIDES [65]

Radionuclide	Possible therapeutic agents	Preferred treatment
Arsenic	BAL, penicillamine, DMPS[a], DMSA	BAL
Barium	Barium sulphate, calcium therapy (see strontium)	See strontium
Bismuth	DMPS[a], DMSA, BAL, penicillamine	DMPS[a]
Californium	DTPA	DTPA
Calcium	Calcium therapy (see strontium), barium	See strontium
Carbon	Consider hydration and stable carbon	Consider hydration and stable carbon
Cerium	DTPA	DTPA
Chromium	DTPA, EDTA, penicillamine, NAC[b]	DTPA
Copper	Penicillamine, DMSA, DMPS[a], trientine	Penicillamine
Fission products (mixed)	Management depends on predominant radionuclides present at the time (e.g. early: iodine; late: strontium, caesium and others)	
Fluorine	Aluminium hydroxide	Aluminium hydroxide
Gallium	Consider penicillamine, DFOA[c]	Penicillamine
Gold	Penicillamine, BAL, DMPS[a]	Penicillamine, BAL
Iridium	DTPA, EDTA	Consider DTPA
Iron	DFOA[c], deferasirox, DFOA[c] and DTPA together	DFOA[c]
Lead	DMSA, EDTA, EDTA with BAL	DMSA
Manganese	Ca-DTPA, Ca-EDTA	Ca-DTPA
Magnesium	Consider strontium therapy (see strontium)	Consider strontium therapy
Mercury	BAL, DMPS[a], DMSA, EDTA, penicillamine	BAL, DMPS[a], DMSA
Neptunium	Consider DFOA[c] and/or DTPA, DMPS[a]	Consider DFOA[c] and/or DTPA

Radionuclide	Possible therapeutic agents	Preferred treatment
Nickel	DDTC[d], DTPA, BAL, EDTA	DDTC[d], BAL, DTPA
Phosphorus	Hydration, oral sodium or potassium phosphate, aluminium hydroxide/aluminium phosphate, calcium	Hydration, oral sodium or potassium phosphate
Potassium	Diuretics	Diuretics
Promethium	DTPA	DTPA
Radium	Radium, strontium therapy	Strontium therapy
Rubidium	Prussian Blue	Prussian Blue
Ruthenium	DTPA, EDTA	DTPA
Sodium	Diuretic and isotopic dilution with 0.9 % NaCl	Diuretic and isotopic dilution with 0.9 % NaCl
Sulphur	Consider sodium thiosulphate	Consider sodium thiosulphate
Technetium	Potassium perchlorate	Potassium perchlorate
Thallium	Prussian Blue	Prussian Blue
Thorium	Consider DTPA	Consider DTPA
Yttrium	DTPA, EDTA	DTPA
Zinc	DTPA, EDTA, zinc sulphate as a diluting agent	DTPA
Zirconium	DTPA, EDTA	DTPA

[a] DMPS: dimercaptopropansulphonate.
[b] NAC: N-acetyl-cysteine.
[c] DFOA: Deferoxamine.
[d] DDTC: diethyldithiocarbamate.

6. SCREENING A LARGE NUMBER OF PEOPLE FOR INTERNAL CONTAMINATION

6.1. INTRODUCTION AND HEALTH CONSIDERATIONS

6.1.1. Introduction

Experience with the accident at Chernobyl (1986), the Goiânia accident (1987), the London polonium incident (2006) and the Fukushima Daiichi accident (2011) have shown that there may be significant demand for early, sustained and scalable delivery of appropriate screening of the public for radioactive contamination with associated provision of information. This demand will probably exceed the available resources, at least during the first few weeks following a major incident. Furthermore, it is likely that, during a major radiation emergency, those skilled in personal monitoring will also form part of the national resource for other essential duties, such as environmental monitoring and support for hospital treatment of patients. It is therefore important that a clear framework be in place for identifying personal monitoring priorities and balancing these against other priorities and available resources.

Screening [66] and monitoring [3] the public for radiological contamination can provide information that serves a diverse range of purposes, from health (both physical and mental) to legal and political, and contributes to the understanding of the spatial extent of any contamination [2, 10, 67, 68].

6.1.2. Health considerations and guiding principles

The objectives of a screening and monitoring programme will normally include the following [10]:

 (a) To quantify absorbed doses to organs and tissues for people exposed to radiation or radioactive material at a level high enough to potentially give rise to deterministic health effects;

 (b) To provide dosimetric information that would allow urgent decisions to be made to remove individuals from a source of external exposure, or remove or reduce contamination on or in the body;

 (c) To quantify committed effective doses for people with lower levels of internal contamination that could result in an elevated risk of stochastic health effects;

 (d) To provide dosimetric information that could be used when making decisions on medical treatment for the groups of people identified in objectives (a) and (c) above;

 (e) To quantify committed effective dose for people with levels of exposure that are very unlikely to have an effect on health or who were not exposed at all.

Secondary objectives include the prevention of further exposures, the provision of information to individuals on their levels of exposure, and the provision of information to the appropriate authorities on the radiological consequences of the incident.

A number of principles are expected to hold true for most scenarios and guide parts of any screening and monitoring strategy. These principles are as follows:

 — Treatment of conventional injuries takes precedence over decontamination;

— Individuals are not likely to exhibit any symptoms related to radiological contamination [69];

— Use of universal precautions, also known as standard precautions, will help prevent the spread of contamination to emergency responders [69];

— If decontamination is thought to be necessary, and facilities are available, a lack of screening resources is not a valid reason for delaying their use;

— Removal of clothing may reduce overall contamination significantly;

— Contamination with radioactive material is highly unlikely to be immediately life threatening, unless embedded high activity fragments of a radioactive source are present in the person;

— Any screening programme needs to provide an individual or public health benefit;

— Any population screening programme needs to also aim at preventing the public from presenting at hospitals unnecessarily.

Planners need to ensure that any radiation screening programme is commensurate with other plans derived for an area and that all relevant organizations are consulted in the planning process.

Responders need to always remain sensitive to the dignity, cultural and religious concerns and requirements of different communities and social groups and of the special needs of individuals [70].

It has to be considered that the number of people seeking medical advice will be substantially higher than the numbers exposed or affected (the worried well). There is previous evidence for a rate of 5 to 1 [70].

6.2. RADIATION MONITORING UNITS

6.2.1. Radiation monitoring units in reception centres

In the event of a significant radiation emergency involving many victims, the identification of a reception centre may be considered to facilitate the triage of victims, screen a large number of people, optimize resources and coordinate the actions by the response teams. It is important that access to this centre not interfere with access to the hospitals accepting casualties. Athletic fields, stadiums, and community centres could be used for this purpose [2].

The establishment of a radiation monitoring unit (RMU) is one of the possible methods for monitoring large numbers of people [68]. An RMU will be useful when those who are to be monitored are able to travel or be transported to one venue for the monitoring to be performed. An RMU is essentially a centre where radiation emergency teams, provided with the necessary equipment, are able to determine the levels of radioactive contamination in or on people and any subsequent requirement for decontamination. Therefore, the basic function of an RMU is to screen people. It will also inform decisions regarding the need for any medical interventions for persons contaminated with radioactive material. It is important to be aware that normal radiation screening will not detect if a person has been exposed to significant external radiation; it can determine only whether people are contaminated with radioactive material [68].

The role of the RMU is likely to change over time. An RMU set up within hours of the declaration of an emergency is likely to focus on identifying people in need of urgent medical treatment and on screening evacuees for high levels of radioactive contamination on skin and clothing. After a period of days/weeks, the focus is likely to shift to an evaluation of lower levels of internal exposure, informing non-urgent treatments and providing estimations of individual health risks and of overall population exposure.

Large scale screening of the public via an RMU can bring a significant workload for the organizations performing it, requiring a large staff resource of both specialists and non-specialists, all of whom will need some form of RMU specific basic training. It has to be kept in mind by those at the strategic response level that the scientific staff used for the screening of people is likely to be the same resource that may be called upon to monitor the environment.

6.2.2. Location and ideal requirements of an RMU

Whenever possible, the RMU will be located at, or adjacent to, a reception centre established to house evacuated populations during a radiation emergency, providing food and temporary accommodation. The reception centre itself needs to be in a location where it can be readily accessed by the relevant population and not situated in an area that is subject to sheltering or evacuation. It may be necessary to identify several potential locations for an RMU, as an incident may preclude the use of the primary location.

When identifying possible locations for an RMU, the transport of people to and from the place, and also the access of medical professionals who may sometimes be required to assist with decontamination procedures, will be considered.

Buildings or venues that could be used for an RMU include: sport centres, schools, warehouses, village/community halls, stadiums [12] or dedicated temporary structures (tented/inflatable).

The following is a list of some attributes considered ideal for any RMU venue (see Fig. 2) [68]):

— Can be established within a few hours (or longer depending upon the aims of the RMU) of the requirement being identified;

— An area for the monitoring of waiting people (indoors or outdoors under shelter);

— A specific area for radiation monitoring to be carried out;

— If possible, an area for collecting bio-samples if internal contamination is suspected;

— Approximately 300 m^2 of indoor space and approximately 300 m^2 of outdoor space in order make it possible to process approximately 1000 people per day;

— Adequate and definable access and egress routes and points which can be controlled (for contamination control and in case of emergency evacuation);

— A segregated area to decontaminate people identified as contaminated (showers are preferable), or an area where decontamination facilities can be rapidly created;

— A quiet area for recording and reporting information with communications equipment (ideally segregated from the monitoring and waiting areas of the RMU and equipped with Internet/telephone connectivity);

— A private area for counselling;

— Adequate toilet facilities for staff and public; separate toilets for pre- and post-monitoring areas;

— Accommodations for people with disabilities;

— Environmental control (against excessive heat or cold);

— Adequate power supply and telephone communication facilities for the public;

— Storage for replacement clothing;

— Storage for contaminated clothing and other contaminated items;
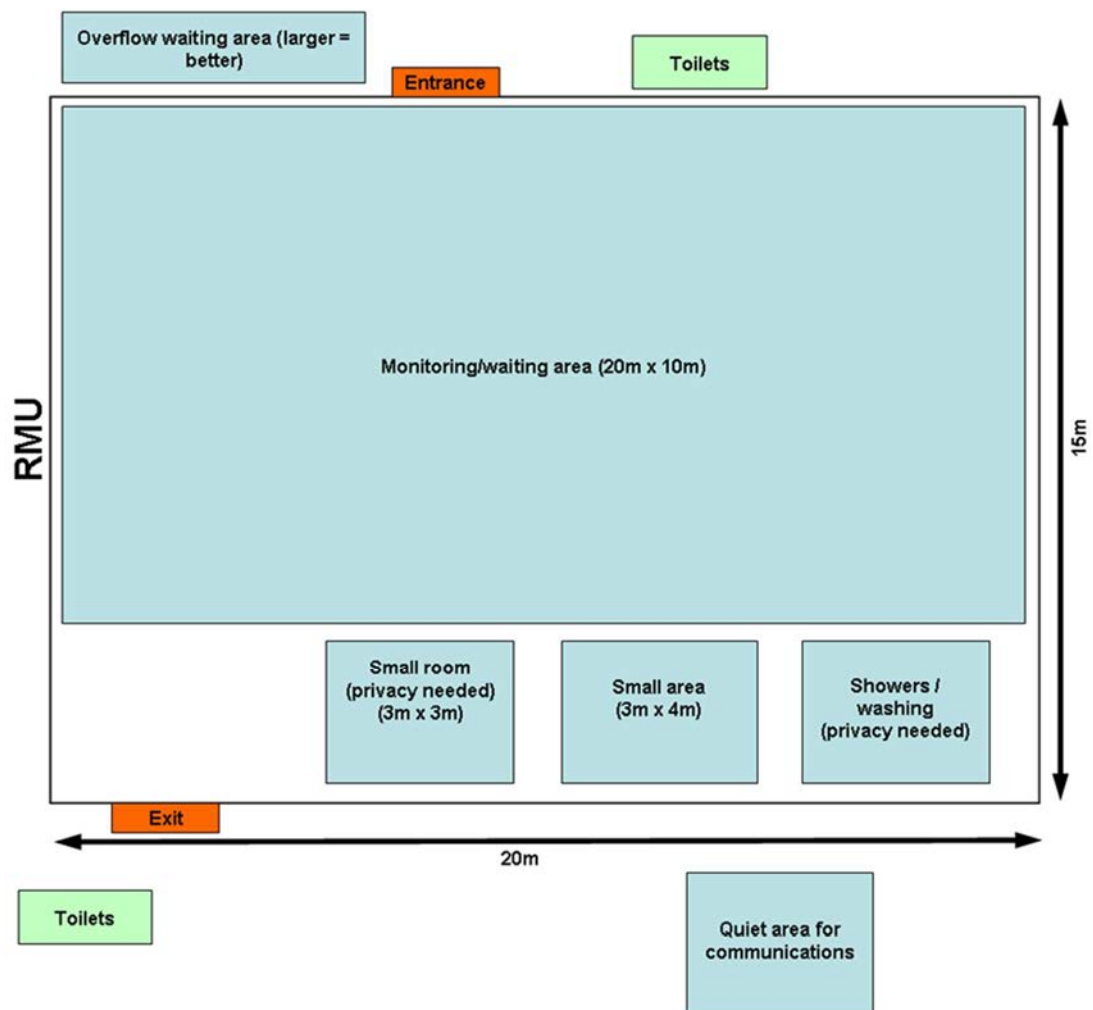
— Staff welfare facilities.

FIG. 2. Diagram of a suggested RMU capable of processing 1000 people per day; reproduced from Ref. [68] with permission.

6.3. CONSIDERATIONS FOR SCREENING AND MONITORING

6.3.1. Methods of measurement

Where the incident has released radionuclides which would be difficult to detect via their photon emissions, it is likely that only external contamination monitoring with handheld detectors will be effective (depending on the radionuclide). If the release contains radionuclides with associated photon emissions of energies greater than 200 keV, most portal style monitors could be used. Monitoring at the RMU may identify people who need additional measurements, which need to be carried out in specialized laboratories. For some suspected cases of internal contamination, bioassay samples (likely to be urine or faeces) will be needed; some sampling could be initiated at the RMU.

6.3.2. Monitoring of external contamination levels on people

Monitoring of external contamination is carried out using either walk-through portals or handheld equipment.

Results will allow decisions to be made on the need for external decontamination of people. Rapid initial screening will enable decisions to be made on which type of further monitoring, if any, will have to be carried out.

6.3.3. Monitoring of internal contamination levels in people

Monitoring of internal contamination levels is carried out using portable, transportable or handheld equipment. Internal monitoring will usually be performed for anyone identified initially as being externally contaminated, or for individuals identified as being at risk owing to their proximity to a radiation emergency involving airborne radionuclides. It is used mainly for measuring radioactive material in the lungs and the thyroid gland (in the case of radioiodines), but can also be used for the whole body. This will often be performed with more specialized equipment, such as a portable whole body counter or a transportable whole body counter, if available. In case of doubt, or if the evaluation cannot be completed in the RMU, the individual needs to be transferred [68].

6.3.4. Screening/monitoring process

The screening/monitoring process may have up to four main components [68]:

— **Stage 1**: Rapid screening to identify those in need of urgent decontamination and to protect the RMU venue.
— **Stage 2**: More detailed external contamination screening/monitoring.
— **Stage 3**: Internal contamination monitoring (may be off-site).
— **Stage 4**: Recording and reporting of results (both to the respective individual and to a monitoring database). This includes the explanation of any result to the individual.

If monitoring for radionuclides that are less readily detectable (such as a pure alpha emitting radionuclide), the rapid monitoring of Stage 1 may not be of any use. In this case, monitoring resources will focus on Stage 2.

Figure 2 (above) and Fig. 3 (below) show examples of diagrams that can be used to plan an RMU. Figures 4 and 5 show these arrangements in operation during an exercise. The use of yellow tape along with other materials that were at hand to create barriers is worth noting. The floor of this monitoring station is completely covered with plastic bags in order to avoid direct contamination of the unit.

FIG. 3. Arrangement of the four stages of the screening/monitoring process and pathways between the various stages; reproduced from Ref. [68] with permission.

FIG. 4. RMU exercise: Stage 2 external monitoring with portals (right) and main queuing area (left); reproduced from Ref. [68] with permission.

FIG. 5. RMU exercise: first and second stages of external monitoring (single portal on the left, multiple portals on the right); reproduced from Ref. [68] with permission.

Any monitoring strategy adopted will aim to identify, and where appropriate to decontaminate, those at risk expeditiously. Monitoring of people affected by emergency countermeasures (evacuation, sheltering and distribution of stable iodine) needs to be given a higher priority than monitoring other groups within the general population, as these people have a higher probability of being contaminated.

6.4. PEOPLE MANAGEMENT AND INFORMATION

6.4.1. Guidance and information

The management of people at the RMU consists largely of providing adequate guidance and information. If possible, communication and educational materials will be provided in the appropriate languages for the population and its demographic distribution. Signs indicating what to do and where to go, may reach a wider audience than written explanations, being easier to understand than handouts with more detailed explanations. As far as practical, cultural or religious factors that may affect the population monitoring process need to be taken into account.

As with any examination of a health related nature, people will be provided with information that allows them to understand the meaning of the results. This is an essential part of including the public fully in the process.

Ideally, when the people leave the RMU they will be given a summary of actions and recommendations. This will detail in plain language what actions, if any, they have to take.

6.4.2. Collection and reporting of information

Detailed record keeping is essential, not only for patient care and subsequent dosimetric and medical follow-up, but also for clinical and legal considerations [5]. Records will be kept of all people who were monitored, both those found to be contaminated and those found not to be [68].

These records may be used to contact people who require short term medical follow-up, or for purposes of long term health monitoring.

As soon as persons enter the RMU, they need to become identifiable in order to allow this information to be recorded effectively. The collection of full personal details (registration) has to be done after the monitoring and decontamination functions of the RMU. This will reduce contamination issues.

The RMU manager will be the conduit of all data from the RMU to other stakeholders who have a legitimate requirement for the data. Timely and accurate information is required for both the individuals who have been monitored and for those directing the response to an emergency.

Everyone monitored will receive information on the monitoring results obtained.

Pre-prepared information for those who are potentially contaminated and those found to be contaminated has to be available.

All data and information that identify individuals have to be treated as confidential, and standard procedures for this type of information will be followed.

6.4.3. Follow-up monitoring

Appropriate health stakeholders need to develop criteria to decide if follow-up monitoring is required along with the format of any such monitoring programme.

6.5. BASIC DECONTAMINATION AND WASTE MANAGEMENT

6.5.1. External decontamination

The management of external contamination is not the primary focus of this manual. However, some considerations regarding external decontamination are given below.

External contamination is more easily managed than internal contamination. The following steps apply to external contamination:

— Ideally, replacement clothing will be available in sufficient quantities before decontamination commences [21].

— Warm water will be used in showers. Cold water can be used if the air temperature is above 20°C or medical advice has been given that the risk of hypothermia is negligible.

— If the contaminated area is limited, showers may only serve to spread the contamination and make it more difficult for staff to assist the individual. Spot decontamination can be more effective in this case [68].

— While decontamination is taking place, it will be necessary to keep families together; where possible, cultural and gender differences will be respected; people with disabilities and/or medical problems have to be assisted; and questions related to radiological protection have to be answered.

— Personnel carrying out decontamination procedures have to wear appropriate personal protective equipment.

— Potentially contaminated items have to be moved to a secure storage location at regular intervals.

— The effectiveness of decontamination of people needs to be confirmed by monitoring.

All contaminated clothing collected before the washing process will be bagged and labelled with the estimated activity and nuclide (if known), the date of measurement to aid waste sentencing and the identification number of the individual to whom the clothing belongs.

6.5.2. Waste accumulation and disposal

RMU plans need to include consideration of the disposal of all waste that could be contaminated by radioactive materials. This would include all solids, liquids, washing effluents and clothing that could possibly have come into contact with radioactive material.

When an RMU will be set up, early contact with the regulator for environmental issues is strongly recommended. This will enable all radioactive waste to be disposed of in a lawful manner.

7. HANDLING OF DECEASED BODIES WITH RADIONUCLIDE CONTAMINATION

7.1. GENERAL COMMENTS

A highly radioactive cadaver would rarely be encountered in clinical practice, since radionuclide therapy is not usually given to moribund patients. An exception is a case described by Parthasarathy et al. [71] of an autopsy on the cadaver of a patient who died suddenly after receiving an oral dose of iodine-131 for a metastatic thyroid carcinoma. The dose rate near the surface of the body was about 2 mSv/h. Another example of the need for autopsies in cases of cadavers with significant external and internal radioactive contamination occurred during the Goiânia radiological accident in Brazil in 1987 [12].

More recently, increased concern has been focused on the possible consequences of a malicious act involving the use of radioactive materials. Among other problems, the detonation of a radiological dispersal device ('dirty bomb') could require responders to deal with bodies with external/internal radioactive contamination and with radioactive shrapnel [72].

Other possible scenarios that could lead to the presence of radioactive contamination in corpses are reactor accidents and incidents during the transportation of radioactive materials (radiopharmaceuticals, for example).

In general, heath personnel, coroners and pathologists are not familiar with radiation protection and are not aware of the risks associated with having to perform their activities where ionizing radiation is present. It is common in such instances for health professionals to perceive a radiation risk as similar to that of other hazards, such as chemical and biological ones. Although many radiation protection procedures are very similar to protective measures against chemical and biological agents, there are some important conceptual and practical differences that have to be addressed (see also Appendix III).

7.2. PROCEDURES FOR THE SAFE HANDLING OF DECEDENTS

Procedures concerning decedents that were exclusively exposed externally to ionizing radiation entail no radiological risks to the professionals and will follow the conventional biosafety rules. When handling a decedent who presents internal contamination with radionuclides, as during an autopsy, health personnel could be exposed to ionizing radiation from the radioactive material located in the body, and could also be contaminated. Normally, only under exceptional circumstances could the internal radioactivity in a cadaver represent a significant risk due to external exposure [12]. However, improper manipulation of a contaminated body with radioactive material can cause external or internal contamination of the professional. Biosafety accidents involving punctures and cuts, or eye and mucosa splashes, are examples of contamination routes when dealing with a radioactively contaminated body.

In all instances when an autopsy needs to be performed on a contaminated body, the planning for the procedure is essential. For this purpose, the participation of a radiation protection officer is required to determine all protective measures that will be implemented according to the national legal framework. Some considerations include:

— Limiting external exposure: This is mainly achieved through implementing time limitations, for example by rotating the working shifts of professionals (pathologists, coroners, technicians and others) during the procedures. It is extremely unlikely, in any event, that a single body would contain sufficient radioactive material for the time of exposure to need to be limited. However, with mass casualties, when many corpses need to be autopsied, this could happen if the number of available forensic and pathology professionals is limited. Another method to limit exposure is to delay the procedures, waiting for the decay of the contaminating radionuclides so that a lower and safer dose rate is reached [12, 14, 72].

— Avoiding radioactive contamination: This can be done by means of protective clothing intended to protect against contamination and not against external exposure. Again, the assistance of an experienced radiation protection officer is strongly recommended for all requirements involving the use of protective clothing. Figure 6 presents an example of a person prepared for his/her duties using protective clothing.

— Protection of the premises: The morgue and the autopsy room and facilities inside can be protected from contamination by using plastic sheets or other appropriate and waterproof material. If necessary, as indicated by a thorough radiological survey, the autopsy room will be properly decontaminated.

— Disposal of biological samples, clothes and material: All biological material from the autopsy and all instruments used have to be checked by competent radiation protection professionals before their release to their conventional destination. If indicated and feasible, instruments have to be decontaminated properly. If this is not possible or worthwhile, they will need to be considered as radioactive waste and disposed of in accordance with the country's legislation. Nothing will leave the autopsy room without a radiological survey and authorization by the radiation protection officer.

— Monitoring of professionals: All personnel involved will wear personal dosimeters, if required, and be monitored throughout the procedures. No one may leave the autopsy room without a radiation survey and the authorization of the radiation protection officer. If contamination is detected, decontamination procedures will be indicated accordingly. It is highly recommended that a shower be made available for personnel decontamination [12, 72].

It has to be emphasized that even if the best practices of radiation protection are followed, pathologists, medical examiners, coroners, technicians and others involved with the medico-legal and/or pathology procedures may receive some radiation exposure in performing their work. Nevertheless, it is paramount to underline that such exposures would be very low, and that no harm is expected to the health of these individuals, as long as proper procedures are followed.
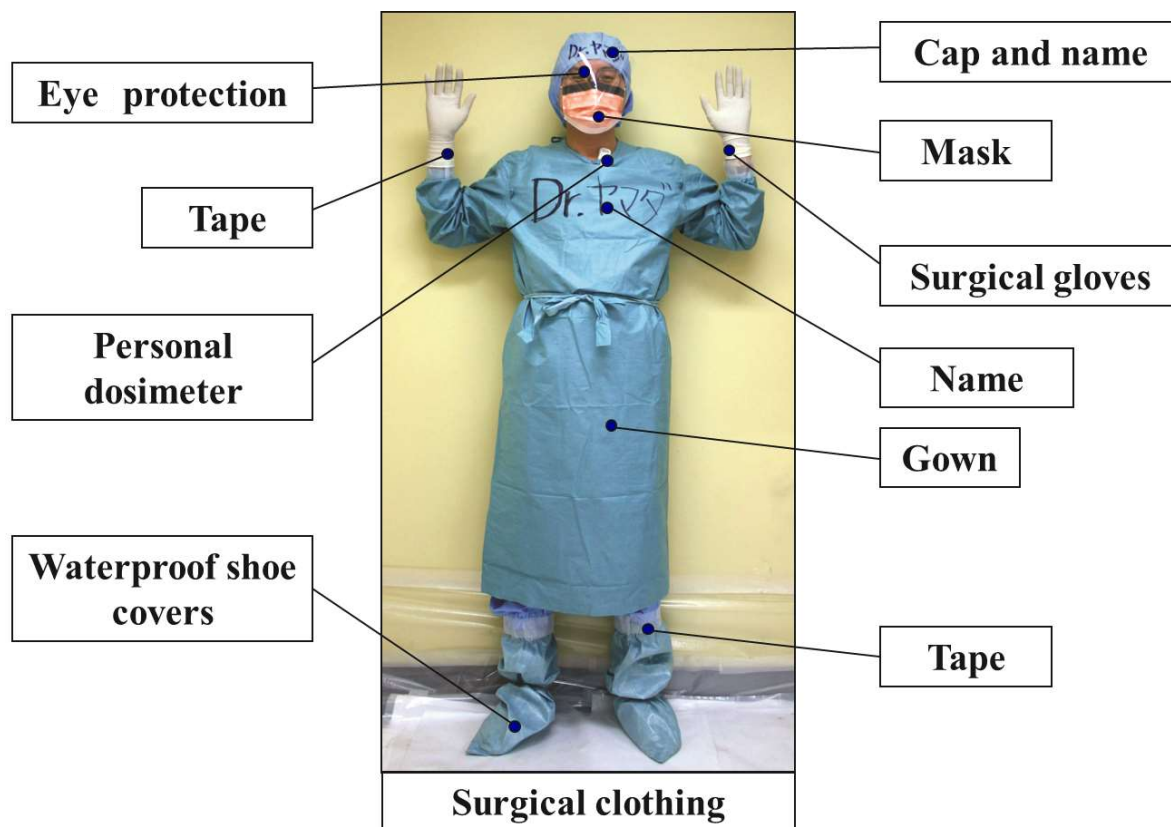
FIG. 6. Protective clothing to prevent contamination.

If forensic or medico-legal interventions, such as autopsies, are to be performed, and radioactive contamination is present, planning for avoiding the spread of contamination (to professionals, premises and equipment) and minimizing radiation exposure is essential [36]. An experienced radiation protection officer will ideally be part of the planning team and assist in developing and following the procedures.

In general, autopsies ought not to be performed on internally contaminated bodies unless absolutely necessary (for medico-legal reasons according to local legislation, for example). However, if the body only contains a small quantity of radioactive material and there is a compelling need, an autopsy would not carry any significant radiological risk and could be performed as long as it is well planned [72].

If a victim is pronounced dead at the scene of an emergency, the body will not be transported to a hospital. In such an instance, guidance will be obtained from the local coroner or a public health official as to the transport of bodies. In a mass casualty incident, refrigerated trucks might be necessary for holding the bodies until thorough assessments can be made. Depending on the amount of contamination, these trucks could be placed in a location so as to minimize exposure to others.

7.3. ON-THE-SCENE RECOVERY OF DECEDENTS

The permitted occupancy time in an area contaminated with radionuclides will normally be determined by the total dose to the most highly exposed person rather than the radiation dose rate to any individual at a given time [11, 73].

It is important that radiation survey team members or other first responders do not disturb a body without permission from the medical examiner or coroner. Preservation of evidence and identification of victims are paramount; thus, for example, clothing is not to be removed from bodies at the scene until authorized by the medical examiner [11]. On the scene of the emergency, deceased casualties may require basic preliminary decontamination before they are moved to the morgue or are ready for release to a designated place. Procedures on the scene with regard to deceased casualties depend on the character of the radiation emergency and the number of injured or deceased victims.

After the medical examiner or coroner authorizes removal of bodies, each body will be surveyed. When surveying a body using a flat surface contamination probe, the probe is held about 2 cm from the body and moved at a rate not exceeding 15 cm per second. If the count rate from a body exceeds three times the normal background, a radiation protection officer has to be consulted regarding whether it is necessary to place a radioactive warning tag on the body and another one on the outside of the body bag before it is sent to the morgue.

7.4. FIELD MORGUE NEAR THE SCENE

A malicious act involving the use of radioactive material can cause a radiation emergency with many deaths and bodies contaminated with radionuclides. If this happens, it would probably be necessary to establish a field morgue near the scene, but in an area where dose rates are low.

Background levels will need to be measured using the available monitoring instruments before receiving the first bodies, and the results for each instrument recorded. Bodies arriving at the morgue may contain embedded and highly radioactive shrapnel, low level loose surface contamination, low level internal contamination or no contamination.

The morgue will need to set up a clean processing line, a contaminated processing line and a refrigeration facility at least 10 metres from the clean and contaminated areas.

7.5. BASIC PROCEDURES IN THE MORGUE AND RELEASE OF BODIES

A typical medical examiner's team consists of two medical examiners, a photographer and a clerical assistant. They will examine the body and then carefully remove and bag all clothing and jewellery, documenting and photographing each step. Typical personal protective measures — wearing coveralls, gloves, a particulate respirator (if necessary) and goggles and bagging all removed clothing — will adequately protect the team and prevent the spread of contamination. The field morgue has to be surveyed periodically and any radioactive contamination cleaned up, under the supervision of a radiation protection professional. This will decrease the spread of contamination and prevent incorrect labelling of uncontaminated bodies as contaminated [72].

After bodies have been released by the morgue team, they can be moved to a decontamination area and washed. Collection of runoff water is not necessary for uncontaminated bodies. The runoff water from contaminated bodies could be collected for later disposal as low level waste if practical.

After washing a decedent and removing any radioactive shrapnel, a last survey will be performed.

To release the body for burial without restrictions, a radiation protection officer will be consulted. A tag can be attached to the body indicating the date, dose rate and distance at which this dose rate was measured, the results of any measurements of external and internal contamination, as well as the equipment used to perform the measurements.

7.5.1. Autopsy

An autopsy normally entails extensive handling of internal organs with gloved hands. Depending on the radionuclide(s) present and their activity, an autopsy may result in significant doses to the pathologist's hands. Also, the procedure disrupts the circulatory system, so an embalmer will have to work longer in close proximity to a body that has been subjected to an autopsy. In the case of a body internally contaminated with radionuclides, an autopsy is therefore only to be performed if absolutely necessary [72]. Protective actions to be adopted in an autopsy of a body with internal contamination with radionuclides have been described above.

7.5.2. Embalming

The embalmer will have to manipulate the body to remove all clothing, bandages, intravenous needles, catheters, etc. Shaving is necessary in many cases.

The embalming table and facilities will be covered with plastic and disposable absorbent materials to the maximum extent possible [11].

A body with internal contamination with radionuclides has to be embalmed under the close orientation and supervision of a radiation protection officer.

7.5.3. Cremation

Internally contaminated decedents are only to be cremated when adequate measurements and, as necessary, procedures can be taken for preventing radioactive contamination of the facility and the surrounding environment. Cremation of decedents contaminated with long lived radionuclides from a nuclear emergency could cause sufficient contamination to require extensive decontamination efforts.

Shrapnel or brachytherapy seeds will not be destroyed in the process of cremation. If cremation is desired, shrapnel, brachytherapy seeds or any other discrete sources have to be removed and dealt with in accordance with the legislation on handling and disposal of radioactive materials [72]. The pieces removed could be characterized as forensic evidence, and medico-legal regulations need to be observed.

7.5.4. Funeral services

Depending on the outcome of the decontamination procedures employed, family members may be allowed to stay or touch the decedent's body. A briefing by the radiation protection officer can be a useful way to make family members aware of any radiation risks [72].

Family members and other persons attending the funeral services and concerned about radiation exposure need to receive a clear explanation of its meaning. It is useful to compare doses with those incurred in medical procedures (for example, 'half the dose received in a chest X ray').

In exceptional cases, the presence of heavy contamination may call for closed metal casket funeral services, wrapping the body in plastic (or leaving it in a body bag) and implementing other contamination control measures.

7.5.5. Burial

Burial of a body that has internal contamination usually constitutes minimal health risk to humans or the environment. Minimizing release of radioactive material into the environment is good practice, even if the amounts are very small [72]. A wooden casket or coffin is not sealed against elements entering or exiting the container. A metal casket can be considered, but only in very rare cases where bodies are heavily contaminated with gamma emitting radionuclides would lead lined caskets be required (as happened in the Goiânia accident, but mainly because of significant public concern) [12].

7.5.6. Religious and cultural aspects

Respect for the religious and cultural traditions of persons dealing with the death of family members is very important [11]. These traditions may include ritual washing or specific preparation of the body. If the medical examiner or coroner removed all loose surface contamination and radioactive shrapnel before releasing the body to a funeral director, doses to family members or a religious leader performing the ritual will be no greater than the doses to family members from the viewing mentioned previously. There is no reason to prohibit these traditions provided the funeral director, family and religious leader understand the minor risks involved.

7.5.7. Occupational accidents

If an occupational accident (punctures, cuts, eye or mucosa splashes, etc.) occurs during an autopsy or handling of a body contaminated with radioactive materials, it has to be immediately reported to the competent radiation protection officer and the occupational physician. Biological and radiological hazards will need to be carefully evaluated and proper countermeasures adopted. Just in terms of the radiation hazard, if a decision is needed on the need for decorporation treatment, the parameters already discussed in previous sections will need to be taken into account.

8.   CASE REPORTS

8.1.   CAESIUM-137: INTERNAL/EXTERNAL CONTAMINATION

On 13 September 1987, in Goiânia, the capital city of the State of Goiás, in central Brazil, two individuals removed the head of a radiotherapy device containing a 50.8 TBq caesium-137 source left behind in a derelict clinic. They brought it home and then sold parts of it to several junkyards. As a result of the violation of the source integrity, many persons were irradiated and incurred external and internal contamination [74–79].

As a consequence of radiation exposure, 20 persons were hospitalized in the Goiânia General Hospital and the Marcílio Dias Navy Hospital in Rio de Janeiro. Seventeen individuals developed bone marrow depression and eight full-fledged ARS; four of them ultimately died [12]. In addition, 112 800 persons were triaged in the city for possible radiation contamination, which was detected in 249 individuals, although restricted to the clothes and shoes of 120 of these persons.

Radiation exposures began immediately after the source violation on 13 September 1987. Thereafter, some individuals developed the prodromal manifestations of ARS, the syndrome itself and variable degrees of cutaneous radiation syndrome. Although many persons sought medical attention in Goiânia clinics and hospitals, they were misdiagnosed as having pemphigus foliaceus, atopic dermatitis, insect bites, etc. The aetiology of the manifestations was only made clear on 29 September 1987 after a physicist was alerted by a physician that patients were admitted to hospitals after having manipulated 'X ray equipment'. The physicist then borrowed a radiation detector and measured high levels of radiation while approaching the Sanitary Surveillance Department of Goiânia, where the remains of the equipment had been taken by the wife of the owner of one of the junkyards [78, 79].

The delay in the correct diagnoses caused medical aggravation of the injuries due to lack of appropriate treatment and additional doses and incorporations. It resulted in additional people being exposed and exacerbated other impacts: environmental, economic and psychological.

An important evident lesson from this situation is that health personnel need to be prepared to identify the medical manifestations of accidental radiation exposures. This applies particularly to personnel of medical emergency departments.

The medical response to the accident was established on a three-level basis: at an out-patient unit in Goiânia; a specially prepared ward in the Goiânia General Hospital; and, for the most severe cases, the Marcílio Dias Navy Hospital in Rio de Janeiro.

The Goiânia accident demonstrated that impacts of radiation emergencies can be extremely severe. It showed the need for planning and preparedness for a medical response to these kinds of emergencies. It also demonstrated that it is essential that information and training, both in local hospitals and at tertiary centres, be widely disseminated and not restricted to nuclear medicine doctors and radiotherapists. Indeed, emergency department personnel, surgeons, internists, haematologists and others need to be well aware of the medical manifestations of an accidental radiation exposure.

The uncertainties regarding the information delivered by the victims, the protracted and non-homogeneous nature of the exposures, the association of conditions (external exposure

and contamination) and the delay between the initial exposures and the identification of the accident all made clinical estimations of doses very difficult [74]. Chromosome analysis was also used for dose estimation, but the same drawbacks are pertinent for this method, too. Caesium burdens were mainly determined by urine and faeces bioassays.

Decorporations were strongly improved by the use of Prussian Blue and were followed up by about 4000 bioassays and also by a specially designed whole body counter.

The average reduction of the biological half-life of caesium-137 with Prussian Blue was the same with a daily dose of 3, 6 or 10 g (69% in adults, 46% in adolescents and 43% in children). The administration of Prussian Blue, even at doses higher than recommended, was well tolerated and caused virtually no side effects [38]. During the first month after the accident, only in vitro bioassay procedures were done. Incorporation into the body and committed doses were estimated using age-specific mathematical models correlating these quantities to the caesium-137 excreted in urine [37].

There was a unique case of a six-year-old girl who ingested a massive burden of caesium while eating a sandwich with her hands, with fragments of caesium being spread on the table she used for eating. This patient developed ARS mainly by virtue of internal contamination and not because of external exposure, which is exceptional. Her initial estimated intake was 1677 MBq; her blood activity was 52.92 MBq/L on day 10 after initial exposure and 18.14 MBq/L on day 24 (she received 6 g/day of Prussian Blue). She died on day 29 after exposure of diffuse haemorrhage in multiple organs and sepsis. Her initial cytogenetic estimated whole body dose of 5.0–7.3 Gy was then re-estimated to a mean dose of 4.4 Gy [12, 36].

The Goiânia accident was the first opportunity to use a cytokine in patients with accidental radiation induced bone marrow failure. This experience opened the way for the indication of bone marrow growth factors, on a much more rational basis, in other radiation accidents, as in San Salvador, El Salvador (1989) [80], Soreq, Israel (1990) [81], and Tokaimura, Japan (1999) [82].

The Goiânia radiation accident has been considered one of the most serious in the Americas [36]. It resulted in four fatalities, serious injuries (one patient had his left forearm amputated) in many people and widespread contamination in the central part of the city. Besides medical consequences, psychological, social and economic impacts were very significant. As a result of contamination, seven houses had to be demolished. The city cleanup resulted in 3500 m^3 of contaminated waste, which was initially accommodated in an interim disposal site. Later, a final waste disposal site was constructed in Abadia de Goiás, about 30 km from the city of Goiânia. The Brazilian National Nuclear Energy Commission built its regional centre for nuclear sciences here [12].

Discrimination against victims and their relatives, friends and neighbours was intense. Vehicles with license plates from the State of Goiás were not allowed to enter other states. Prejudice against Goiás citizens in airports and in an interstate bus station was also observed. For example, the Goiás representation was not allowed to attend a traditional beneficent Catholic fair in Rio de Janeiro in December 1987 [36].

Police force had to be used to permit burials of the corpses of the deceased victims in Goiânia, as many locals were afraid the cemetery would be contaminated.

Following a boycott of local products, the gross internal product of the State of Goiás dropped by 30% four months after the accident [36].

The medical, psychological and social follow-up and assistance to the victims of the accident was organized and delivered by the Centre for the Assistance of Radiation Victims within the structure of the State of Goiás Health Secretariat.

A survivor of ARS died in 1994 (mean cytogenetic re-estimated dose of 5.3 Gy) of alcoholic liver cirrhosis (an adenocarcinoma of the lower oesophagus and a carcinoma of the prostate were found during autopsy). In February 2014, another ARS survivor died from complications of a melanoma, at age 84. Her mean cytogenetic re-estimated whole body dose was 2.8 Gy [36].

Besides recurrences of local radiation injuries in three patients, the most relevant problems observed were psychosocial ones, like psychosomatic manifestations, drug abuse and fear of death by radiation related diseases, especially cancer.

The Goiânia accident was characterized by protracted exposures to ionizing radiation. The violation of the caesium source happened on 13 September 1987 and the accident's nature was only disclosed 16 days later. This fact was mainly due to the inability of local health personnel to identify the clinical manifestations in the victims as radiation induced. One lesson from the accident is that health personnel need to be aware of the clinical manifestations of whole body and local radiation exposures ('acute' radiation and cutaneous radiation syndromes). The suspicion by health personnel that people are being exposed to radiation may be an important clue to identifying lost or planted sources. If clinical manifestations of radiation exposure are not recognized in a timely manner, it is evident that the consequences will be made much worse [10, 12, 76, 77].

Another aspect refers to both internal and external contamination. Besides conventional injuries, the detonation of a radiological dispersal device could also cause both external irradiation and internal contamination (as in Goiânia) [36]. It is possible that the preferred radiation source in a 'dirty bomb' would be a caesium-137 source, because of its chemical properties. In this respect, authorities in charge of responding to a malicious dispersal of radioactivity need to consider aspects like hospital preparedness to cope with patients with both conventional trauma and radiation contamination, the supply of specific drugs like Prussian Blue, medical protocols for triage and treatment of victims with radiation injuries, communication with the public, and the handling of the psychological impact and the immediate and long term consequences of a radiation emergency.

An evident and serious problem in the Goiânia accident was that emergency physicians and other health staff did not recognize the manifestations in the patients as being radiation induced. Misdiagnoses such as pemphigus, food intoxication, insect bites, etc. were made instead. This fact was an important component in aggravating all the consequences of the accident [36].

8.2. POLONIUM-210: A LETHAL INDUSTRIAL INHALATION ACCIDENT

In 1954, a male worker in the former Soviet Union accidentally inhaled an estimated 530 MBq of a polonium-210 aerosol over a period of 5 hours at an industrial site. Within a few days, he developed signs of a severe radiation pneumonitis and severe dyspnoea;

about 6 days later, he developed severe bone marrow toxicity. He died on day 13 after contamination. The post-mortem activity analysis in tissue samples estimated the cumulative radiation dose to the lungs at 140 Gy, that to the liver at 9 Gy, that to the kidney at 30 Gy and that to the bone marrow at 1.7 Gy [83].

The acute cause of this worker's death was acute radiation pneumonitis.

Today, the person could potentially have survived owing to the availability of newer countermeasures (BAL, DMSA, penicillamine [11]) and with the performance of an early lung lavage with more advanced bronchoscopy techniques/equipment. The physicians have to keep in mind that medical intervention and mitigation of acute organ death (such as acute pneumonitis) have to be followed up by dedicated attention to the next organ at risk at a later time (bone marrow and liver, in this case). In such situations, it may well be necessary to provide special, organ specific medical care for several different organ systems at different times during the course of treatment, especially following severe internal contamination from radionuclides such as polonium-210, in order to provide an optimal chance of survival.

8.3. PLUTONIUM-239: THREE CASES OF OCCUPATIONAL CONTAMINATION

Case 1 involves an individual who suffered a wound on the left index finger from a screwdriver, while working in a glovebox containing plutonium metals [84]. After washing and irrigation, the wound count measured 629 Bq. Assuming as a worst case scenario that all of the measured activity was absorbed to blood instantaneously, and using the committed effective dose coefficient of 489 µSv/Bq, a total committed effective dose E(50) of 308 mSv would be expected. The chelation therapy comprised a total of 29 administrations of DTPA, and was initiated with an injection of 500 mg of Zn-DTPA. On the day after the intake, 1 g of Ca-DTPA was administered. After that, daily injections of 1 g of Zn-DTPA took place on the following days after the intake: 2, 3, 4, 5, 6, 8, 9, 10, 11, 15, 17, 22, 24, 29, 31, 44, 52, 58, 66, 78 and 92. Additional injections of 1 g of Ca-DTPA were performed at 106, 121, 135, 151 and 163 days after the intake. In addition, the person requested a late injection of 1 g of Ca-DTPA, which was done at 590 days after the intake (see Fig. 7).

There is a remarkable correlation between the chelation treatments and the higher urinary activity excretion results for samples right after each treatment, but there is no apparent explanation for the 'peak' that occurred around 200 days after the intake. The same degree of urinary excretion enhancement could be observed for the single chelation treatment which was carried out at 590 days after the accident. The total estimated averted dose was 99.4 mSv.
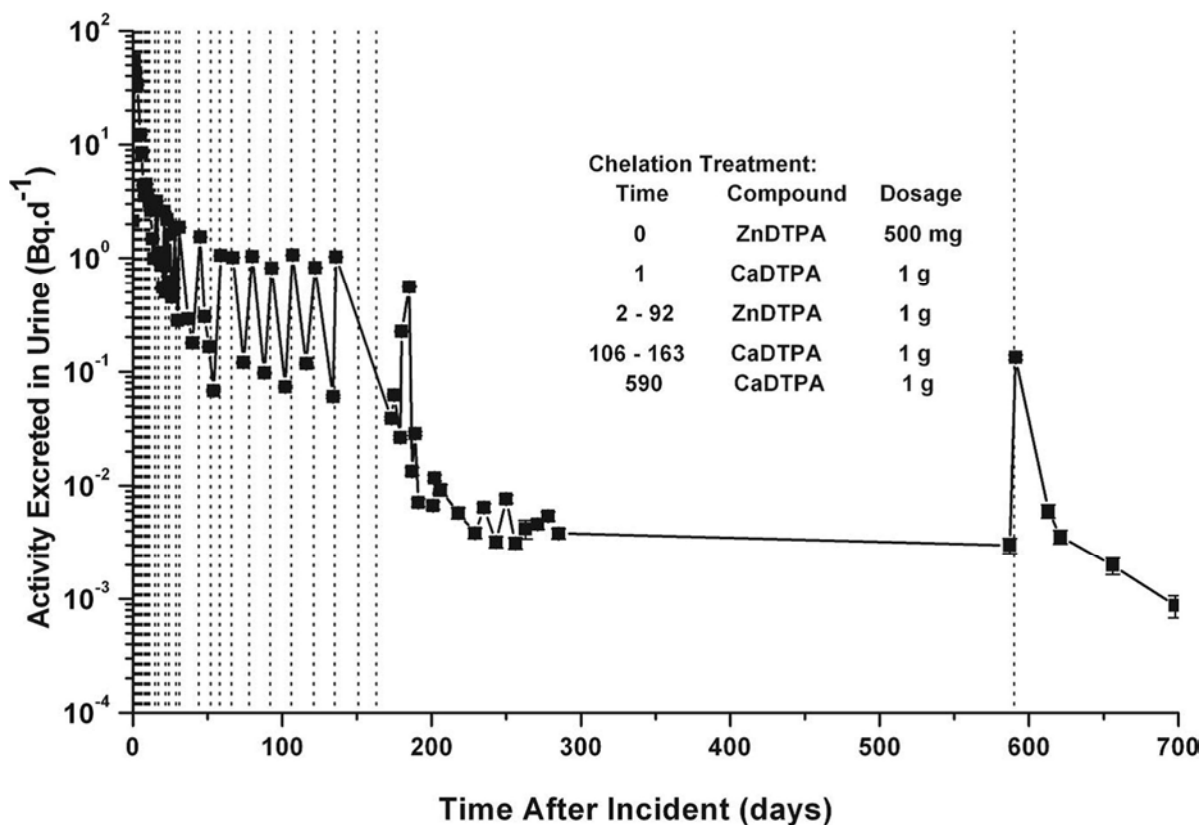
FIG. 7. Plutonium-239 activity excreted in urine vs. time after the incident showing the chelation treatment, Case 1. The dotted lines represent the chelation treatment; reproduced from Ref. [84] with permission.

Case 2 concerns a worker who lost his grip while working in a glovebox machining plutonium metal and hit a sharp edged surface within the glovebox, resulting in a shallow laceration on the wrist [84]. Prompt decontamination procedures took place until the external activity was reduced to non-detectable levels. The first wound count measured 62.9 Bq. After new skin decontamination, the wound measurement showed 48.1 Bq. Subsequently, 1 g of Ca-DTPA was administered, and, after the skin flap was removed, a subsequent wound count was performed, which showed no detectable remaining activity. The excised skin flap contained 44.4 Bq, or essentially all the remaining plutonium activity.

One bioassay sample was collected before and three more after the chelation therapy. The total calculated averted dose was 150 μSv. Subsequently, more bioassay samples were collected at 90, 96 and 102 days after the accident. They were used to estimate the committed effective dose, which was 210 μSv. Figure 8 shows the urinary excretion measurements, including an additional urine sample collected at 280 days after the accident.
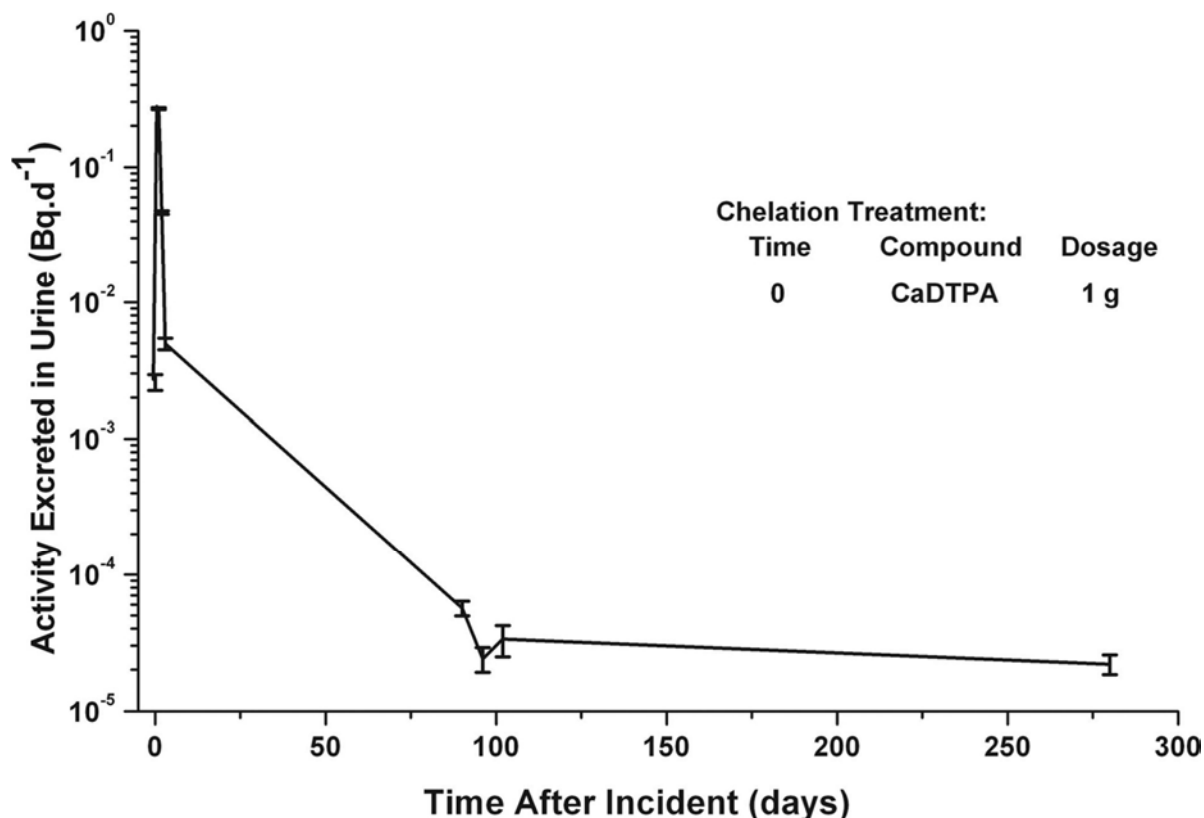
FIG. 8. Plutonium-239 activity excreted in urine vs. time after the incident, Case 2; reproduced from Ref. [84] with permission.

Case 3 concerns an individual who incurred a wound on his right thumb, also while working in a glovebox [84]. A metallic fragment containing plutonium-239 became deposited in the wound. Several excisions and four DTPA administrations were used for treatment. Twelve urine bioassay samples were submitted and were analysed for plutonium-238 using Routine Analytical Service; for plutonium-239, both this technique and thermal ionization mass spectrometry were used. At Los Alamos National Laboratory, Routine Analytical Service remains the technique for the determination of plutonium-238 and plutonium-239 in routine monitoring. Thermal ionization mass spectrometry is used as an adjunct for baseline and frontline plutonium workers, providing more sensitive determinations of plutonium-239 and the 239/240 ratio. The samples were used to evaluate the efficacy of the decontamination treatment and to estimate the committed effective dose equivalent due to this accident.

Figure 9 shows the measurement results for wound counts, excised tissues, a cotton glove and the first six urine bioassay measurements, covering the first 10 days after the incident. The four chelation treatments (each with a dosage of 1 g of Ca-DTPA), which took place at 0, 1, 5 and 7 days after the incident, are represented by dotted lines. The text on the right hand side of the graph shows the estimated averted dose, corresponding to each of the first six bioassay samples.

A gamma spectrometry analysis was performed on a sample of tissue and material excised from the right thumb. Activities of 39.2 and 6660 Bq were found for americium-241 and plutonium-239, respectively. The results clearly show that plutonium-239 was the main radionuclide of concern. A subsequent wound count showed 671.6 Bq for plutonium-239. The 7332 Bq activity of plutonium-239 represents the total initial source activity available to become systemic if no countermeasures had been taken. Due mostly to surgical

procedures, this value was reduced to only 25.5 Bq in less than one day after the accident. Six days later, after all surgical procedures had taken place, the final wound count for plutonium-239 was only about 18.5 Bq. The americium-241 activity was negligible. No other radionuclides were identified as being present.
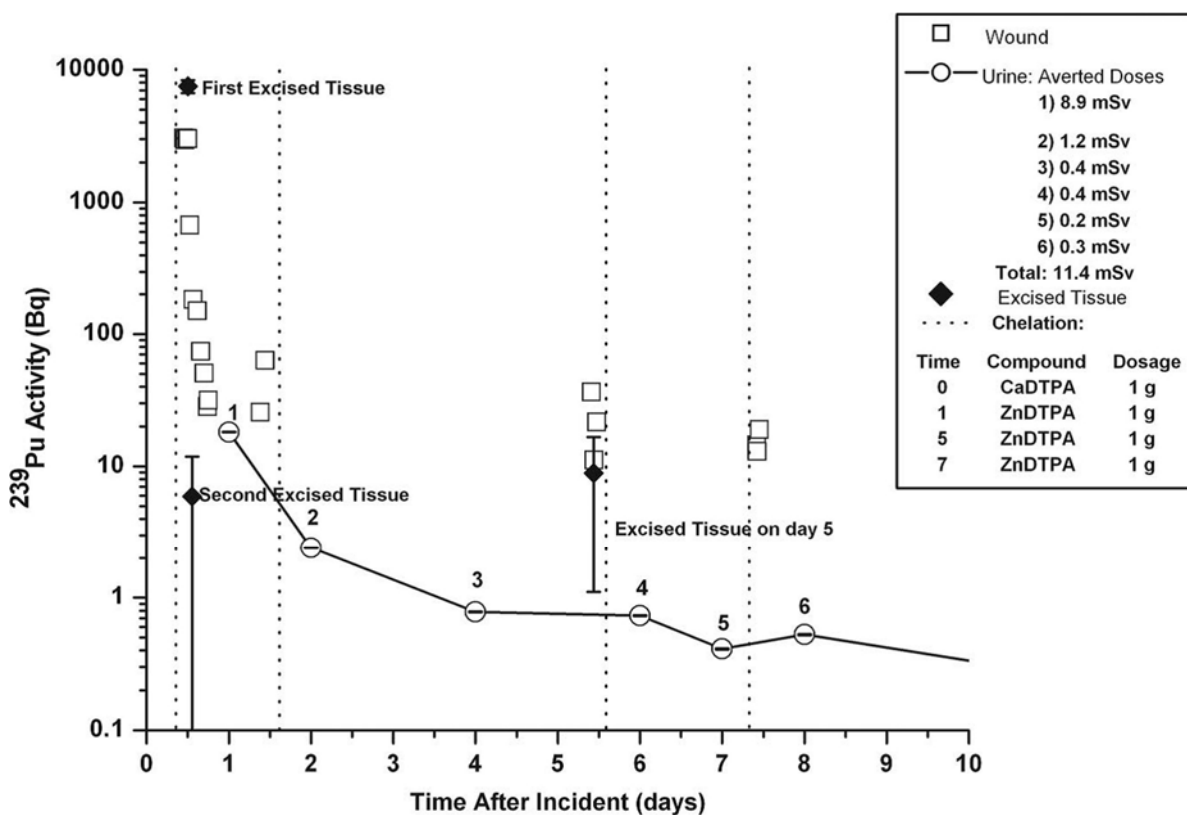

FIG. 9. Plutonium-239 activity measured in wound, urine and in other relevant samples vs. time after the incident. The treatments are also represented in the figure. Case 3; reproduced from Ref. [84] with permission.

The results of the urinary excretion after cessation of chelation therapy are presented for all three cases in Fig. 10; they show that the daily urinary excretion normalized at the time of the last chelation. Since Cases 1 and 3 were treated more than once, 'negative' time values are shown. The analyses of the data showed that considerably different intake amounts and corresponding doses were estimated for the three cases. However, in spite of this fact and in spite of the different number of treatments, a difference of four orders of magnitude can be seen between the highest excretion data point and the values observed at about 100 days for all cases.

FIG. 10. Plutonium-239 activity excreted in urine vs. time after the last chelation, all three cases; reproduced from Ref. [84] with permission.

The simulation of a single injection of plutonium-239 using the AIDE software [85] showed that the decrease in the daily urinary excretion values between the first and the hundredth day is two orders of magnitude. Hence, the extra factor of 100 can be attributed to the efficacy of the chelation, which is normally greatest soon after the intake. Since in all cases the administered dosages were 1 g of either Zn-DTPA or Ca-DTPA, a correlation with an efficacy factor of 100 could be tentatively established. La Bone [86] has observed efficacy factor values ranging from 1 to 150, where 1 means that chelation had no effect. He also recommended an average value of 50 for the initial evaluation of urinary excretion data following an intake of plutonium-239. Differences between efficacies of Zn-DTPA and Ca-DTPA could not be observed in these cases.

As shown in Fig. 7, Case 1 included a DTPA administration at 590 days after the incident. The excretion peak is similar to those for chelation at earlier times. The efficacy factor is about 50, which shows that the chelation was still effective more than 1.5 years after the incident. The averted dose due to this chelation can be approximately calculated by

multiplying the urinary excretion value of 0.13 Bq by the committed effective dose coefficient due to a single injection of plutonium-239, which is 489 μSv Bq^{-1}. The resulting averted dose was only about 64 μSv.

8.4. YTTRIUM-90: THERAPEUTIC RADIOPHARMACEUTICAL ACCIDENT

In the United States of America, in the 1970s and 1980s, oncologists were attempting to develop better ways of treating hepatic metastases [87]. One type of therapy under development at the time in several US cancer centres was the use of yttrium-90, which was generally bound to 20–50 μm glass or plastic spheres. These yttrium-90 labelled spherical particles (about 45–85 mCi or 1.73 GBq) were injected into an artery supplying the hepatic tumour (generally the common hepatic artery, or some other regional artery). These particles were then trapped in the capillary sized tumour vessels, thereby allowing delivery of the yttrium-90 beta radiation (average energy of 934 keV) primarily to the local tumour tissue (beta range in soft tissue is about 5 mm). Unfortunately, at one of the clinical investigation sites, perhaps the most severe radiotherapy accident ever to occur in the United States of America involved this type of radiotherapy procedure. Specifically, the physicochemical attachment process of the yttrium-90 to the microspheres was apparently faulty. Soon after the intra-arterial injection, the radionuclide became dissociated from the 20–50 μm particles, and the free yttrium-90 atoms then targeted the bone marrow rather than the tumour tissue.

Eight of the patients in this series died, which is perhaps not unexpected, since they all had metastatic cancer. But seven out of eight patients died shortly after the yttrium-90 administration, from the loss of yttrium-90 from therapeutic microspheres used as the transport mechanism [88, 89], with significant depressions of haematopoietic function. This is consistent with the estimated bone marrow radiation doses from the yttrium-90 beta irradiation (estimated to be from 3.5 to 6.2 Gy). This radiation dose, if delivered in a relatively short time (yttrium-90 physical and effective half-lives are 64.1 hours), is in the dose range that can cause lethal ARS, haematological type.

As a result of these types of therapeutic radiopharmaceutical accident, the US Nuclear Regulatory Commission developed new guidelines and regulations on the use of unsealed by-product materials.

8.5. AUTOPSIES ON CONTAMINATED BODIES

Four patients died from ARS in the Goiânia accident (see Table 16) [12]. Autopsies were legally required and performed on all the corpses at the Pathology Department of the Marcílio Dias Navy Hospital in Rio de Janeiro.

All bodies had internal and external contamination; a six-year-old girl had massive internal contamination, and the dose rate close to her skin reached 2.5 mSv/h. Information on the medical, pathological and radiological conditions of these victims is shown in Table 16.

Planning the autopsies was an essential action, to avoid contamination of the personnel and to minimize radiation exposure. Pathologists, coroners, morgue technicians, radiation medicine doctors and radiation protection personnel met and planned the procedures. For example, it was established that personnel would rotate every 10 minutes during autopsies and that outer gloves would be changed frequently.

All radiation protection measures, including the kind of protective clothing to be used, were determined by radiation protection personnel. Respiratory protection other than surgical masks was not judged necessary. Otherwise, conventional biosafety techniques were fully adopted [10, 12, 73, 74].

All autopsy team members used personal dosimeters (including dosimetric rings), and dose rates were constantly monitored. No one received any significant radiation dose, and no radiological contamination or occupational accident occurred.

TABLE 16. MEDICAL, PATHOLOGICAL AND RADIOLOGICAL CONDITIONS OF DECEASED VICTIMS IN THE GOIÂNIA RADIOLOGICAL ACCIDENT [12]

Case	Death (day after initial exposure)	Cause of death	Cs-137 burden (MBq)	Mean cytogenetic re-estimated dose (Gy)
LNF — 6 y, Female	29	Diffuse haemorrhage of multiple organs, sepsis	1677	4.4
IBS — 22 y, Male	34	Acute pulmonary oedema, bilateral bronchopneumonia, sepsis	60	2.9
MGF — 36 y, Female	34	Diffuse haemorrhage of multiple organs, sepsis	34	3.9
AAS — 18 y, Male	35	Lung collapse, lobar pneumonia, sepsis	120	3.7

APPENDIX I.
DRUGS THAT MAY BE USED FOR DECORPORATION TREATMENT

Pharmacological presentations, dosage and clinical studies may vary among countries. National health regulations of each Member State concerning the use of the drugs that are included in this Appendix need to be fully considered.[7]

I.1.   ACETAZOLAMIDE

— How supplied: 250 mg tablets. A parenteral presentation is available in some countries.

— Mechanism of action: Diuretic that inhibits the carbonic anhydrase. It is used in particular in the treatment of glaucoma and in the prophylaxis of high altitude disease. It could be indicated in an internal contamination with uranium to reduce its absorption at the renal tubule level.

— Indication: Uranium contamination.

— Dosage and administration: 1 tablet, 3 to 4 times a day. If available, 1 ampoule per day, in intramuscular or intravenous shots.

— Contraindications and adverse effects: Pregnancy. Adverse effects are infrequent and can include hypersensitivity reactions (skin, for example), fever and bone marrow depression.

I.2.   ALGINATES

— How supplied: In distinct presentations.

  • Granulated powder (1 g envelopes);

  • Chewable tablets (0.5 g);

  • Liquid (0.05 g/mL).

— Mechanism of action: Normally presented as sodium or calcium alginate. It is a product used for the treatment of gastro-oesophageal reflux. It forms a high viscosity gel.

— Indication: For the inhibition of the intestinal absorption of alkaline earth metals such as strontium, calcium, barium and radium.

— Dosage and administration: 10 g/day orally, single dose or divided in two administrations on the first day. Treatment can be continued depending on the contamination grade. Preferably, the patient will be fasting and will not eat immediately after an administration.

— Contraindications and adverse effects: None. However, troubles with sodium ingestion can occur, particularly if the patient is under sodium restriction. In diabetics, the sugar content of each tablet has to be considered (700 mg). In rare cases, constipation may occur.

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[7] The information provided in this appendix is based on Annex I of the IAEA publication Informe de la Reunión Final de Coordinadores del Proyecto ARCAL RLA/9/031 — XXXVII — Tratamiento Médico en Casos de Accidentes Radiológicos [90].

I.3. ALUMINIUM HYDROXIDE

— How supplied: Variable.

— Mechanism of action: Complexation, reducing intestinal absorption of strontium.

— Indication: Contamination with strontium.

— Dosage and administration: 100 mL/day in three administrations.

— Contraindications and adverse effects: Hypophosphatemia and renal failure. Constipation.

I.4. AMMONIUM CHLORIDE

— How supplied: 0.5 g capsules.

— Mechanism of action: Through medium acidification by the liberation of hydrogen and chlorine ions, favouring the creation of ionized forms of alkaline earth ions. This leads to an improved urinary excretion of these radioelements.

— Indication: Contamination with alkaline earths, such as radium, barium and strontium.

— Dosage and administration: The recommended dose is 6 g (12 capsules) orally divided in three administrations (4 capsules each time), if possible during meals. Treatment can be continued in the following days, depending on the contamination grade (3–6 g/day).

— Contraindications and adverse effects: Acidosis, urate lithiasis, severe liver failure with hyponatremia, uremic nephritis and hyperchloremic renal acidosis. Overdoses cause metabolic acidosis that can be treated with intravenous injections of alkalizing solutions (sodium bicarbonate) under strict kalaemia control.

I.5. BARIUM SULPHATE

— How supplied: Aqueous suspension for oral use.

— Mechanism of action: Significantly reduces the intestinal absorption of strontium and radium by producing insoluble sulphates with these radionuclides.

— Indication: Contamination with strontium and radium.

— Dosage and administration: 300 mg, single dose.

— Contraindications and adverse effects: No toxicity or contraindications.

I.6. CALCIUM GLUCONATE

— How supplied: 5 and 10 mL ampoules for injections and ingestion, containing 100 mg of calcium gluconate/mL of water (10% solution) — equivalent to 9 mg/mL of calcium.

— Mechanism of action: Isotopic dilution and competition from chemical analogy.

— Indication: Contamination with alkaline earths (calcium, strontium, barium and radium).

— Dosage and administration: orally, 6–10 g/day in three administrations with meals (6–10 ten-mL ampoules). Via intravenous route, as a slow 1–5 g (1 to 5 ampoules) infusion in 500 mL of a 5% glucose solution. Treatment will continue in the following days depending on the severity of the contamination.

— Contraindications and adverse effects: hypercalcaemia, hypercalciuria, calcium lithiasis and nephrocalcinosis are contraindications. It is not to be given to patients under digitalization, because it can enhance the effects of digitalis (in selected cases, administration can be done under strict monitoring). In prolonged administration, calcium blood levels and its renal excretion will need to be monitored. Thirst, polyuria, polydipsia, nausea, vomiting, dehydration, hypertension, vasomotor disturbances and constipation can be manifestations of overdose.

I.7. CHLORTHALIDONE

— How supplied: 50 or 100 mg tablets.

— Mechanism of action: Diuretic. Increases the renal elimination of sodium, potassium, tritium and other radionuclides.

— Indication: Contamination with sodium, potassium, tritium and other radionuclides.

— Dosage and administration: Usually 100 mg, single dose on the first day, followed by 50 mg/day in the following days, depending on the contamination level.

— Contraindications and adverse effects: Severe renal failure, liver encephalopathy, hypersensitivity to sulphonamides and nursing (concentrates in the maternal milk). The water and mineral balance will need to be controlled (especially sodium and potassium). In diabetics, glycaemia will need to be strictly controlled. A dose reduction is recommended for patients with gout (do not use during a gout attack). It is not recommended for patients using lithium, antihypertensive drugs, hypoglycaemics, digitalics and corticosteroids. Overdosage can cause hyponatremia, hypokalaemia, acute pancreatitis and neutropenia.

I.8. COBALT GLUCONATE

— How supplied: 2 mL ampoules, containing 450 µg (0.45 mg) of cobalt gluconate, corresponding to 59 µg of cobalt.

— Mechanism of action: Isotopic dilution.

— Indication: Contamination with cobalt.

— Dosage and administration (may vary among countries): 900 µg of cobalt gluconate (2 ampoules) intramuscular or sublingual. Treatment can be continued in the following days, depending on the contamination level, with 1–2 ampoules/day. This dose can vary up to 10 ampoules/day sublingual [39].

— Contraindications and adverse effects: None described so far.

I.9. COLLOIDAL ALUMINIUM PHOSPHATE

— How supplied: Envelopes with 11 g of aluminium phosphate.

— Mechanism of action: Reduction in the absorption by the GI tract.

— Indication: Contamination with alkaline earths, such as radium, barium and strontium.

— Dosage and administration: In emergencies, 5 envelopes (55 g of aluminium phosphate), single administration. Treatment is to be continued in the following days, with 1–2 envelopes, 2–3 times/day, depending on the grade of the contamination.

— Contraindications and adverse effects: Administration with caution to diabetic patients (each envelope contains 3 g of glucose). The most frequent side effect is constipation. It can interact with other drugs, delaying or reducing the absorption of furosemide, tetracycline, digoxin, isoniazid, indomethacin and anticholinergic.

I.10. DEFEROXAMINE (DFOA)[8]

— How supplied: 500 mg lyophilized bottles with a sterile water 5 mL ampoule for intramuscular or subcutaneous injection or slow intravenous injection.

    — Mechanism of action: The drug is presented as methanesulphonate of deferoxamine B. Its mechanism of action is chelation followed by excretion of the radionuclide–deferoxamine complex through the urine.

— Indication: Contamination with manganese, iron and chromium.

— Dosage and administration: 1 g/day (2 ampoules) on the first day followed by 500 mg in the following days, depending on the contamination level. Administration can be via:

- Very slow intravenous injection, in 250 mL of an isotonic 0.9% NaCl solution;

- Very slow intravenous injection, in 250 mL of an isotonic 5% glucose solution;

- Nasogastric tube, up to 8 g (16 ampoules).

— Contraindications and adverse effects: Tachycardia, hypotension, pseudo-shock, erythema, urticarial reactions, digestive disturbances, vertigo, convulsions, visual and auditory alterations. Deferoxamine has shown teratogenicity in animal models.

I.11. DIMERCAPROL (KNOWN AS BRITISH ANTI-LEWISITE — BAL)

— How supplied: 2 mL ampoules with 200 mg of dimercaprol.

— Mechanism of action: Formation of stable chelates by competing with exogenous sulphydryl groups.

— Indication: Intoxication with heavy metals such as lead, polonium, antimony, bismuth, cadmium, copper, mercury and gold.

— Dosage and administration: 3 mg/kg body weight via intramuscular injection every 4 hours. The median administration for an adult is 1 ampoule every 4 hours. Treatment needs to be under strict control (in hospital). The individual sensitivity has to be tested with ¼ ampoule before the first administration.

— Contraindications and adverse effects: Efficacy is variable and numerous adverse effects may result, such as hypertension, tachycardia, nausea, vomiting and headaches. Because of this, administration is not to continue for more than three days. The alternative use of dimercaptopropansulphonate (DMPS) has been proposed as it has fewer adverse effects.

I.12. DIMERCAPTOPROPANSULPHONATE (DMPS)

— How supplied: 100 mg capsules containing sodium salt of DMPS; 5 mL ampoules containing 250 mg sodium salt of DMPS.

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[8] Also known as desferrioxamine.

— Mechanism of action: Chelation.

— Indication: Internal contamination with mercury, lead and polonium. Some evidence exists as to its efficacy for contamination with arsenic, copper, antimony, chromium and cobalt.

— Dosage and administration: Depends on the severity of the contamination. Three capsules every 3–6 hours in the first day is recommended; in the following days, every 8–12 hours. Parenteral administration is only indicated if the oral route is not possible:

- First day: 250 mg (1 ampoule) by slow intravenous injection each 3–4 hours (1.5 to 2 g/day);

- Second day: 250 mg by slow intravenous injection each 4–6 hours (1 to 1.5 g/day);

- Third day: 250 mg by slow intravenous or intramuscular injection each 6–8 hours (0.75 to 1 g/day);

- Following days: Depending on the patient's condition, 250 mg one to three times, parenteral route or orally (capsules).

— Contraindications and adverse effects: Hypersensitivity; occasionally fever, chills, skin reactions, nausea, vertigo, vomiting, transient increase in transaminases and hypotension. In prolonged treatment, the mineral balance and the renal function will need to be monitored.

I.13. DTPA (DIETHYLENETRIAMINE-PENTAACETATE)

— How supplied (for example):

- Sterile concentrated solution at 20–25% (0.20–0.25 g of DTPA/mL) in 2 mL and 4 mL ampoules;

- Micronized capsules for aerosol (40–100 mg/capsule);

- 1% (pH 4) acid solution (1 g of DTPA/100 mL of the solution, in 500 mL bottles).

— Mechanism of action: DTPA is used either as a trisodium calcium or zinc salt (Ca-DTPA or Zn-DTPA). It is a chelating agent that acts by forming complexes with certain radionuclides.

— Indication: Contamination with plutonium and, in general, transuranics and lanthanides. It is convenient for contamination with manganese, iron, lead, cobalt, zirconium, ruthenium, yttrium, indium and chromium. Exceptionally, it can chelate mercury in its valence II chemical form (Hg^{2+}). Zn-DTPA is indicated for zinc contamination.

— Dosage and administration:

- Systemic use: The usual dose is 0.5 g (for a person weighing about 70 kg). It can be administered slowly by intravenous route or by intravenous infusion, diluted in 250 mL of a 0.9% NaCl isotonic solution or a 5% glucose solution.

- In severe cases, dose can be doubled in the first administration after the accident. Ca-DTPA is more efficient in the beginning of the treatment. If treatment extends beyond the first week because of the severity of the accident, it would be advisable to continue with the potentially less toxic Zn-DTPA. Doses are not to exceed

0.5 g/day for prolonged treatments. This also applies to doses of Zn-DTPA in prolonged treatments.

- Inhalation: A DTPA aerosol can be used for a 30-minute inhalation (1 ampoule of DTPA in 4 mL of saline solution). DTPA can also be inhaled using capsules of micronized powder (100 mg), or non-micronized capsules, which contain 40 mg (the dosage is 5 capsules, 3 breaths per capsule) [39].

- Skin washes:
  - Intact skin: 1–2% Ca-DTPA acid solution (pH 4–5);
  - Wounds: sterile 20–25% Ca-DTPA solution;
  - Mucosae: 1–2% Ca-DTPA solution.

— Contraindications and adverse effects:

- Renal, intestinal and haematological diseases;

- Pregnancy;

- Massive uranium contamination (acute nephritis can be induced through precipitation of uranium in the kidneys);

- Because of DTPA's potential renal, liver and GI toxicity, the functions of these systems will need to be monitored in prolonged treatments.

I.14. FUROSEMIDE

— How supplied: Tablets containing 40 mg and ampoules containing 20 mg.

— Mechanism of action: Diuretic.

— Indication: Contamination with sodium, potassium, chlorine and tritium.

— Dosage and administration: 20 to 80 mg/day orally; minimum dose of 20 mg/day.

— Contraindications and adverse effects: Contraindications are renal failure with anuria, hepatic coma, hypokalaemia, hyponatremia, hypovolemia, hypotension and sensitivity to sulphonamides. Adverse effects include water and electrolyte disturbances (hypokalaemia, hyponatremia), increase in the urinary excretion of calcium, allergic reactions, haematopoietic alterations, auditory and GI disturbances.

I.15. MAGNESIUM SULPHATE

— How supplied: 5 mL (1.25 g) and 10 mL (2.5 g) ampoules with a 25% concentrated solution (0.25 g/mL).

— Mechanism of action: It is a saline laxative that accelerates the intestinal transit and therefore the elimination of radionuclides from the digestive tract.

— Indication: Contamination with radium and strontium. It is also indicated to accelerate the elimination of cobalt, polonium, plutonium and transplutonics.

— Dosage and administration: 10 to 15 g orally per day (4–6 ampoules of 10 mL) in the first day. Treatment can be continued for several days depending on the contamination grade and on the individual susceptibility to the laxative action. In this case, subsequent doses will be 5–10 g/day (2–4 ampoules of 10 mL).

— Contraindications and adverse effects: Severe renal failure, inflammatory diseases of the colon and biliary tree obstruction. No adverse effects.

I.16. PENICILLAMINE

— How supplied: 250 mg capsules.

— Mechanism of action: Chelation.

— Indication: Chelation of copper, lead, gold, iron, mercury and other heavy metals.

— Dosage and administration: 1–3 capsules every 8 hours.

— Contraindications: Pregnancy, nursing, anaemia and renal diseases.

— Adverse effects: Haematological, renal and dermatological reactions, epigastric pain, nausea and vomiting.

I.17. POTASSIUM BICARBONATE

— How supplied: Powder.

— Mechanism of action: Isotopic dilution. Potassium is quickly and almost completely absorbed in the intestine and excreted via the kidneys.

— Indication: Contamination with radioactive potassium.

— Dosage and administration: 4 g of stable potassium orally, as potassium bicarbonate, for no longer than three days.

— Contraindications and adverse effects: Renal failure, alkalosis, heart toxicity (hyperkalaemia).

I.18. POTASSIUM IODIDE (KI)

— How supplied: The most frequently used presentation is as potassium iodide tablets (130 mg, containing 100 mg of active iodide). Solutions are not recommended because of imprecision in doses and also because of problems with storage and distribution.

— Mechanism of action: Stable iodine blocks about 98% of the thyroid uptake of radioiodines if given several minutes before incorporation. If administration is simultaneous to incorporation, its efficacy is reduced to 90%. After 4 to 6 hours following incorporation, protection is about 50%.

  • Through an isotopic dilution mechanism, stable iodine competes with the radioiodine thyroid uptake. An overload of stable iodine can partially saturate the mechanism of internal transportation of iodine, causing the so-called Wolff–Chaikoff phenomenon, leading to a decrease in the circulating level of the thyroid hormones.

  • The efficacy of thyroid blocking depends on intrinsic glandular factors related to its functional situation and on the nutritional iodine intake. These variables will determine differences in the uptake of radioiodines by the gland and in its sensitivity to stable iodine blocking.

— Indication: Contamination with radioactive iodines.

— Dosage and administration: Recommended dose is 130 mg of potassium iodide (100 mg of active iodine) orally in a single administration. There is international consensus on adjusting doses according to age in order to minimize the risk of side effects.

— Contraindications: Known hypersensitivity to iodine, Hashimoto's thyroiditis, Basedow's disease, other autoimmune thyroid diseases, low-complement vasculitis and herpetiform dermatitis.

— Adverse effects: A prolonged blockade of the iodine uptake needed for the synthesis of thyroid hormones can lead to a reduction of metabolic activity and eventually to a compensatory increase in the gland's volume. In general terms, these effects are not observed in normal individuals after appropriate doses for a period no longer than two weeks. Stable iodine overload can trigger autoimmune thyroid problems in susceptible individuals or aggravate pre-existing thyroiditis. The existence of hypersensitivity to radiological iodine contrast agents is known, especially in cases of intravenous administration. Reactions are not so severe or frequent in oral administration. The risk of adverse effects after the use of stable iodine is estimated to be 5×10^{-7}.

I.19. PRUSSIAN BLUE (FERRIC HEXACYANOFERRATE [II])

— How supplied: 500 mg capsules.

— Mechanism of action: Acts as an ion interchanger to certain monovalent cations. The most effective form is the colloidal soluble form. Prussian Blue does not cross the intestinal barrier. It prevents the initial absorption of the radionuclide in the digestive tract and breaks the caesium secretion/reabsorption cycle that happens in all cases of contamination with this nuclide.

— Indication: All kinds of radiological contamination with caesium, rubidium and thallium.

— Dosage and administration: 3 g orally, in three administrations. Treatment can be continued in the following days, depending on the contamination grade. The most important experience with this product was in the Goiânia accident. On this occasion, much higher doses were used without severe adverse health effects (some cases of constipation occurred).

— Contraindications and adverse effects: None.

I.20. RHODIZONATE

— How supplied: Hydrosoluble crystalline powder with a violet colour (colour changes to orange as dissolved in water). It is insoluble in alcohol. Solutions are unstable even under refrigeration.

— Mechanism of action: Insolubilization.

— Indication: Wounds contaminated with strontium.

— Dosage and administration: 1 g in the wound.

— Contraindications and adverse effects: None.

I.21. SODIUM BICARBONATE

— How supplied: Aqueous isotonic solution with 14 g/L (1.4%). Sodium bicarbonate is commercialized by many companies in 150, 500 and 1000 mL bottles and also in ampoules of 10 and 20 mL (other concentrations exist as well).

— Mechanism of action: Its main use is for uranium contamination. In corporal fluids, uranium is present as uranyl ion UO_2^{++}. Alkalinization leads to the formation of an anionic complex, probably $UO_2(CO_3)_3$, which is quickly eliminated via the urine.

— Indication: Uranium contamination.

- Skin washes: On intact skin or wounds contaminated with uranium, washes with 1.4% sodium bicarbonate could be indicated. Depending on the contamination grade, this treatment could be continued during the following days.

— Contraindications and adverse effects: Blood pH and electrolytes will need to be monitored. Sodium bicarbonate can cause or aggravate hypokalaemia. This can be prevented by means of potassium supplementation. Possible drug associations will need to be considered: there are many alkaline related non-compatible conditions. Contraindications are alkalosis, respiratory acidosis and sodium retention. A risk of a sodium bicarbonate overdose exists in the following situations: metabolic alkalosis with respiratory depression, hypokalaemia, acute pulmonary oedema and heart failure.

I.22. STRONTIUM LACTATE/GLUCONATE

— How supplied: Tablets and solution for intravenous infusion.

— Mechanism of action: Isotopic dilution that increases the metabolic cycle of strontium and its excretion.

— Indication: Contamination with strontium.

— Dosage and administration:

- Strontium lactate: 500 to 1500 mg/day orally in many administrations during meals;

- Strontium gluconate: slow intravenous injection, 600 mg in 500 mL of a 5% isotonic glucose solution;

— Contraindications and adverse effects: None described.

APPENDIX II.
PROTECTION OF HEALTH CARE PROVIDERS AND PREPARATION OF THE EMERGENCY DEPARTMENT AT THE HOSPITAL

II.1. PROTECTION OF HEALTH CARE PROVIDERS

Health care providers in a radiation emergency need to be protected from unnecessary radiation exposure. Ideally, all responders will be trained on radiation protection and have participated in drills or exercises. Information about risks from radiation exposure is an essential part of the training programme. In many instances, first responders will not immediately count on the support of radiation protection officers. This underlines the importance of training, so that a distorted risk perception will not negatively influence the response or that, at the other extreme, responders will not ignore easily achievable self-protection measures against undue radiation exposure.

The fundamentals of radiation protection — time, distance and shielding — will be used to avoid or minimize external doses to responders. However, it is usually difficult, or even impossible, to take advantage of shielding on the scene.

It is worth mentioning that radiation doses to responders, including health staff, have been extremely low in previous radiation emergencies.

Radiological contamination can be external, internal or both. External contamination can be transferred to other individuals through contact with the contaminated patient's clothes or skin. Protective clothing, if properly used, offers protection against radiological contamination but not against external exposure. In most instances, when full protective clothing is not available, as in the case of on-scene first response, the usual biosafety practices will also protect against radiological contamination. Internal contamination can be transferred to other persons via the contaminated individuals' excreta and secretions. Besides protective clothes and good biosafety practices, there may be rare occasions when other personal protective equipment such as respiratory filters and masks will be used in accordance with specialized guidance.

All assisting personnel will need to wear personal dosimeters and be monitored by radiation protection officers during their activities and before leaving the scene of the radiation emergency or the hospital. A self-alarming personal dosimeter is highly recommended.

Although it is unlikely, if one of the attending staff is detected with radiological contamination, facilities and radiation protection personnel need to be ready for proper decontamination procedures.

II.2. PREPARATION OF THE EMERGENCY DEPARTMENT OR OTHER HOSPITAL FACILITIES

II.2.1. Preparation for dealing with internally contaminated patients

II.2.1.1. Decorporation drugs

Ideally, at least one institution in the country, especially in a country with nuclear facilities, will maintain in storage a stock of drugs for decorporation therapies. The following suggested list includes the most frequently used drugs:

— Dimercaprol (usually known as British Anti-Lewisite — BAL);

— Diethylenetriamine-pentaacetate (DTPA);

— Penicillamine;

— Potassium iodide (KI);

— Prussian Blue (ferric hexacyanoferrate [II]);

— Dimercaptopropansulphonate (DMPS);

— Deferoxamine (DFOA).

II.2.1.2. Collecting samples for counting and bioassays

Supplies for collecting samples:

— Cotton-tipped applicators for nasal swabs;

— Containers for collecting urine or faeces samples;

— Gauze for collecting blood samples from wounds;

— Shield/pig for storage of radioactive shrapnel.

Even in cases where external exposure is not likely, collection of blood samples for a complete blood count is recommended, with emphasis on lymphocytes. There may be occasions when cytogenetic biodosimetry could also be indicated. For cytogenetic analysis, lithium heparinized tubes (10 mL of peripheral blood) are required and samples will not be frozen.

Tissue excised from a contaminated wound or material removed by debridement can be analysed to determine the type and activity of radionuclides, but not the activity in the wound. The indication for tissue samples is limited to some cases, and is not recommended as a routine procedure for internal contamination dose assessment.

II.2.1.3. Direct dose assessment for internal contamination

Whole body counters, thyroid monitors and lung counters are used for direct measurement of internal contamination. Most hospitals do not have these detectors, but after medical stabilization, patients may be moved to other facilities where direct monitoring is available. Portable devices can also be used in order to avoid removal of the patient. Urine, faeces, blood and other samples can be sent for bioassays in specialized centres whenever necessary.

II.2.2. Supplies that might be necessary for dealing with contaminated patients[9]

II.2.2.1. Personal protective equipment

— Coveralls or surgical scrub suits;

— Plastic aprons;

— Surgical caps;

— Plastic or rubber gloves;

— Shoe covers;

— Respiratory protection devices (e.g. N95 mask or any other that filters 95% or more of airborne particulates); surgical masks and full-face masks can be used but these have lower filtering rates);

— Eye protection equipment;

— Tape to close open ends of clothing;

— Personal dosimeters.

II.2.2.2. Radiation detectors

— Geiger–Müller survey meter (for beta/gamma radiation);

— Zinc sulphide scintillation survey meter (for alpha radiation);

— Ion chamber (for gamma radiation);

— Sodium iodide scintillation survey meter (for gamma radiation);

— Spectrometers (for identification of radionuclides);

— Whole body counters, lung and thyroid counters.

II.2.2.3. Contamination control

— Plastic sheets and paper sheets for covering floor;

— Tape;

— Rope;

— Radiation area signs (e.g. 'Do not Enter');

— Radiation tags, radiation tape for marking areas;

— Plastic bags (various sizes) for collecting waste or contaminated clothes;

— Adhesive labels and tags for labelling contaminated samples.

II.2.2.4. Decontamination

— Scissors (not used for cutting hair);

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[9] Supplies need to be in compliance with medical and radiation protection protocols to deal with patients contaminated with radionuclides.

— Soap, detergents, shampoo;

— Soft brushes or sponges;

— Physiological saline solution;

— Water or solution for wound irrigation;

— Eyewash solution;

— Nail brushes;

— Nail clippers;

— Hair clippers;

— Drapes and masking tape for covering non-contaminated skin or area during decontamination;

— Indelible felt pens for marking contaminated spots;

— Data forms (e.g. decontamination forms);

— Large towels and clean patient gowns or clothing.

II.2.2.5. *Others*

— Ordinary medical equipment, supplies and drugs for conventional medical emergency assistance.

II.3. MANAGEMENT OF RADIOACTIVE WASTE

Equipment and supplies used for decontamination have to be isolated and kept in plastic bags or containers with radiation labels and appropriately checked for radiation dose rate, both at the surface and at different distance levels. If possible, medical equipment can be decontaminated for safe re-utilization; otherwise it will have to be dealt with as radioactive waste and stored in accordance with the local legislation.

APPENDIX III.
DIFFERENCES BETWEEN RADIOACTIVE AND CHEMICAL OR BIOLOGICAL HAZARDS

There are differences between radioactive and chemical or biological hazards, and these are important from the safety perspective and relevant for planning the response to an emergency or a situation where radioactive contamination is present or suspected to be present. It is very important to highlight that, in the evaluation of patients involved in radiation emergencies, the priority is the stabilization of the patient; this is more important than decontamination or dose assessment procedures. Some of the main differences are summarized in Table 17.

TABLE 17. DIFFERENCES BETWEEN RADIOACTIVE AND CHEMICAL OR BIOLOGICAL HAZARDS

Agent	Radiological	Chemical or biological
Detection	Small amounts of radioactive material can be detected and located with appropriate portable radiation detection equipment.	Requires specialized laboratory testing.
Decontamination	The radioactive material cannot be destroyed by chemicals or fire. Medical stabilization is the first action indicated on scene and not internal or external decontamination.	Substances can be destroyed or neutralized. In some instances, there is an absolute need for on-site chemical decontamination, which is not the case for radiological contamination.
Protective garment	Any outer garment protects the wearer from alpha and most beta radiation, but it will not block gamma radiation (external exposure). However, coveralls will help prevent contamination from all types of radioactive material and are to be worn if any possibility of radioactive contamination exists.	Some types of protective clothing provide protection against chemical or biological agents.
Respiratory and eye protection	Respiratory protection normally used by emergency responders reduces the risk of inhalation of radioactive particles and internal contamination with radioactive material. Eye protection reduces the risk of radioactive material being absorbed by the tissues of the eyes.	Different types of respiratory protection may or may not protect against inhalation of some biological or chemical agents. Eye protection reduces the risk of chemical or biological material being absorbed by the tissues of the eyes.
Decay	The quantity of radioactive material always decreases over time, and, in many instances, this characteristic provides an advantage in radiation protection.	No decay.

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DEFINITIONS

Terms from the IAEA Safety Glossary[10] have been indicated with *. Those from IAEA Safety Standards Series No. GSR Part 7[11] have been indicated with **. New definitions apply for the purposes of the present publication only.

absorbed dose*: The fundamental dosimetric quantity D, defined as:

$$D = \frac{\mathrm{d}\bar{\varepsilon}}{\mathrm{d}m} \tag{2}$$

where $\mathrm{d}\bar{\varepsilon}$ is the mean energy imparted by ionizing radiation to matter in a volume element, and $\mathrm{d}m$ is the mass of matter in the volume element. The unit of absorbed dose is J/kg, termed the gray (Gy).

activation*: The process of inducing radioactivity. Most commonly used to refer to the induction of radioactivity in moderators, coolants, and structural and shielding materials, caused by irradiation with neutrons.

activity*: The quantity A for an amount of radionuclide in a given energy state at a given time (t), defined as:

$$A(t) = \frac{\mathrm{d}N}{\mathrm{d}t} \tag{3}$$

where $\mathrm{d}N$ is the expectation value of the number of spontaneous nuclear transformations from the given energy state in the time interval $\mathrm{d}t$.

becquerel (Bq)*: Name for the International System of Units (SI) unit of activity, equal to one transformation per second; supersedes the curie (Ci). 1 Bq = 27 pCi (2.7 10^{-11} Ci) approximately. 1 Ci = 37 GBq.

bioassay*: Any procedure used to determine the nature, activity, location or retention of radionuclides in the body by direct (in vivo) measurement or by in vitro analysis of material excreted or otherwise removed from the body.

biokinetic model: A mathematical model describing the intake, uptake and retention of a radionuclide in various organs or tissues of the body and the subsequent excretion from the body by various pathways.

biological half-life*: The time taken for the quantity of a material in a specified tissue, organ or region of the body (or any other specified biota) to halve as a result of biological processes.

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[10] INTERNATIONAL ATOMIC ENERGY AGENCY, IAEA Safety Glossary: Terminology Used in Nuclear Safety and Radiation Protection, IAEA, Vienna (2007).

[11] FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS, INTERNATIONAL ATOMIC ENERGY AGENCY, INTERNATIONAL CIVIL AVIATION ORGANIZATION, INTERNATIONAL LABOUR ORGANIZATION, INTERNATIONAL MARITIME ORGANIZATION, INTERPOL, OECD NUCLEAR ENERGY AGENCY, PAN AMERICAN HEALTH ORGANIZATION, PREPARATORY COMMISSION FOR THE COMPREHENSIVE NUCLEAR-TEST-BAN TREATY ORGANIZATION, UNITED NATIONS ENVIRONMENT PROGRAMME, UNITED NATIONS OFFICE FOR THE COORDINATION OF HUMANITARIAN AFFAIRS, WORLD HEALTH ORGANIZATION, WORLD METEOROLOGICAL ORGANIZATION, Preparedness and Response for a Nuclear or Radiological Emergency, IAEA Safety Standards Series No. GSR Part 7, IAEA, Vienna (2015).

committed effective dose*: The quantity $E(\tau)$, used as characteristic of internal exposure and defined as:

$$E(\tau) = \sum_T w_T \times H_T(\tau) \tag{5}$$

where $H_T(\tau)$ is the committed radiation weighted dose to tissue T over the integration time τ and W_T is the tissue weighting factor for tissue T. When τ is not specified, it will be taken to be 50 years for adults and up to the age of 70 years for intakes by children.

contamination*: Radioactive substances on surfaces or within solids, liquids or gases (including the human body), where their presence, or the process giving rise to their presence, is unintended or undesirable.

decorporation: The action of the biological processes, facilitated by chemical or biological agents, by means of which incorporated radionuclides are removed from the human body [D]. It is also described as a process of treatment for persons with internally deposited radionuclides that aims to reduce the internal dose of exposure and hence the risk of health effects. It can be accomplished by reducing absorption, preventing incorporation and internal deposition of radionuclides within organs, and promoting elimination or excretion of absorbed nuclides.

deposition: The initial processes determining how much of a material in inhaled air remains in the respiratory tract after exhalation. Deposition of material may occur during both inhalation and exhalation.

deterministic effect*: A health effect of radiation for which, generally, a threshold level of dose exists above which the severity of the effect is greater for a higher dose. Such an effect is described as a 'severe deterministic effect' if it is fatal or life threatening or results in a permanent injury that reduces the quality of life.

dose*: A measure of the energy deposited by radiation in a target.

dose assessment*: Assessment of the dose(s) to an individual or group of people.

effective half-life (T_{eff})*: The time taken for the activity of a radionuclide in a specified place to halve as a result of all relevant processes, where T_i is the half-life for process i.

$$\frac{1}{T_{eff}} = \sum_i \frac{1}{T_i} \tag{6}$$

emergency**: A non-routine situation or event that necessitates prompt action, primarily to mitigate a hazard or adverse consequences for human health and safety, quality of life, property or the environment. This includes nuclear and radiological emergencies and conventional emergencies such as fires, release of hazardous chemicals, storms or earthquakes. It includes situations for which prompt action is warranted to mitigate the effects of a perceived hazard.

emergency (response) action**: An action to be taken in response to a nuclear or radiological emergency to mitigate the consequences of an emergency for human life, health, property and the environment. Emergency response actions comprise protective actions and other response actions.

'Other response actions' are emergency response actions other than protective actions. The most common other response actions are: medical examination, consultation and treatment;

registration and longer term medical follow-up; providing psychological counselling; and public information and other actions for mitigating non-radiological consequences and for public reassurance.

emergency worker**: A person having specified duties as a worker in response to an emergency. Emergency workers may include workers employed, both directly and indirectly, by registrants and licensees, as well as personnel of response organizations, such as police officers, firefighters, medical personnel, and drivers and crews of vehicles used for evacuation. Emergency workers may or may not be designated as such in advance to an emergency. Emergency workers not designated as such in advance of an emergency are not necessarily workers prior to the emergency.

equivalent dose: The product of the median absorbed dose in an organ or tissue and the radiation weighting factor, corresponding to the kind of radiation — alpha, beta, gamma, neutrons, etc.; its SI unit is the sievert (Sv). 1 Sv = J/kg.

exposure*: The act or condition of being subject to irradiation. Exposure can be either external exposure (due to a source outside the body) or internal exposure (due to radioactive material within the body).

external exposure*: see exposure.

first responders**: The first members of an emergency service to respond at the scene of an emergency.

generic criteria**: Levels for the projected dose, or the dose that has been received, at which protective actions and other response actions are to be taken.

gray (Gy)*: The SI unit of kerma and absorbed dose, equal to 1 J/kg.

half-life*: (1) For a radionuclide, the time required for the activity to decrease, by a radioactive decay process, by half. Where it is necessary to distinguish this from other half-lives (see (2)), the term radioactive half-life should be used. The half-life $T_{1/2}$ is related to the decay constant, λ, by the expression:

$$T_{1/2} = \frac{\ln 2}{\lambda} \tag{7}$$

(2) The time taken for the quantity of a specified material (e.g. a radionuclide) in a specified place to decrease by half as a result of any specified process or processes that follow similar exponential patterns to radioactive decay.

individual monitoring*: Monitoring using measurements by equipment worn by individual workers, or measurements of quantities of radioactive material in or on their bodies. See also monitoring.

intake: (1) The ingestion or inhalation of a radioactive material. (2) The amount of radioactive material (activity, Bq) taken into the body by inhalation, ingestion, absorption through the skin, injection or via a wound.

internal (radiation) exposure*: Exposure due to a source within the body (because of deposition of radionuclides in body tissue).

in vitro bioassay*: See bioassay.

in vivo bioassay*: See bioassay.

ionizing radiation*: For the purposes of radiation protection, radiation capable of producing ion pairs in biological material(s).

justification**: The process of determining for an emergency exposure situation or an

linear energy transfer (LET), L_Δ*: Defined generally as:

$$L\Delta = \left(\frac{\mathrm{d}E}{\mathrm{d}l}\right)_\Delta \tag{8}$$

where $\mathrm{d}E$ is the energy lost in traversing distance $\mathrm{d}l$ and Δ is an upper bound on the energy transferred in any single collision. A measure of how, as a function of distance, energy is transferred from radiation to the exposed matter. A high value of linear energy transfer indicates that energy is deposited within a small distance. $L\infty$ (i.e. with $\Delta = \infty$) is termed the unrestricted linear energy transfer in defining the quality factor. L_Δ is also known as the restricted linear collision stopping power.

mass casualty event: Any event resulting in a number of victims large enough to disrupt the normal course of emergency and health care services.

medical response in radiation emergencies: Medical actions taken during a radiation emergency, with the following goals:

— Save lives and perform required emergency medical procedures;

— Treat radiation injuries and injuries resulting from an emergency situation;

— Perform required public health actions, including public advice and counselling, and long term medical follow-up.

Actions of medical response need to be in line with the goals of emergency response.

monitoring*: The measurement of dose or contamination for reasons related to the assessment or control of exposure to radiation or radioactive substances, and the interpretation of the results. See also individual monitoring.

non-radiological consequences**: Adverse psychological, societal or economic consequences of a nuclear or radiological emergency or of an emergency response affecting human life, health, property or the environment. The term non-radiological consequences as defined here relates to emergency preparedness and response only.

operational intervention level (OIL)*: A calculated level, measured by instruments or determined by laboratory analysis, that corresponds to an intervention level or action level. OILs are typically expressed in terms of dose rates or activity of radioactive material released, time integrated air concentrations, ground or surface concentrations, or activity concentrations of radionuclides in environmental, food or water samples. An OIL is a type of action level that is used immediately and directly (without further assessment) to determine the appropriate protective actions on the basis of an environmental measurement.

preparedness stage**: The stage or phase at which arrangements for an effective emergency response are established prior to a nuclear or radiological emergency.

radiation emergency (nuclear or radiological emergency)*: An emergency in which there is, or is perceived to be, a hazard due to: (a) the energy resulting from a nuclear chain reaction or from the decay of the products of a chain reaction, or (b) radiation exposure.

radioactivity*: Emitting or relating to the emission of ionizing radiation or particles. This is the 'scientific' definition and should not be confused with the 'regulatory' definition designated in the national law of each Member State.

radiological dispersal device: A device constructed by terrorists to spread radioactive materials using conventional explosives or other means.

relative biological effectiveness (RBE): For a particular organ or tissue T, the RBE is the ratio of the absorbed dose from a reference type of radiation that produces a specified biological effect relative to the absorbed dose from the radiation of interest (R) that produces the same biological effect. In general, the value of RBE for biological effects of radiation depends on such factors as the quality of the radiation, the irradiated organ or tissue, the committed effect and the dose rate.

sievert (Sv)*: The SI unit of equivalent dose and effective dose. 1 Sv = 1 J/kg.

stochastic effect*: A radiation induced health effect, the probability of occurrence of which is greater for a higher radiation dose and the severity of which (if it occurs) is independent of dose. Stochastic effects may be somatic effects or hereditary effects and generally occur without a threshold level of dose. Examples include thyroid cancer and leukaemia.

target organ/tissue: Organ or tissue in which, for physiological and physicochemical reasons, a specific radionuclide is preferentially deposited.

uptake*: (1) A general term for the processes by which radionuclides enter one part of a biological system from another. (2) The processes by which radionuclides enter the body fluids from the respiratory tract, gastrointestinal tract or through the skin, or the fraction of an intake that enters the body fluids by these processes.

ABBREVIATIONS

AMAD	activity median aerodynamic diameter
ARS	acute radiation syndrome
BAL	British Anti-Lewisite (Dimercaprol)
Bq	becquerel
Ca-DTPA	calcium diethylenetriamine-pentaacetate
Ci	curie
DFOA	deferoxamine
DMPS	dimercaptopropansulphonate
DMSA	dimercaptosuccinic acid
DTPA	diethylenetriamine-pentaacetate
EDTA	ethylenediamine tetraacetic acid
EPR	emergency preparedness and response
FDA	Food and Drug Administration (United States)
GI	gastrointestinal
Gy	gray
IAEA	International Atomic Energy Agency
ICRP	International Commission on Radiological Protection
mSv	millisievert
OIL(s)	operational intervention level(s)
RBE	relative biological effectiveness of radiation effects
RMU	radiation monitoring unit
SI	International System of Units
Sv	sievert
WHO	World Health Organization
Zn-DTPA	diethylenetriamine-pentaacetate

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