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REVIEW

Radiation accidents over the last 60 years

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Abstract

Since the end of the Second World War, industrial and medical uses of radiation have been considerably increasing. Accidental overexposures of persons, in either the occupational or public field, have caused deaths and severe injuries and complications. The rate of severe accidents seems to increase with time, especially those involving the public; in addition, accidents are often not immediately recognised, which means that the real number of events remains unknown. Human factors, as well as the lack of elementary rules in the domains of radiological safety and protection, such as inadequate training, play a major role in the occurrence of the accidents which have been reported in the industrial, medical and military arenas.

1. Introduction

An accident, whatever its origin, can be defined as an unforeseeable event which leads, or may lead, to injuries or damage to individuals who are directly involved. In the context of accidents caused by ionising radiation—the so-called radiation accidents²—and in the light of past experience, this simplistic definition seems too broad and requires some comments.

Radiation-induced health damage that is caused by wars or by suicides does not enter the frame of the above definition. The situation is less clear for terrorism; as a matter of fact, the definition applies to victims, who are facing identical situations in both cases—accident and malevolent action. In addition, the medical and health consequences of a terrorist action using radiation as a weapon show narrow similarities with those caused by a radiation accident; in addition, the means needed to handle the situation are similar in both cases. Only the approaches and resources necessary for preventing such deleterious events differ fundamentally (ICRP 2005). These common characteristics explain why some rare malevolent

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² Radiation accidents may be classified into two categories: ‘radiological accidents’, involving installations that use the properties of radiation, and ‘nuclear accidents’, resulting from the direct use of atomic fission and affecting nuclear facilities and weapons. Both may expose the workforce and/or members of the population.

actions resulting in particularly dramatic outcomes, perpetuated for either personal revenge or political conviction, are described in the frame of the present review paper.

Accidents that involve radiation are rare and have a very low reproducibility rate. Since each radiation accident can be considered as a unique event with its own characteristics, any attempt to derive generic rules only on the basis of an individual accident constitutes a difficult challenge, especially when the principal objective is to prevent or best manage potential future accidents.

The injuries and damage that radiation accidents cause, although generally non-specific, have particular features which may delay or compromise recognition of the accidental situation and of its cause. For example, the mute latency period of the acute radiation syndrome (ARS) may lead to unjustified optimism and to maladjusted or wrong medical decisions.

Deleterious effects that are induced by radiation are extremely various and depend upon several parameters: the absorbed dose level, which determines the degree of severity, the exposed volume size (external whole body exposure, partial exposure or strictly localised exposure) as well as the irradiated organs, and the nature of radiation (from low to high energy radiation). These various radiation-induced injuries require different medical care: for example, haematological intensive care in the case of ARS coupled with specific treatment for each organic failure, or specialised surgery in the case of acute skin injuries comparable to burn surgery.

The range of radiation accidents is very wide. In the simplest case, the radiation source is identified, the aetiological diagnosis is relatively easy, the management of the accident as well as the treatment of the patient does not raise major difficulties and the medical input is confined to dialogue between a limited number of actors, such as physician–victim, thus corresponding to the features of normal medical management; this explains why an unknown number of accidental situations is not reported in the open literature and remains completely ignored. Unfortunately, the situation is often more complicated, because of medical problems (doubtful diagnosis, uncertain prognosis and difficulty in the choice of treatment), management problems (large number of victims, combined injuries), or finally the magnitude of the accident.

In general, the definition of accidents applies to events that result in quickly appearing injuries. This is true for radiation accidents when they result in high doses inducing acute effects, appearing within a few days or weeks. Judgement is more difficult when large groups of the population have been exposed to doses at levels below the threshold for acute tissue reactions (deterministic effects) but potentially able to induce a long term risk (of stochastic nature) at a level which is considered as unacceptable for society. In addition, large scale accidents, especially the catastrophic ones, whatever their causal agent, always induce indirect effects, in general related to induced stress, which sometimes may be more deleterious than the direct acute effects and may affect unexposed individuals.

The place where the accident occurs determines its characteristics: feedback over more than half a century shows that more than 50% of the severe accidents occurred in industrial facilities, one-fifth in the research field, one-eighth in nuclear power civilian applications, one-tenth in medicine, and one-20th in military facilities or after military tests (Chambrette *et al* 2001). Nevertheless, the number of victims, when considered by sector, appears to be in various proportions. Accidents in industrial facilities often cause one victim only; in the case of industrial irradiators the consequences are frequently lethal, while for small gammagraphy the resulting damage currently consists in localised skin injuries with possible successful treatments, but may involve several individuals, especially when a small source is lost and found by members of the general public who ignore its dangerousness. It should be mentioned that statistics cannot apply to the civilian nuclear power sector, since the Chernobyl accident in 1986 is the major one responsible for fatal ARS. In contrast, in the medical field, radiotherapy

accidents related to overdoses imply classically a whole series of patients, since accidents are recognised only when identical alarming symptoms appear in several patients, often a few weeks after initiation of the treatment. In industry, radiation sources are schematically restricted to ^{60}Co (irradiators) and ^{192}Ir (radiography devices); in contrast, medicine uses several types of radiation which include γ radiation from ^{60}Co , ^{137}Cs and ^{192}Ir , x-rays, and electrons from linear accelerators (radiotherapy) and β emitters (nuclear medicine).

During the Cold War, most of the radiation accidents which occurred in the military arena were kept secret, especially on the east side of the wall. The improvement of the east–west relations resulted in an appreciable openness, which brought interesting revelations; however, it is not proved that accidents that have or may have political or military implications are now revealed with a complete transparency.

Out of these general considerations, a classification of radiation accidents emerges that, like any classification, is arbitrary, but takes account of the management difficulties, which depend on the way accidents come to light, their extent, and the medical and/or public health problems they present, etc (Nénot 1996a, 1998). This approach allows a clear distinction between accidents that do not present any special problems, those that are difficult to handle and those that bring major resources into play. Sub-categories include the accidents that are diagnosed from their initiation, those that are discovered later, and those that are kept secret for military or political reasons. The accidents that are considered as good examples and further described are given in table 1, which is not intended to be exhaustive. A compilation of exposures due to radiation accidents has been published by the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR 2007). On the basis of current literature as well as of credible non-official reports, it may be assessed that during the last 60 years (1) at least 600 events caused significant radiation exposures of about 6000 individuals, (2) about 70 serious accidents resulted in one or more death each, and (3) a total of 200 lethal issues were due to ARS (Nénot and Gourmelon 2007).

This table, which is supposed to be numerically representative of the relative frequencies of all reported accidents, calls for three general remarks: (1) the frequency of severe accidents shows a tendency to increase; (2) radiation accidents occur in any type of country and seem not to be directly related to the degree of economic and technical development; (3) the number of accidents that are recognised only when symptoms suggest the radiological nature of the accident seems to represent the largest fraction of the total number; it is therefore legitimate to wonder about the possibility of a large number of serious unrecognised accidents, their victims being wrongly attributed to classical causes. In addition, reported military accidents can never be classified in the category ‘easy to manage’.

Table 1 does not include accidents causing exclusively internal exposures³. From a historical point of view, this choice may seem arbitrary, since the first exposures to radiation that have caused severe health damage were related to medical practices when deleterious effects of radiation were unknown. Thus, although it seems difficult to classify these events as ‘accidents’, some complications of these ancient practices are comparable to those of recent accidents. This is the case of the use of ^{232}Th as a contrast material for angiographies and of radium administered for various reasons between the 1930s and 1950s to thousands of patients, resulting in excesses of liver cancers, angiosarcomas, osteosarcomas and mesotheliomas (Finkel *et al* 1967, Stannard 1988). In the 1940s and 1950s, before the strict codification of the handling of sealed sources in nuclear medicine, repetitive contaminations of the workforce were not rare; since then, contaminations have been exceptional and concern mainly patients.

³ In fact, some accidents referenced in table 1 also resulted in internal exposure; for example the accidents in Ukraine (Chernobyl) and Brazil (Goiânia).

Table 1. An example of classification for severe radiation accidents, in terms of chronology of recognition and management difficulties.

	Easy to manage (few victims)	Difficult to manage (technically and medically)	Catastrophic (health and environment consequences)
Immediate recognition	France 1981 Norway 1982 Israel 1990 Belarus 1991 Russia 1997 Chile 2005	Peru 1999 Japan 1999	Ukraine 1986
Delayed recognition	Mexico 1962 Italy 1975 Algeria 1978 Morocco 1984 Salvador 1989 Spain 1990 France 1991 Vietnam 1992 Estonia 1994 Egypt 1994 Georgia 2001 France 2004–05 France 2004 Belgium 2006 Senegal 2006 Tunisia 2008	USA 1974–76 UK 1982–91 USA 1985–87 USA 1992 China 1992 Georgia 1997 Panama 2000–01 Poland 2001	Mexico 1983 Brazil 1987 Costa Rica 1996 Thailand 2000
Secret (military/political)		USSR 1961, 1968 Sahara 1962 UK 2006	Marshallese islands 1954 USSR 1957 Spain 1966 Greenland 1968

Between 1960 and 1980, 11 fatalities were reported due to internal exposure only, most of them originating from errors in the medical administration of radiopharmaceuticals. A demonstrative example is the dramatic case in 1968, which happened after the injection of an activity of ^{198}Au one thousand times higher than the prescribed one (confusion between μCi and mCi) in the course of a hepatic exploration and which ended in the patient's death (Baron *et al* 1969).

2. Radiation accidents that are recognised immediately

2.1. Accidents that are easy to manage, with a limited number of victims

The common aspects of radiation accidents that do not raise particular difficulties are awareness of the event, unequivocal identification of victims who are presenting or likely to present lesions entering the classical frame of conventional medicine, and possible access to available logistical resources. However, medical mistakes may occur, especially in the fields of diagnosis and treatment. Demonstrative examples are drawn from an accident in a radiotherapy department, three accidents in industrial irradiation facilities, a critical excursion in a military installation, and an accident caused by a small industrial source. In each of these six cases, a human error was the initiating event. All these accidents were extremely severe, since all that occurred in industrial and military facilities resulted in rapid death of the victims and the two others in severe complications such as amputations and repeated surgery.

In *Saintes, France* (1981), three operators were severely exposed during the loading of a new radiotherapy device with a 137 TBq ^{60}Co source; the source was blocked in the transport container and confusion between the real source and the fictitious source caused the fall to the ground of the real source. The technician, in spite of his 25 years of experience, picked up the source by hand and replaced it in safe position. His assistant, who was supposed to collect the fictitious source, received high doses to both hands. Dosimetric reconstruction showed that any conservative surgery was hopeless (Nénot 1985). This accident resulted in amputations of both hands for two men and partial amputation of the prehensile part of the right hand for the third operator.

In *Kjeller, Norway* (1982), an experienced worker entered the exposure room as the 2.4 PBq ^{60}Co source was in operating position (Stavem *et al* 1985). It was estimated that his mean whole body dose, although heterogeneously distributed, was around 20 Gy. The victim died 13 days after exposure of acute renal failure with underlying aplasia. In *Soreq, Israel* (1990), the initiating circumstances were identical to those prevailing in the Kjeller accident: the worker entered the exposure room despite two conflicting warning signals and consequently was exposed to the 12.6 PBq ^{60}Co source, resulting in a whole body dose between 10 and 20 Gy (IAEA 1993). Although the victim received high quality medical care, such as growth factor therapy combined with bone marrow transplantation, he died 36 days after the accident of severe intestinal syndrome and pulmonary failure. In *Nesvizh, Belarus* (1991), the conditions were virtually the same as those in the two other preceding accidents (IAEA 1996a). The worker was rapidly evacuated to a specialised hospital in Moscow, where the exposure by a 28 PBq ^{60}Co source was estimated as between 12 and 16 Gy. Through various refined means, the exposure was shown to be extremely heterogeneous: 11 and 18 Gy on the left and right sides of the waist. Russian physicians believed that haematological restoration was possible and that risks of transplantation outweighed its potential advantages, and gave their preference to growth factor therapy. Haematopoiesis was restored within a few weeks, but a multi-organ failure appeared rapidly, complicated by extensive skin burns. The patient survived more than three months and died of respiratory complications.

In *Sarov, Russia* (2005), errors in handling uranium at the Arzamas-16 military facility resulted in a criticality excursion, which exposed the operator to a high neutron flux (IAEA 2001a). The resulting dose was estimated at about 20 Gy, but some regions received up to 60 Gy. The victim died on the third day.

In *Concepción, Chile* (2005), three workers were exposed to a ^{192}Ir industrial radiography source which was lost in a working site. One of them was severely exposed, in particular at one hand and the buttock, after he placed the source in his pocket, where it stayed for about 15 min. Since the severity and evolution of the lesions overstepped the national medical capabilities, the patient was evacuated to France. Conservative surgery was used on the buttock and auto-grafts combined with stem cells and specific growth factors were performed for the hand, avoiding drastic surgical treatment (Gourmelon 2006a, Jeanblanc 2006). The patient was back in his country after six months in satisfactory healing conditions.

These apparently simple cases provide valuable lessons, especially in the medical field. (1) As well as the dose level, the distribution of exposure within the body is determinant for therapeutic decisions; bone marrow transplantation may be indicated only in the case of homogeneous exposure and at high doses. This statement underlines the need for the physician to rely on physical data, such as those obtained from the accident reconstruction. (2) Bone marrow should not be considered as an isolated tissue, since radiation exposure induces a series of interdependent effects, which occur at a rate that depends on specific cellular dynamics. (3) Two of these accidents (Soreq and Nesvizh) were the first occasions where growth factors were used; although it is difficult to correctly assess their effectiveness, it seems that this therapy

contributes to rapid engraftment and cell maturation. (4) Since the 1980s, treatment of localised exposures has been improved considerably; the use of auto-grafts has proved their efficiency. (5) Overall, these accidents demonstrate the importance of the human factor in the development of radiation accidents; in each event, the respect of simple rules and common sense would have avoided severe consequences.

2.2. Accidents that are difficult to manage

The management of a radiation accident meets difficulties as soon as several people are involved. Most of the time, difficulties are of medical nature, although the structures required to cope can easily be overwhelmed when there are a consequent number of actual or potential victims. Handling can be complicated by the fact that group accidents attract media attention, which is not always justified. Two recent examples of the pitfalls inherent to this category are provided by an accident caused by an industrial gammagraphy source and a criticality accident.

In *Yanango, Peru*, in the San Ramon district 300 km east of Lima (1999), a welder placed in the back pocket of his trousers a 1.37 TBq ^{192}Ir industrial source that he had found on the ground, continued his work for 6 h and went back home. These circumstances are about the same as those which happened in Chile in 2005, as described above. In the Peruvian accident, during the 10 h preceding the source recovery by the plant staff, four family members (his wife, her breastfeeding 18 month old child and two older children) were also exposed to the source (IAEA 2000a). Tissue doses were estimated at 10–30 Gy to right thigh, 20–30 Gy to sciatic nerve, 10–15 Gy to femoral artery and 20 Gy to femur. As the severity of the lesions increased rapidly, Peru authorities requested foreign assistance and the patient was hospitalised three months later in France; appropriate treatments such as xenografts and additional surgery resulted in temporary improvement but could not avoid a dramatic relapse six months later, that neither the clinical evolution nor the dosimetric findings allowed forecasting. One year after exposure, the patient was in a hopeless situation. In *Tokai Mura, Japan* (1999), three workers were severely exposed to mixed neutron–gamma radiation (ratio 60/40) in a fuel conversion plant during the processing of highly enriched fuel for an experimental fast reactor (IPSN 1999, IAEA 1999). An enriched uranium solution of 16 kg, which was several times greater than the specified mass limit (2 kg) and the critical mass (5.5 kg), had been poured into a precipitation tank, bypassing a dissolution tank and a buffer column, both intended to avoid a criticality phenomenon. This resulted in a critical excursion. The event was immediately recognised and medical management of the three workers performed with the most reliable and modern means; the most exposed victim, with about 10 Gy, resulting in severe aplasia and deep burns, received a stem cell transplantation together with a haematopoietic growth factor; after a transitory improvement, the patient died 83 days after his exposure. Another patient, with about 6 Gy, received a cord blood transplantation, of limited efficiency; he died 211 days after his exposure. In both case, death was due to multiple organ failure (kidney, liver, heart and lung). The third victim, who received less than 3 Gy, was not confronted with any problems that modern medicine could not solve. Approximately 200 residents living in a 350 m radius were evacuated, 90% of them receiving less than 25 mSv.

2.3. Catastrophic accidents, with a large number of victims

An example of a catastrophic event that was immediately recognised is the *Chernobyl* nuclear plant accident, *Ukraine* (1986), which, on its own, brought together a large number of direct and indirect health consequences and affected the whole of the northern hemisphere. These consequences were not only purely medical; large regions of the USSR were contaminated

by radioactive materials that were released by the plant (Poiarkov and Robeau 2001). Two radionuclides raised serious problems, because of their potential effects and the released quantities: 85 PBq of ^{137}Cs and 1760 PBq of ^{131}I . Three republics—Ukraine, Belarus, and Russia—had large parts of their territories with ^{137}Cs deposits higher than 37 Bq m^{-2} . During the week after the accident, it was proceeded to the evacuation of populations, which resulted in the relocation of more than 135 000 individuals. Between 1986 and 1990, about 645 000 people, the ‘liquidators’, were employed for site cleaning and decontamination: it is assumed that most of their doses were between 50 and 250 mSv (with an average at 100 mSv). However, the first day rescuers most probably received much higher doses, up to 750 mSv.

The Chernobyl accident health consequences concern three categories of individuals: the rescuers (plant personnel, firemen and medical rescuers), the liquidators and the population in general. Among the 600 firemen who intervened during the first hours, 134 suffered rapidly from ARS; 20 individuals had doses higher than 6 Gy, 21 between 4 and 6 Gy, 55 between 2 and 4 Gy and 140 between 1 and 2 Gy. The most exposed patients were treated with bone marrow transplantation (13 victims) or foetal liver transplantation (six victims). Among these 19 grafted patients, only two survived (Gale 1986, 1987, 1988, Guskova 1987, Guskova and Gusev 2001, UNSCEAR 1988, Baranov and Guskova 1990). However, it is not possible to derive definitive conclusions, since the most irradiated victims presented severe skin radiation burns caused by deposits of ^{137}Cs on skin and clothes, which complicated prognosis. Among the 56 most injured, 11 died. The total number of deaths was 28 within a few weeks; three others died immediately after the accident, because of trauma. During the following 12 year period (1986–1998), there were 11 deaths among the rescuers: eight could not be attributed to radiation, two were due to pre-malignant diseases and one to acute leukaemia (UNSCEAR 2000).

Data on liquidators are difficult to interpret, especially because of the collapse of the USSR. In 1997, an increase of leukaemia among Russian liquidators was announced but no credible report was further produced. Among the 27 000 deaths that were attributed to ‘natural causes’ between 1986 and 1995, ‘wounds and intoxications’ represented 54%, cardiovascular diseases 20% and tumours about 15%; this distribution is about the same as that of non-exposed comparable populations.

Within the population, while no excess of leukaemia has been demonstrated, there is an unquestionable high rate of childhood radiation-attributable thyroid cancer in specific regions of Ukraine, Belarus and Russia (Williams 1996). Between 1990 and 1998, the total number of thyroid cancers detected in children living in these affected regions and who were less than 18 years old when the accident occurred was around 1800 (Tronko *et al* 1999, Ivanov *et al* 1999, UNSCEAR 2000). This value corresponds to a 10–100-fold increase of the natural background of this very rare childhood cancer. Ten years after the catastrophe, it was estimated that the total number of thyroid cancers that could be expected could reach 10 000 cases, although it was impossible to indicate a mean value (Cardis 1996, Nénot 1996a, 1996b). Recent reports confirm these predictions: United Nations competent organisations assess the number of thyroid cancers in the period 1992–2000 at about 4000 (Chernobyl Forum 2005) and one of the most recent reports announces about 5000 cases in Ukraine and Belarus (Cardis *et al* 2006). A slight excess in adults is established in the three republics, especially after the age of 50 and more pronounced in women than in men. It is difficult to attribute this increase to the Chernobyl accident, since an identical phenomenon is seen in western countries, where it may be related to progress in early detection of thyroid cancers. Besides this localisation, no excess of solid cancers and leukaemia has been reported (UNSCEAR 2000). The Chernobyl radiological health consequences should be dissociated from effects that were directly caused by drastic changes of societal, political and economic impact: in 1993 life expectation had decreased to 59 years for men (from 65

in 1987); mortality rate increased by nearly a factor two (from 488×10^{-5} to 741×10^{-5}). In addition, it was recognised in 1992 that fear of radiation may have caused more harm than radiation itself (Nénot 1994a).

3. Accidents with delayed recognition

The number of accidents for which aetiology is recognised by chance is increasing with time. The question of the number of severe accidents which remain completely unknown and is attributed to common causes has no real answer. Finally, it is often the type and nature of the injury which allows the physician to evoke and find the real cause.

3.1. Accidents with a limited number of victims

There are several representative examples of such accidents. The following examples provide a relatively good indication of severe accidents which occurred in the industry (ten accidents), medicine (four accidents) and military fields (two accidents). The large number of these examples—the longest list in table 1—is a correct relative expression of reality.

3.1.1. Industrial field. In *Mexico City* (1962), a whole family was wiped out by a ^{60}Co source, found on a dump (Andrews 1963, Martinez *et al* 1964, Mettler and Nénot 2001b). A 10 year old boy died after one month, followed by his mother and 3 year old sister a few months later; it is only at this time that the origin of these three deaths was discovered. Death of another relative could not be avoided seven months after the accident. The father was the only family member who survived, because of the short periods of time he spent at home. In *Brescia, Italy* (1975), at a cereal irradiation facility with four ^{60}Co sources a worker entered the irradiation room by climbing onto the conveyor belt. His first symptoms of exposure (nausea, vomiting, headache and erythema) were attributed to insecticides. For more than two days, his exposure to an unshielded 500 TBq source remained unknown to the physicians. He died 13 days after his exposure; his whole body dose was evaluated at 12 Gy, non-uniform (Jammet *et al* 1980a). In *Setif, Algeria* (1978), and *Casablanca, Morocco* (1984), ^{192}Ir sources (925 and 600 GBq, respectively) were lost and picked up by families. Diagnoses were only made after 38 and 80 days, respectively (Jammet *et al* 1980b, Parmentier *et al* 1980, Mettler and Nénot 2001b). Accidents were revealed by chance, after a physician identified the origin of symptoms. In all, the Algerian accident caused the death of a 47 year old woman, four serious life-threatening whole body exposures of four women aged 14–20 and multifocal localised overexposures in two young boys aged 3 and 7. The Moroccan accident resulted in eight or even more deaths: four young children died from severe aplasia a few days after their parents, and several relatives were affected by haematological depression at various degrees.

In *San Salvador, El Salvador* (1989), three workers at an industrial sterilisation plant were exposed to a ^{60}Co source of 0.66 PBq by the time of exposure, when attempting to unblock the source holder (IAEA 1990). Radiation exposure was only identified when a burn appeared on the third day. On site, it was only three days later that the accident was diagnosed and two weeks that the irradiator was back in a safe situation. Individual doses were evaluated as 8, 4 and 3 Gy, with some body areas exceeding 10 Gy for one victim. The three victims were transferred to a specialised hospital in Mexico City. Two patients each had a leg amputated; one of them had his second leg amputated and the other one developed a respiratory complication, which caused his death. In *Forbach, France* (1991), three handlers at a linear accelerator were exposed during repeated reparations and maintenance on the device, while only the electron source was cut off but accelerator voltage maintained in order to save time (Chanteur 1992).

Under these conditions the residual dose rate was a few gray per second. When the first skin injuries appeared, they were attributed to sunburn and it was only after several days that the cause was suspected, when the serious health deterioration in one of the victims justified his hospitalisation. This patient underwent repeated skin grafts during a whole year. He was in a precarious state up to his death in spring 2007, 16 years after exposure, from a digestive haemorrhagic syndrome; the question of causation remains open. In *Hanoi, Vietnam* (1992), at a physics institute an engineer suffered severe overexposure of both hands from a linear accelerator beam, while positioning a sample for analysis (IAEA 1996b). Although the victim was immediately aware of the accidental exposure and reported it, his burns were only linked with the real initiating event two weeks later, when his clinical state became serious. Four months later, he was transferred to France, where the only possible therapeutic decision was to amputate his right hand fully and his left hand partially (doses from 30 to 45 Gy to wrist and fingers).

In *Meet Halph* village, near *Cairo, Egypt* (2000), a 61 year old farmer found in the sand a 1 TBq ^{192}Ir source, lost by a welding company (El Naggar 1997, IAEA 2000c). It seems that this loss had not been reported to national authorities. It was only after two deaths (the farmer and a 9 year old boy, 30 and 42 days after exposure, respectively) and transfer of family members to a Cairo hospital that the cause was recognised. Seven victims, who had been exposed for seven weeks, survived doses of 3–4 Gy. During this period of time, about 150 inhabitants of the village received doses around 25–150 mGy, and about 100 rescuers 15–100 mGy. In *Fleurus, Belgium* (2006), a technician entered an irradiation room in order to turn off the alarm which had been out of order for a few days. Consequently, he followed the prescribed procedures, i.e. verifying that nobody was present in the room before closing the door, potentially responsible for the alarm failure. During about 20 s, he was in the radiation field of the 30 PBq ^{60}Co source, which was not entirely in safe position (IRSN 2006a). The first symptoms appeared rapidly, but were attributed to some alcoholic excess on the previous evening. The aetiology was only evoked three weeks later, when the occupational physician discovered a recent alopecia. The overexposure, estimated higher than 4 Gy (heterogeneous exposure), resulted in a deep aplasia and the victim was transferred to a French hospital, where a treatment with haematopoietic growth factors was efficient (Gourmelon 2006b). In *Dakar, Senegal*, and then in *Abidjan, Ivory Coast Republic* (2006), overexposures caused by a gammagraphy ^{192}Ir source occurred during several weeks. The cause was a defect in the device, which happened in Dakar, and was only discovered in Abidjan. In the meantime, two attendants and two operators had received high doses, which justified their evacuation to a specialised medical unit in France (IRSN 2006b). All victims exhibited localised radiation injuries and one suffered from aplasia. In addition, the number of individuals likely to have been exposed between the initiating event and its recognition was large; however, their doses were expected not to have been sufficiently high to result in acute effects. In *Tunisia* (2008), an operator dismantled a gammagraphy device in order to loosen the 3 TBq ^{192}Ir source; then he placed the flexible part in his pocket, without knowing that the source was still inside. One month later, his hands showed evident signs of overexposure, with doses estimated at around 30 Gy for some areas, or more.

3.1.2. Medical field. In *Zaragoza, Spain* (1990), 22 patients were exposed to higher than intended doses (Esco *et al* 1993). Previously, the cause of a malfunction had been wrongly identified and the subsequent repair resulted in an unexpected change in electron energies. During 10 days, patient doses were three to seven times higher than the prescribed ones, depending upon the chosen energies. Patients, especially those treated for cervical and thoracic tumours, developed pulmonary, oropharyngeal and bone marrow lesions, complicated by

vascular and cutaneous damage. Since all patients were treated for cancers in their severe evolution phase, it is difficult to assess precisely the real participation of this overexposure in the lethal issues; nevertheless, it is assumed that this accident caused at least 13 deaths. In *Epinal, France* (2004–2005), 23 patients treated for prostate cancer were recognised as having received doses 20% higher than those prescribed (ASN 2006a). This accident had three main causes: error in dosimetric computation, lack of program ergometry and insufficient training of personnel. The subsequent complications were recognised as related to this misadministration about one year after treatment. The consequences were very severe: one death could be rapidly attributed to the accident, while 13 patients showed disabling complications. This event is too recent to establish the complete consequences, especially since all conclusions have not yet been drawn. In *Lyon, France* (2004), because of an erroneous handling when treating a patient for a non-malignant tumour, a larger area than prescribed was exposed. This error was due to confusion in the unit used to determine the surface to be irradiated—millimetre *versus* centimetre—(ASN 2006b). Several months after treatment, severe injuries, first attributed to hypersensitivity, caused the death of the patient.

3.1.3. Military field. In *Tammiku, Estonia* (1994), an abandoned military 1.6 TBq ^{137}Cs source was stolen from a waste repository (devoted to medical low activity β waste) and kept in a house for 27 days (IAEA 1998a). During this period of time, the death of the young man, who had placed the source in his pocket before keeping it at home, was attributed to traumatic toxæmia. It was not until a 14 year old boy (the previous victim's nephew) was found suffering from a haematological disorder and hand burns that the origin of the diseases was discovered by a well educated paediatrician. The alarm was raised in the night following recognition of the radiation accident nature, and all the inhabitants in a 200 m radius around the house where the source was recovered evacuated (dose rate was higher than $0.4 \mu\text{Gy h}^{-1}$ at 100 m). Source activity could not be determined. In all, seven received doses higher than 100 mGy and five were severely injured. The five rescuers who intervened in the source recovery and the most exposed inhabitants in the neighbouring houses were exposed to low doses, around 100 mGy and a few hundred mGy, respectively. Near a village named *Lia, Georgia* (2001), a few hundred kilometres west of Tbilissi, three woodcutters found on the ground two metallic cylinders around which snow was melting. During the following cold night, they used these devices as heating sources. After a few hours, all three presented classical prodromal signs of ARS (IPSN 2002). Extended burns appeared within one to two weeks. The radiological cause was recognised three weeks later, when the suspect cylinders were discovered to be thermoelectric generators functioning with a 1.3 PBq ^{90}Sr source (x rays, 1 Gy h^{-1} at 1 m), which were probably used as radar beacons for neighbouring military air fields of the Soviet Army. Two victims, with doses between 2 and 3 Gy, exhibited an aplasia which improved within one month. All three had their backs severely burned and in addition one showed injuries on his hands and legs. Three months later, available medical means were judged insufficient and two patients were transferred to a French burn unit, where they were grafted (artificial skin graft followed by auto-graft). The third patient was transferred to a Russian hospital.

3.1.4. Malevolent actions. Some rare criminal actions, using radiation sources, have been reported during the past decades. Two attempted murders in the 1970s have brought their authors in front of courts of justice. The first attempt occurred in the *USA* in 1974: for revenge, a man deliberately exposed his son, five times in six months, to a 37 GBq ^{137}Cs source that he was holding for oil prospecting (Bailey and Wukasch 1977, Collins and Gaulden 1980).

The origin of the radiation-induced injuries was recognised two years later, after the victim had suffered several surgical interventions. One of the most serious sequelae was a functional castration. The second attempt occurred in *France*: a reprocessing plant employee, intending to cause severe injury to a colleague, placed under the seat car a radioactive bar that he had stolen from the workshop. The attempt was revealed by chance when the car passing through the plant exit activated the alarms. The exposure was too short to cause serious effects. Other malevolent actions have been reported: in the *USA*, a complaint was lodged by a pregnant scientist in 1995, for ^{32}P poisoning. A Russian publication reports at least four cases of criminal actions with γ radiation sources, three of which with the source being placed under the targeted victim's seat (Krasniouk 2004); in fact, these few cases constitute isolated criminal acts, motivated by desire for revenge and, consequently, do not strictly correspond to the definition of malevolence.

Finally, the assassination in *London, UK* (2006), of a Russian citizen by poisoning with ^{210}Po , apparently for political reasons, was an unprecedented event (IRSN 2006c, Harrison *et al* 2007, Westminster City Council 2007). After the high specific activity α emitter had been poured into his drink, the victim became rapidly severely ill and died within a few days from multi-organ failure (kidney, heart, bone marrow). A remediation process aiming to reduce the risk to public health from exposure to radioactive internal contamination, monitoring public areas, hotels, hospitals and transportation means, control of waste, communication with media, verification and clearance required great efforts and mobilised a large number of experts and large workforce (City of Westminster 2008). Among 100 people or so with measurable intakes of ^{210}Po , 17 were assessed to have doses higher than 6 mSv.

3.2. Accidents with a large number of victims

Probability that an accident causes radiation exposure of many people increases with the duration of the source control loss. This may happen when errors occur in medical irradiations, which may result in many accidental exposures, or when industrial or military sources are lost. Six accidents which occurred in hospitals and two cases of lost source (industrial and military) represent good examples of the relationship between the accident frequency and the source nature and worsening of health state with time spent before accident recognition.

3.2.1. Medical field. The first serious accident happened in *Columbus, OH, USA* (1974–1976). Between 1974 and 1976, a wrong calibration due to an error in the ^{60}Co half-time resulted in the overexposure of 426 patients; their doses were 15–45% higher than the prescribed doses, depending on the time where they were treated (Cohen *et al* 1995). Among the 183 patients still alive one year after treatment, more than one-third had severe complications of the central nervous and gastrointestinal systems. An opposite result was discovered at the hospital of *Stoke-Upon-Trent, UK* (1982–1991), after the underexposure of 1045 patients, who received during a nine year period doses 5–35% lower than expected (Ash and Bates 1994). Consequences cannot be precisely evaluated, especially as comparison of recoveries and prolonged remissions in correctly treated patients with those who were underexposed is very difficult to interpret. Another accident occurred in *four hospitals in the USA* between spring 1985 and winter 1987, after five series of overexposures (Newman 1990). The initial event was an operator error in programming the machine, although the error was actually indicated on the checking report. The fifth accident occurred although all hospitals equipped with such a machine had been warned and a safety procedure laid down. This series of accidents caused severe damage, including burns, myelitis, paralysis and other complications, which resulted in deaths. A fourth accident happened in *Indiana, PA, USA* (1992): an elderly female patient returned a post-treatment unit without the brachytherapy ^{192}Ir

source (high dose rate) being removed (US NRC 1993, Mettler and Ortiz-Lopez 2001). Four days later, a nurse threw a catheter discharged by the patient—which contained the source—into the waste. The next day the patient died without her death being attributed to radiation. During waste transport more than 90 people were exposed to doses that were not high enough to cause acute effects. The alarm was finally raised by a monitoring device at a waste processing facility. A fifth accident occurred in *Panama* (2000), where an error in determining doses delivered by a ^{60}Co source caused 28 victims (IAEA 2001b). The error was due to a modification in the computerised treatment, which aimed to introduce additional shielding in order to reduce the radiation field. Although the computer did not accept the modification, treatment was given and doses were much higher than expected; among the victims, treated for genital cancer, three died within one year and the 20 surviving patients developed severe digestive and urinary complications. 15 patients were expected to develop serious complications, which may prove fatal. A sixth accident occurred in *Bialystok, Poland* (2001), due to a malfunctioning of a linear accelerator used for the treatment of breast cancer (Wojcik *et al* 2004, IAEA 2004). Five patients were overexposed at their 22nd fraction (currently 2 Gy per fraction with 8 MeV electrons). Later on, breast doses to the most exposed patient were evaluated around 56 ± 10 Gy (electrons only) or 42 ± 8 Gy (photons, which cannot be excluded). As evolution was worsening for two victims, they were transferred to France, where they were skin grafted. After one year, all five were in a satisfactory state. However, the dose levels to the thorax justify a strict follow-up, especially for early detection of radiation-induced lung fibrosis or cardiopathy.

3.2.2. Industrial field. In *Xinzhou*, province of *Shenxi, China* (1992), a worker found a 100 GBq ^{60}Co source in a deep hole in the ground and took it home. The hole happened to be an ancient site for radiation source storage, closed in 1980 after 20 years of operation. The source residual activity in 1992 was 400 GBq (Wu 1993, Pan 2001). The worker kept the source in his trouser pocket, and his father and his brother died after two and three weeks in hospital, their death being attributed to an infectious disease. In the meantime, his wife, who assisted in care, and about 100 people (nurses, physicians, visitors and workers who took care of the waste transportation) were exposed to the source. It was only after the patient deaths that the real cause of the injuries was discovered. The source was found more than two months after its discovery. Among the 12 most exposed individuals, doses ranged from 1.2 to 2.3 Gy.

3.2.3. Military field. At the *Lilo Training Centre, Georgia* (1996–1997), 11 young frontier guards were exposed to some of the several military radioactive sources, previously used for nuclear war training, which had been abandoned by the Soviet troops when they left the country. These ^{137}Cs sources were dispersed on the training site (12 were identified), together with 200 ^{226}Ra sources for night aiming. The victims were exposed for approximately one year; the accident was recognised when the injuries became evident and the number of affected guards large, especially as each of the victims suffered from one or more acute localised radiation injuries (IAEA 2000b, Peter *et al* 2001), because of the long period of time during which the source, first located in a greatcoat that was passed round from one guard to another, especially during cold nights, where it was used as a blanket. Four severely injured victims were evacuated to France and seven to Germany. For the first time in the case of skin radiation injuries, artificial skin grafts were used for deep lesions and demonstrated their efficiency. Because of the large number of sources which have been discovered since, it cannot be ascertained that any other recruit has not been exposed.

3.3. Accidents with severe consequences for the population and environment

Three accidents, in addition to their serious health consequences, had severe impact on the environment and caused extensive economic and societal damage; their common cause was the abandonment of a radiotherapy source and the further dissemination of its radioactive material. A fourth accident, resulting in the direct overexposure of more than 100 treated patients, was a real national drama.

In *Juarez, Mexico* (1983), a teletherapy machine consisting of some 6000 ^{60}Co pellets (15.6 TBq) was dismantled without subsequent control of disposal. During disassembly the source container was punctured and 800–1000 pellets were spilt into a truck bed. The machine was sold to a scrap yard and then to foundries in Chihuahua and Durango, resulting in various metal products becoming contaminated. The problem was discovered by chance six weeks later when concrete reinforcing irons triggered alarms in the Los Alamos Military Centre (USA). These irons came from a foundry which had processed radioactive residues recovered from the source (Sec. de Energ. 1984). It was estimated that 4000 individuals from the general public were exposed to non-trivial doses; of these, about 800 received more than 50 mSv and eight between 1 and 7 Gy, fortunately delivered over a two month period. No death occurred, mainly because exposure was spread over time. Rehabilitation of land and roads took time; more than 100 pellets were found and it was only three months after the initial event that the last 27 pellets were recovered. The environment was declared safe four months post-accident, which necessitated control of 17 000 houses, of which more than 800 were destroyed because they were judged impossible to be decontaminated.

In *Goiânia, Brazil* (1987), although the initiating scenario was strictly comparable, consequences were much more severe, as the radiotherapy source was made of highly soluble ^{137}Cs chloride (51 TBq). The first signs of ARS developed by the two scrap merchants who had retrieved the device were attributed to a tropical disease, and two weeks elapsed before the accident was recognised (IAEA 1988, 1998b). The radiological nature of the accident was suspected by an oil prospector who needed two successive measurements to believe in the dose rate magnitudes. During this two week period, the two dealers continued to dismantle the device, resulting in the large dissemination of radioactive powder and subsequent exposure of their families. Children were especially exposed, since they played with this ‘magic’ luminescent powder. Authorities requisitioned the soccer stadium for triage of about 100 000 persons. Among the 20 individuals who required urgent hospitalisation, ten presented signs of ARS, with whole body doses between 3 and 7 Gy. Many of the most severely exposed were also suffering from skin injuries and internal contamination (some children had very high committed doses up to a few gray). Four victims died and 28 had to undergo surgery, consisting in grafts or amputations. Cleaning the environment, including decontamination of 85 residences and demolition of seven houses, took place three weeks after the accident discovery. The town and its surroundings were considered acceptably free of radioactive contamination three months later. The volume of waste generated by the environmental cleaning was huge and a provisional storing site was created for 3500 m³ of waste under various forms. Total on-site activity was estimated at about 44 TBq, corresponding to 85% of the initial source activity. Ten years passed before responsible authorities could find a viable solution for this deposit. The total economic impact was very severe as the whole regional economy was affected for a long period of time, regardless of the real radiological impact.

In *Samut Prakarn, Thailand*, near Bangkok (2000), a teletherapy 15.7 TBq ^{60}Co machine, which had never been used since it had been bought in 1974, was stolen by four scrap collectors and rapidly resold. For almost three weeks, 13 people (four thieves, two young junk dealers, one second-hand shop holder and his six family members) were exposed. Ten of them were

hospitalised for haemorrhages and burns (Suzuki 2000, IAEA 2002). The cause was recognised very late. Three victims—18, 23 and 44 years old—died during the second month following the theft. Information on the other injured individuals remains contradictory; probably in order to avoid any panic among the population, and, confronted with a possible high number of potentially irradiated people, national authorities were remarkably quiet. Nevertheless, it could be established that about ten people necessitated intensive medical care and some required amputations. Some 44 individuals exhibited signs that might have been due to an overexposure. In spite of lack of transparency, which favoured the most incredible information, this accident was considered as a national catastrophe.

In *San José, Costa Rica* (1996), the overexposure of 114 patients, including children, was a national tragedy. Errors in the calibration of a new ^{60}Co radiotherapy source resulted in exposures which were 50–60% higher than the prescribed doses; the error was due to a confusion in the time unit, the second versus 1/100th of a minute (IAEA 1998c). As in any overexposure during the course of a treatment, the error was recognised only when a large series of patients exhibited abnormal signs of radiation injuries and consequently evoked the real cause. The time period between the initial event and its discovery was a full month, and explains the great number of injured patients. The overexposure resulted in severe consequences, which, for some patients, were worsened by maladjusted treatment procedures (insufficient fractionation, extended fields, etc). The accident caused dramatic effects (quadriplegia, paraplegia, spinal cord demyelination, severe digestive and cutaneous injuries) in four patients, marked effects with reserved prognosis in 16 patients and limited risks in 26 other patients; only 22 patients did not suffer from the accident, because their treatments were interrupted before any dose in excess could be delivered. The number of deaths directly related to the accident is difficult to assess; among the 61 deaths within two years it is likely that 13 can be directly attributed to their overexposures and four to radiation-induced complications. Among the 51 patients still alive two years later, two were suffering from late severe complications and 12 exhibited marked and disabling sequelae (Mettler *et al* 2001a).

4. Accidents that are kept secret

In general, secret accidents belong to the military arena and were common during the Cold War. However, the improvement in east–west relations does not mean that complete openness has become the norm for radiation accidents, since some of them may have political or military implications or disclose secret information. The great nuclear powers have perhaps not yet fully lifted the veil of secrecy over all accidents and incidents that punctuated the weapons race. Demonstrative examples come from a US weapon test in the Pacific Ocean in 1957 resulting in environmental contamination and severe health consequences, the disastrous management of Soviet military plants in the 1950s and 1960s, the loss at sea of various nuclear devices by both superpowers between the 1950s and 1960s, and the atmospheric release during a French nuclear test in 1962, as well as the massive contamination of large territories in Spain and Greenland in the 1960s.

In *Kyshtym, Ural Mountains, Russia* (1957), a very large stretch of land was contaminated by fission products released after the explosion of a storage tank in a secret plant dating from the post-war period (UNSCEAR 1993, Nénot 1994b, Nénot and Robeau 2001). The release of some 700 PBq of radioactive products contaminated about 20 000 km² in the regions of Chelyabinsk and Sverdlovsk, with a population of nearly 300 000 inhabitants. More than 1000 individuals were living in areas with a ^{90}Sr deposition concentration higher than 40 MBq m⁻². The accident was only revealed in 1990, 33 years later, by a political refugee. The resulting exposure of the population and the workforce came on top of the chronic exposure they were

already experiencing from operational practices that were considered normal at this time and in this country (current releases in the river were of the order of 40 EBq). Following the accident, 20 villages with 7500 inhabitants were permanently evacuated. The most exposed groups of the population show a significant increase of leukaemia and solid cancers (Ostroumova *et al* 2008).

The accident which happened in the *Atlantic* (1961) shows the potential consequences of the quest for secrecy at any price: in order to prevent a nuclear submarine being recovered by a foreign navy, the Soviet authorities ordered the crew to carry out makeshift repairs; several crew members received high doses and at least eight died as a result, but the vessel could be brought back to its home port.

Although losses at sea of radiation-emitting devices cannot be strictly classified as accidents, loss at sea of nuclear weapons after air accidents or failed nuclear missile launches, sunk ship and submarine reactors, plutonium-based reactors from satellites that have broken up when re-entering the atmosphere, etc should be mentioned, simply because of their considerable number and frequency. The US official list for nuclear weapons contains 32 events in the period 1960–1980 (Mettler and Allen 1990), while for losses at sea in the period 1950–1965 the total number includes seven incidents with nuclear weapons (accidents in the air), three missile launches, two submarines lost with their reactors and three satellites. Very few have been recovered. On the Soviet side, most of the losses came from the submarine fleet; between 1968 and 1989 seven weapon-armed submarines sank, in addition to a destroyer lost in the Black Sea in 1974.

Military activities have led to three serious documented incidents with environmental contamination. At *Bikini Atoll, Marshallese Islands, Pacific Ocean* (1954), the US Army performed a thermonuclear test. The unexpected power coupled with unfavourable meteorological conditions resulted in high-activity fallout on four Marshallese islands (Rongelap, Ailinginae, Rongerik and Utirik), involving 239 Marshallese plus 28 US servicemen (Conard 1980). The highest doses came from the deposits, especially in the Rongelap atoll; skin injuries developed within the following days or weeks. Islands were evacuated for long periods, then judged sufficiently safe for normal living, and again re-evacuated before definitive clean-up. The follow-up of the affected population during a 25-year period shows mainly the development of thyroid abnormalities, with growth retardation in a number of exposed Rongelap children, as well as the development of thyroid nodules, hypothyroidism and thyroid hypofunction, appearing 10–20 years later. The re-evaluation of thyroid exposures indicates doses between 3 Gy in adults and 7–14 Gy in children of less than 10 years of age (Rongelap). At the test time, a Japanese fishing boat, *Fukuryūmaru—The Lucky Dragon*—was about 100 miles from Bikini, out of the prohibited area, but unfortunately exposed to radioactive fallout produced by the test (Kumatori *et al* 1980). Three hours after the test, white ash began to fall on the vessel for about 4–5 h. The 23 fishermen rapidly showed signs of localised as well as whole body overexposure. Their doses were estimated at around 2–6 Gy. The boat returned to its base two weeks later. The fisherman with the highest dose died from ARS three weeks after his exposure. For the others, spermatogenesis was severely depressed and lasted up to eight months.

In the *Hoggar Desert, Sahara* (1962), on the occasion of a nuclear weapon test, the underestimation of power combined with a wrong appreciation of the prevailing weather conditions caused the contamination of the command site and staff. Finally, exposure levels (external and internal) were considered trivial, although they involved a relatively large number of individuals.

Near *Palomarès, Spain* (1966), following a mid-air collision between an US bomber carrying nuclear weapons and its refuelling plane, the contents of three nuclear devices were

spread over the ground around the town, while a fourth bomb fell into the sea (Mettler and Allen 1990). Seven crew members died and four survived. More than 600 people took part in the search for debris and in clean-up. About 150 m² of earth and vegetation were removed and transported to the USA. The device in the sea was recovered after three months. No contamination could be detected in the inhabitants. Near *Thulé, Greenland* (1968), a US plane crashed onto the ice field, causing the explosion and dispersal of the content of four nuclear bombs (US AF 1970, Mettler and Allen 1990). The accident killed one crew member. The clean-up operation, complicated by extreme climatic conditions in the polar night, involved more than 700 military personnel helped by American and Danish scientists and workers. The quantity of plutonium dispersed was estimated at more than 3 kg, most of which was captured in the upper layer of ice. Land decontamination included collecting ice, snow and debris in 167 tanks of 100 m³ each, which then were dealt with in the same way as the Palomarès waste. More than 30 years later, all Danish citizens involved in the cleaning operation and who claimed for compensation for any illness likely to be attributable to radiation were automatically considered as entitled to be compensated. These two accidents show that, despite adequate emergency plans, the setting up of suitable arrangements is difficult, especially because of the number of specialised personnel required.

5. Conclusions—main lessons learnt

The main general lessons which can be derived from the accidents that are described above are the following. (1) There is an unacceptable probability of scenarios likely to produce an accident. (2) There are too many cases where it takes too long for the accident to be identified; whatever the time elapsed between the event and its recognition, wasted time has severe consequences, such as increase in the number of casualties, worsening of their condition, and difficulties in handling the situation and the victims. (3) Common factors in catastrophic events—absence or lack of regulation, failure in source control, inadequate training and little awareness of staff and facility managers—are serious handicaps to prevention; experience, especially from the Chernobyl accident, demonstrates that, without meticulous preparation and emergency plans based on potential accident scenarios, the situation will get out of control and end in fiasco. (4) With regards to management of health consequences, authorities often have to face the inadequacy of resources. (5) Special attention should be paid to the psychosociological factors, which can outweigh the medical or even public health factors. (6) Almost all accidents which have occurred in hospitals are related to overexposures; it should not be forgotten that medical underexposures, although they do not result in immediate deleterious effects, may have severe consequences for patients. (7) The last but not the least item of this list is information, which should flow in all directions and bring into play all the networks involved, which include authorities, physicians, experts, casualties, the population and the media. Attention to these matters, which are simply common sense, would help to reduce the number of events and their consequences.

In the medical field some lessons may be considered as encouraging: (1) new generation drugs (antivirals/antibiotics, growth factors (cytokines), etc) show great promise in saving lives of victims with severe ARS in the range of lethal doses; (2) in the treatment of accidental ARS, indications of bone marrow transplantation or even of haematopoietic cell transplantation are limited, especially when other radiation-induced injuries, such as burns, are associated; (3) great advances in the management of burns, whatever their cause, have radically changed the medical approach of radiation-induced skin injury treatments.

However, it should be kept in mind that a worsening of hazards related to radiation can be expected, since the number of sources is increasing (more than half a million of

sources in Europe), a significant fraction of them being out of use or obsolete—the so-called orphan sources, the expansion of the medical use of radiation with sophisticated machines and protocols, and the emerging threat of terrorist and malevolent actions.

Any registry of the various types of accident could give the wrong impression that such events are not rare and always result in serious consequences. In reality, when compared with the total number of operations involving radiation, the number of accidents resulting in consequences on humans and/or environment is small, especially when the accidental rate is compared with the corresponding rate in other industries, medical and occupational activities. For example, in the medical field, in the years 1991–1996, the number of worldwide radiotherapy prescriptions exceeds one million per year. On the other hand, since most of the serious consequences, as well as their causes, could have been avoided, it should be stressed that this small number is still too high. Consequently, all efforts should be made in the fields of radiological safety and protection to reduce to a minimum the number and magnitude of the potentialities for accidents to occur.

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