Lessons from Major Radiation Accidents

P. Ortiz, M. Oresegun, J. Wheatley
International Atomic Energy Agency

ABSTRACT

Lessons have been learned from investigations into a relatively large number of accidents that have occurred in three major practices, namely: industrial radiography, gamma irradiators and electron accelerators used in industry and research, and radiotherapy.

This paper provides an overview of the lessons learned and specifically considers the human actions and omissions that have resulted in an accident.

INTRODUCTION

The retrospective study of accidents is essential to prevention, which is why the IAEA have devoted a considerable amount of resources to this area. The body of knowledge gained from these investigations can, in general, be grouped as follows: a) accidents involving industrial radiography are the most frequent cause of severe or fatal overexposure to workers and the public; b) accidents involving gamma irradiators normally result in fatalities of workers, whereas accidents with electron beam accelerators often result in amputation of limbs; c) accidents in radiotherapy can effect large numbers of patients, resulting in their death (directly or indirectly) or severe degradation in quality of life; d) the loss of control of sources (“orphan” sources) has resulted in death and severe deterministic effects to members of the public and has caused widespread contamination of the environment. In addition to published reports, an additional tool for dissemination of lessons learned from accidents is IAEA’s international reporting system of unusual radiation events (RADEV), which is currently being finalised prior to world-wide release.

Defence in depth is a well established principle that is applied to safety. A single equipment fault or a human mistake should not directly result in an accident. The provision of multiple layers of safety should ensure that the intended safety objective is attained even if one protective measures fails. Technological means such as interlocks, or procedures such as cross checking, are normally used to achieve this objective. The problem arises when these multiple safety layers are not in place, allowing a single error or failure to develop into an accident. Studies of accident case histories show that even when safety layers are initially in place, for instance at the licensing stage, an accident can occur later if the components of the safety layers are not maintained or are deliberately by passed. A recent example of this occurring is the accident in Tokaimura, which is discussed elsewhere during this Congress.

This paper focuses on accidents that have occurred in industrial radiography, irradiators used in industry and research, and radiotherapy (1,2,3) and those resulting from a more general loss of control of sources (“orphan sources”). Reference is also made to investigations of individual accidents in the IAEA Accident Report Series (4,5,6,7,8,9,10) .

INDUSTRIAL RADIOGRAPHY

A review of published information (1,11,12,13) shows that the main victims of accidents involving industrial radiography sources were members of the public and workers who were not associated with the use of the source. A feature common to this type of accident is that the source becomes separated from its shielded container. To the untrained eye, this unshielded source appears to present little hazard and often persons have put the source in their pocket and taken it home, resulting in death or the amputation of limbs. Accidents involving the loss of control of sources (“orphaned” sources) are discussed later in this paper.

Statistics[1] relating to the accidental exposure of industrial radiographers show that:

3/4 There was one case of death due to leukaemia, which was most likely caused by chronic excessive radiation exposure (10 Sv).;

3/4 In about 15 % of cases, whole body doses exceeded 0.25 Gy, in three cases radiographers suffered acute radiation syndrome

3/4 In about 30 % of cases, local radiation doses exceeded the threshold for deterministic effects. In two of these cases the radiographer’s hands/fingers were amputated; in two cases the skin of the chest wall required surgical intervention (skin grafts); and in one case the chest wall was so severely irradiated that a metal plate had to be inserted to replace the ribs in order to protect the heart.

3/4 In about 65 % of cases whole body doses were lower than 0.25Gy, with localised radiation doses below the threshold for deterministic effects.

[1] Some of the radiographers received both substantial whole-body exposure in addition to high localised doses, and are therefore inlcuded in more than one of the above groups.

Safety related features of industrial radiography

A typical mobile radiography incident involves the source failing to retract to the shielded position when it becomes accidentally detached from the drive cable or becomes jammed in the guide tube. This may occur as the result of poor maintenance of the exposure equipment or physical damage to the guide tube. The example of an event tree shown in (14) indicates that the path from a source disconnection/jam towards an accident is dependent on: a) the use of a survey meter after each exposure; b) the survey meter working properly; c) the radiographer believing the monitor; d) implementation of emergency procedures. Safety measures in industrial radiography thus rely largely on human behaviour as the radiographer is expected to use a survey meter in order to confirm that the source is shielded.

Reasons why accidents occur in industrial radiography

The causes identified in the review of accidents include: failure to follow procedures, insufficient training, insufficient regulatory control, inadequate maintenance, equipment malfunction and in a few cases wilful violation. In virtually all of the accidents, the same problem invariably appeared: the radiographer did not use a survey meter to confirm that the source was shielded. In some cases, the radiographer even switched off their personal alarm, or just ignored the signal.

It seems important to understand this human behaviour, in order to successfully apply preventive measures. For example: an average radiographer may perform more than one hundred exposures a week, after each of them he should verify the source is shielded by using a survey meter. After many thousands of times following this procedure with the radiation monitor, some overconfidence is bound to develop. The radiographer's expectation is that "nothing will happen" as was the case in the thousand times before. The feeling of danger fades with time and becomes remote if measures are not taken to boost awareness.

Safety measures constitute a major part of radiography work and this effort is often perceived as a burden since it is not necessary to produce a radiograph. These safety measures will include: cordoning the controlled area, placing warning signs/signals, clearing the controlled area, making audible and visual signals, patrolling the area and checking radiation levels around it during exposure, performing visual checks of the integrity of cables, guide tubes and fittings. During meal breaks the exposure containers need be locked and safely stored (15). Also much of the heavy equipment to be carried is only for safety: temporary barriers, tapes, warning signals, collimators and local shielding, emergency equipment and handling tools, survey meters and personal alarm and direct reading dose meter.

Industrial radiography is a competitive business and reducing cost is a matter of survival for some companies. The cost of obtaining a radiograph is influenced by the work devoted to safety. Often radiographers are paid for the number of radiographs taken. The following circumstances add to the problem: radiographs are often taken in difficult locations, some times during the night or with low light, and radiographers often work alone without direct supervision.

Considering the above points it becomes understandable why radiographers are tempted to use shortcuts and to do the work faster. The fact that shortcuts often work "successfully" and nothing happens, encourages radiographers to keep doing them, especially if management policy does not discourage them.

Measures to increase safety in light of the lessons learned

Managerial measures

Managers need to:

3/4 Actively encourage and foster a safety culture, in which safe work is unambiguosly praised and unsafe "shortcuts" are discouraged.

3/4 Be aware of the potential for accidents and the consequences to the persons as well as for the company. Training should provide full knowledge of the consequences of accidents, illustrated with pictures of radiation effects, in order to instil awareness and a cautious attitude.

3/4 Implement a radiation protection programme, in which safety measures are based on the principle of defence in depth. The programme should include requirements to ensure that: radiography work is assigned only to fully qualified staff, procedures are followed, supervision is provided, emergency procedures/equipment are available and rehearsals are performed regularly, personal monitors and survey meters are used appropriately and that all equipment is correctly maintained and tested regularly.

3/4 Ensure that the safety layers remain effective over time by providing appropriate resources and supervision, including carrying out internal audits/inspections.

Regulatory control

At the application stage, licensees must be able to demonstrate that managers, radiographers and radiation protection officers are fully aware of the potential for accidents and their consequences. Regulatory Authorities can actively contribute to this awareness by disseminating information on accidents involving radiography sources, including pictures of radiation effects. Also, the Regulatory Authority should require that national training programmes for radiographers and radiation protection officers include a module on accidents and their consequences.

Not only should radioactive sources be subject to regulatory control but also the radiography devices. Licensees must ensure that there is technical compatibility between source assembly, radiography device, cables and guide tube.

When the Regulatory Authority is considering a license application, acceptability should be based on the provision of sufficient defence-in-depth in accordance with systematic safety assessments, such as the fault tree given in (14). Regulatory authorities should be aware, however, that the likelihood of an accident increases significantly if layers of safety are lost or are not maintained over time. For this purpose, when evaluating an application for a license the licensing officers should keep in mind key questions, for example:

- What is the policy for using a survey meter and other safety related equipment ?
- If a survey meter or other safety equipment becomes inoperable whilst on-site what is the radiographer expected to do ?
- What is the policy on maintenance ?
- What are the provisions for supervising the work ?
- What is the policy on initial and continuing training ?

If licensees cannot successfully answer these questions at the initial stage it is likely that, over time, radiography work will be done with reduced layers of safety until an accident occurs.

Industrial radiography should be assigned high priority in terms of frequency of inspections and expertise of inspectors. Site inspections targeted at detecting signs of degradation of safety should go beyond formal compliance checks, i.e., visual oversight of work and safety systems, availability and correct function and proper use of survey meters, observation of working practices, interviews with radiographers and checking that safety procedures are respected and emergency procedures rehearsed. Regulatory authorities should carefully plan a strategy for site inspections that includes the provision of unannounced inspections, and inspections during night-time operations.

IRRADIATORS FOR INDUSTRIAL AND RESEARCH APPLICATIONS

This section considers accidents related to gamma irradiators and electron accelerator facilities.

Workers have been exposed to high intensity non-collimated radiation fields inside gamma irradiation facilities. This has resulted in very high whole body doses that are usually fatal, as shown in table 2 (2,11,12,13). Accidental exposure of workers to collimated radiation beams from electron accelerators has lead to partial exposure of the body, resulting in severe injuries that often require the amputation of limbs.

Defence in depth in the design of irradiator facilities

Due to the presence of extremely intense radiation fields, defence in depth for irradiators is largely implemented through physical means (interlocks and barriers), which provide a low probability of exposure. ICRP publication 76 (14) recommends that designs be constrained by an occupational reference risk of $2{\cdot}10^{-4}$ in a year, which, assuming 200 entries per year, corresponds to a failure probability of 10^{-6} per entry. This implies that accidental entry in the irradiation chamber must be prevented by several layers of safety. In practice a combination of technical interlocks and procedures are normally used. In a simplified manner, doors have at least two redundant, independent and different-type interlocks (one linked to the source position and another linked to a radiation monitor) and procedures require that a survey meter is used every time the irradiation room is entered. An additional layer of safety can be provided by ensuring that the key to the door of the irradiation room is the same key used to operate the control console, plus a survey meter can be physically attached to this key. These measure ensure that the source cannot be exposed whilst someone is in the irradiation room, and at the same time, that the operator does not forget to take the survey meter when entering the room.

Even when all of these safety systems are in place there is still the possibility of human intervention, such as an operator ignoring or misinterpreting an alarm. It is important that this fact is not ignored. For example, the safety assessments presented in (14) suggest a probability of 0.01 that a trained operator will ignore the reading of a survey meter or an alarm. This probability can be drastically increased if: training is not effective, the awareness of danger has reduced with time, work pressure is high, or if there is an ongoing mistrust of warning signals. These are common factors in most of the reported accidents.

TABLE 1. LIST OF ACCIDENTS AT INDUSTRIAL IRRADIATION FACILITIES

Year	Place	Type of facility	Outcome	Estimated dose	Remarks
1965	Illinois, USA	Accelerator	One person, Amputation of leg and arm	290-2400 Gy	
1967	Pittsgurg, USA	Accelerator	3 persons irradiated, one of whom required the amputation of both	1-6 Gy whole body, and one patient up to 5.9 Gy dose to the hands	Failure of interlocks
1974	New Jersey, USA	Gamma	1 person, Acute radiation syndrome	~4 Gy	Short exposure 5-10 s, because he realized that the source was exposed and left immediately
1975	Stimos, Italy	Gamma	1 fatality	~12 Gy	
1977	New Jersey, USA		1 person, Acute syndrome	~2 Gy	Short exposure, because he realized that the source was exposed and left immediately
1982	Kjeller, Norwat	Gamma	1 fatality	~22 Gy	
1989	San Salvador, El Salvador	Gamma	1 fatality	~8 Gy	Two other persons with whole body doses 2.9-3.7 Gy and
1990	Soreq, Israel	Gamma	1 fatality	~10-20 Gy	
1991	Nesvizh, Belarus	Gamma	1 fatality	~11 Gy	
1991	Hanoi, Viet Nam	Accelerator	Amputation of one hand and fingers of the other	~10-50 Gy	
1991	Maryland	Accelerator	Amputation of four fingers of each hand	~55 Gy	
1991	Forbach, France	Accelerator	Skin lesions	~40 Gy	

Reasons why irradiator accidents occur

It is important to have a close look at the sequence of actions or omissions leading to an irradiation accident. In one reported accident, for example, a jam occurred in the transport mechanism of an irradiator. The "source down " signal indicated that the source was in the shielded position, but the gamma alarm indicated the contrary. From the two conflicting signals, the operator decided to believe that the "source down" signal was correct and that the gamma alarm signal was false. This decision implies such a biased opinion, that from then onwards any evidence against the decision was ignored or removed without hesitation (the operator had to disconnect the monitor cable and simulate background radiation to unlock the door) and little attention was paid to other means that could confirm the alarm, such as the use of a survey meter. All this was done in violation of the local procedures. The wrong perception was favoured by the fact that previously the "source down" signal had never failed whereas the gamma alarm had given a false reading once before. So the wrong decision was readily rationalized and supported by part of the evidence.

Other factors such as overconfidence by the operator or a wish to resume operations may also bias decisions and lead to the deliberate removal of multiple layers of safety (e.g. bypassing interlocks or ignoring procedures and warning signals).

Measures to increase safety in light of the lessons learned

Managerial measures

As long as technological safety barriers remain effective, the probability of an accident with an irradiator is extremely low, in the order of 10^{-6} per entry. The operational safety programme should ensure that all safety interlocks remain effective over time, so that the overall probability is not increased by the removal of any of the layers. For irradiators, maintenance of these systems and trust in them is essential to the behaviour of staff. For these reasons, the programme needs to specifically address:

3/4 All false alarms must be immediatley reported to the radiation protection officer who should investigate the problem and take prompt action to rectify the fault. This arrangement should avoid developing a culture of ignoring alarms and a "de facto" policy of tricks and unsafe habits aimined at resuming operations. The overall philosphy should include a prudent approach, trusting interlocks, alarms and warning signals.

3/4 Operators must be trained how to react in the case of conflicting warning signals. Written procedures should clearly prohibit the ignoring of alarms.

3/4 Safety devices must be maintained and spares of essential components should be readily available to ensure that the irradiator is not operated with reduced layers of safety. For example, if a radiation monitor needs to be sent for repair, a spare must be made available as it is unlikely that the facility would shut down until the monitor was returned. Therefore, provisions to deal with these situations should be carefully considered in advance. In two of the reported accidents, defence in depth was drastically reduced by allowing operations to continue with only one of the two door interlocks, namely the one controlled by the radiation monitor, which was sent for repair months before (Norway) or was non-existent for years (El Salvador). Spare parts that can be obtained in a few hours in a developed country may entail weeks of waiting in a developing country, unless specific provisions are made. This problem is also applicable to the availability of expertise for repairs and maintenance.

The recommendations given earlier for industrial radiography, with respect to illustrating the consequences with pictures for training purposes, praising safe work rather that production, and close supervision with the objective of detecting early signs of degradation of safety, are also valid for irradiators.

Licensing and inspection

The recommendations given for industrial radiography with respect to licensing and inspection procedures are also applicable to irradiators. At the application stage the following issues should be addressed:

- What are the rules in case of conflicting signals?
- Who is responsible for arranging maintenance and repairs ?
- What is the policy with regard to spare monitors or other devices?
- What is the operator expected to do when there is a false alarm?
- Which supervisory measures and policy statements are in place to ensure sufficient contact between th operator and radiation protection officer (RPO) to detect the early failure of safety systems, unauthorised tampering of safety systems, or failure to report and/or record a safety event?

RADIOTHERAPY

A summary of major accidents which have occurred in external beam radiotherapy and brachytherapy is given in Table 2. Based on the analysis of the causes and main contributing factors, the most important deficiencies, common to the majority of accidents, have been identified.

The potential for an accident in radiotherapy

From the point of view of safety, radiotherapy is a special application of radiation because:

3/4 humans are deliberately placed in very intense radiation beams (external beam therapy), or sources are placed in direct contact with tissue (brachytherapy) with the intention of delivering very high localised doses (20-75 Gy),

3/4 doses significantly below that prescribed can have severe consequences to the patient and may constitute an accident,

3/4 a radiotherapy treatment, from prescription to delivery is a very complex process. It involves many professionals, a large number of steps and, in the case of external beam therapy 20 to 40 treatment sessions with many variable parameters. A radiotherapy technologist may be required to treat some 50 patients a day, for which the parameters are similar and yet different from one patient to the next, often with personalized ancillary devices.

Because of this complexity of equipment, techniques and procedures, there is considerable scope for errors and mistakes and it may not be possible to compensate for an error in under or over exposure.

Causes and contributing factors to accidents in radiotherapy

The reported accidents with the most severe consequences were those related to the incorrect calibration of external beam equipment or brachytherapy sources. A single mistake in calibration will affect all the patients treated until the error is discovered, i.e., it may involve a very large number of patients, as is shown in table 2. This type of accident is normally caused by poor education and training of radiotherapy medical physicists and by a lack of quality assurance (and therefore reduced defence in depth) which allowed the error to remain undetected.

Insufficient training of medical physicists, medical doctors, radiotherapy technologists and brachytherapy nurses is often a contributory cause of accidents. Maintenance staff, not understanding the implication of mis-adjustments may also trigger severe accidents, such as the one in Spain (table 2). This accident resulted in devastating consequences to many patients when, following maintenance, the equipment was put back into use for treatment without verification and acceptance testing.

TABLE 2. MAJOR REPORTED ACCIDENTS INVOLVING RADIOTHERAPY PATIENTS

Country	**Year**	**No of patients affected**	**Causes and main contributing factors**
USA	1974-76	426	Co-60 dose calculations based on erroneous decay chart (varying overdoses) No independent verification of decay charts and dose calculations More than two years without beam measurements Physics manpower and attention shifted to other tasks, such as a new accelerator
Germany	1986-87	86	Co-60 dose calculations based on erroneous dose tables (varying overdoses) No independent determination of the dose rate
UK	1988	207	Error in the calibration of a Co-60 therapy unit (25% overdose) No independent calibration of the beam
UK	1988-89	22	Error in the identification of Cs-137 brachytherapy sources (-20 to +10% dosimetry errors) No independent determination of source strength
Spain	1990	27 (18 deaths from radiation)	Error in the maintenance of a clinical linear accelerator. Procedures for transferring machine from and to maintenance (informing physicists) not followed. Conflicting signals and displays ignored Procedures for periodic beam verifications (QA) not implemented Overdosage ranging from 200% to 700%
UK	1982-91	nearly 1,000	Inappropriate commissioning of a computerized Treatment Planning System (5-30% underdosage) No written procedures for commissioning and use
USA	1992	1 (death from radiation)	Brachytherapy source (High Dose Rate) left inside the patient. Source dislodged from equipment Conflicting monitor signals and displays ignored
Costa Rica	1996	115 (at least 17 deaths from radiation)	Error in calculation during the calibration of Co-60 therapy unit Lack of independent calibration and of QA Recommendations from an external audit ignored Overdosage about 60%

The absence of written procedures and protocols for acceptance tests and the commissioning of new equipment has led to the use of incorrect values of basic parameters subsequently used for the treatment of patients. This problem applies not only irradiation equipment but also, very importantly, to treatment planning systems, such as the accident involving underdosage of nearly 1,000 patients (see table 2). Underdosages are usually more difficult to detect clinically than overdosages, especially if the dose deviation is only moderate so that the error stays undiscovered very long time, long after the treatment has been completed, and tumour recurrence has already appeared.

Change of personnel, without a formal transfer of information relevant to calibration and treatment planning, was also among the causes of many reported accidents.

A frequent cause of accidents was the misunderstanding of a treatment prescription, of a treatment plan, or of data related to the identification of patients. These cases can be considered to be due to ineffective procedures for communication and documentation. Treatment preparation and delivery requires a high degree of concentration which may be difficult to maintain in a noisy environment and in conditions of a heavy workload.

A major problem area in radiotherapy, that often does not receive enough attention, is maintenance. This problem tends to be more acute in developing countries where there may be a lack of national maintenance organizations and spare parts can be difficult to obtain, leading to the use of equipment in an unsafe condition in order to avoid disruption to the patient's treatment.

Looking at the factors contributing to the major accidents in table 2, it becomes apparent that in all cases, either a quality assurance programme was not in place or some verifications were omitted. In many of the accidents, there was a combination of causes: a deficient training in radiotherapy physics was combined with lack of procedures, and absence of supervision. A combination of causes clearly indicates an ineffective management which allowed patients to be treated in the absence of essential institutional policy and provisions, such as a quality assurance programme.

Measures to increase safety in light of the lessons learned

Given the complexity of radiotherapy and its sensitivity to errors and mistakes, nothing should be left to chance, but rather, a structured and systematic approach is needed. Licensing of a radiotherapy department should be conditional on a comprehensive quality assurance programme being in place. The system should include, not only the traditional technical and physical aspects, but also embrace treatment prescription, planning and delivery, as well as the organization of the radiotherapy department, maintenance of radiotherapy equipment and the staff qualifications and training, as well as auditing provisions.

Once the programme is in place and the facility has been licensed, as indicated above for industrial radiography and irradiators, the major is challenge to maintain the level of safety over time, which means looking at indicators of slow degradation. For this purpose, inspectors should not only look for formal compliance, but also for early warnings of potential problems.

ACCIDENTS RELATED TO LOSS OF CONTROL OF SOURCES

Sources that become accessible to people who are not familiar with radiation effects and radiation sources pose a major threat. Table 3 gives a list of reported accidents with such sources, which resulted in fatalities and table 4 gives a list or reported accidents resulting in major injuries (11,12,1316). Tables 3 and 4 also include accidents involving large-scale contamination (Goiania (Brazil) and Ciudad Juárez (Mexico)).

TABLE 3. LOSS OF SOURCE CONTROL: DEATHS OF MEMBERS OF THE PUBLIC

Year	Place	Radionuclide	Source from	Estimated dose	Number of deaths	Remarks
1962	Mexico City, Mexico	Co-60	Industrial radiography	9.9-52 Gy	4	
1963	China	Co-60	Industrial irradiator	0.2-80 Gy	2	Source taken home from a burial place (waste repository)
1984	Morocco	Ir-192	Industrial radiography	Unknown	8	loss of control of source;(failure to control retraction to shielding)
1987	Goiania, Brazil	Cs-137	Medical teletherapy	Up to 7 Gy ext and int	4	Radiation unit with source unsecured after decommissioning
1992	China	Co-60	Industrial irradiator	.25-10 Gy local	3	Source taken home from an irradiator during decommissioning
1994	Tammiku, Estonia	Cs-137	Waste repository	4 Gy whole body, 1800 local	1	loss of control of source; unsecured waste storage
1997	Georgia	Co-60	Medical teletherapy	Unknown	1	Source about to be returned; unsecured near a station

As both tables show, mobile radiography sources are the most important contributor to this type of accident, accounting for the largest number of accidents and the largest number of fatalities and severe injuries. The typical scenario was a radiography source that dropped from the radiography device and was placed in a person's pocket. In many of these accidents, the source was dropped at the radiography site, and was picked up by a construction worker who was not associated with the use of the source and therefore not aware of the potential hazard. Accidents have also occurred when sources have fallen out of unlocked exposure devices during transportation and resulted in the exposure of several members of the public. This "source in the pocket" scenario has led to fatalities and to high localised radiation doses to limbs, resulting in amputation or major surgery (skin grafting). An additional scenario, as in the Algerian case, was a "source in the mouth" of a child.

It should be noted that in one of the incidents with industrial radiography sources, two canteen workers found a source and saw the danger marking on it and reported the discovery. The dose to the whole body was less than 0.2 Sv and the dose to the fingers was estimated to be about 8 Sv. Thus, recognizing the source as something dangerous avoided more severe exposures.

The second contributor to severe accidents is medical teletherapy sources. Their high activity gives the potential for irradiating a large number of people and their physical and chemical form (thousands of pellets in the case of Co-60, or salt in the case or Cs-137) can lead to large-scale contamination, as in Goiania (Brazil) and Ciudad Juárez (Mexico). Sources involved in these accidents were either in the therapy device or in the transport container waiting for a decision on disposal or transfer.

TABLE 4: LOSS OF CONTROL OF SOURCES: SEVERE INJURIES

Year	Place	Radionuclide	Activity	Source from	Dose	Consequences
1968	La Plata, Argentina	Cs-137	Unknown	Industrial radiography	Local dose from	Amputation of both legs, permanent sterility
1971	Chiba, Japan	Ir-192	5.26 Ci	Industrial radiography	From 0.15 to 1.3 Gy whole body	Six persons (construction workers) exposed, three of them with acute syndrome
1978	Algeria	Ir-192	25 Ci	Industrial radiography	1 to 1.4 Gy whole body, 25 Gy skin dose	Irradiation of a family, including two children, amputation of fingers, grafting and flap at the buttock, injury in the mouth, four other patients suffered acute syndrome
1979	Los Angeles, USA	Ir-192	28 Ci	Industrial radiography		11 persons exposed, one of them needed skin drafting at the buttock,
1977		Ir-192	260 GBq (7Ci)	Industrial radiography	Up to 10 Gy to fingers and more than 50 Gy to the skin on chest wall	Amputation of fingers in both hands, skin grafting in chest wall
1978		Ir-192	300 GBq (8 Ci	Industrial radiography	10 Gy local	18 cm x 18 cm injury on the chest wall
1983	Ciudad Juárez, Mexico	Co-60	15 TBq	Teletherapy	3.0 to 7.0 Gy (five persons) and from 0.25 to 3.0 Gy (75 persons)	Acute syndrome
1999	Yanango, Perú	Ir-192		Industrial radiography	Local dose from	Amputation of leg
1999	Istanbul, Turkey	Co-60		Teletherapy	From	10 persons with acute syndrome
1996	Lilo, Georgia	Cs-137	Four sources, 150 GBq (4 Ci) each	Sources for exercises by the army, were later abandoned	From	Injuries
1996	Iran			Industrial radiography	From	11 people with radiation injuries

In many cases, teletherapy sources were purchased before regulatory control was in place and no provisions were made for their return or disposal. This has resulted in disused teletherapy sources being stored (normally in the irradiation head of the machine) in the premises of hospitals and clinics that are no longer in operation. IAEA missions of assistance to some countries have detected sources which were often readily accessible, with no warning labels. It can be therefore be assumed that throughout the world there are a considerable number of teletherapy sources waiting for a decision on source disposal or transfer, and that the security conditions of these sources is uncertain. Given their high initial activity and the half live of the radionuclides, even sources that are 20-25 years old may still have an activity of the order of 1 to 4 TBq (20 to 100 Ci).

Given the presence of physical barriers and strict control of access associated with gamma irradiators, it would be expected that the loss of control of such sources is unlikely. However, the two accidents in China (table 3) show that this cannot be ruled out, especially during decommissioning.

An increasing number of accidents involving the melting of radioactive sources has raised concern about sources found in scrap metal. The Mexico case involving a teletherapy source is an example of disastrous consequences, both in human exposure and financial cost. However, sources found in scrap may stem from other applications, notably gauging devices, and include Cs-137, Co-60, Am-241 (17,18,19). Most of these devices are robust and intrinsically safe during normal operations, needing minimal training to operate, and very little maintenance. They generally do not need close regulatory control while in operation. After years of operation, however, warning labels may disappear and the fact that the device contains a radioactive source may be completely forgotten. When a production line is modified or closed down there is the potential for these devices to enter the public domain in an uncontrolled manner (17, 18).

Although accidents with such devices have not been reported to have caused deaths or serious injuries, they can not be ignored due to the fact that the sources could enter the public domain. Given that the activities range from MBq up to a few tens of GBq, contact with these sources could cause injuries, especially if the device is dismantled and source was to be placed in a persons pocket.

Measures to increase safety in light of the lessons learned

The simple knowledge of these facts should lead to straightforward regulatory actions to prevent major accidents arising from loss of control of sources (such as the examples in the tables). Since governmental resources are limited, priorities need to be assigned. The first priority should be the verification that sources in industrial radiography, irradiators and medical teletherapy are under control - if they are not then control must be regained. In developing countries, the small number of irradiators and medical teletherapy facilities should make this control relatively straightforward.

The control of industrial radiography sources is, however, complicated by the fact that mobile sources may be lost any time during operation or transport. Measures to prevent this from occurring are given in the section on industrial radiography. The majority of mobile radiography devices house sources of Ir-192, of the order of TBq (a few tens of Ci). Since irdium-192 has a relatively short half-life, sources older than two years will not pose a significant threat and therefore priority should focus on iridium sources lost in recent months and on any Cs-137 and Co-60 sources.

Search for sources lost in the past could be made by inspections of the records of the facilities and through interviews with managers and radiographers.

Other applications, such as gauging devices, which are generally not subject to frequent inspections, still need to be accounted for in order to avoid their becoming forgotten over time and finally becoming orphan sources.

CONCLUSIONS AND RECOMMENDATIONS

History shows that accidents rarely occur due to a single equipment failure or a single human error. In most accident cases there was a combination of elements such as: a) no prior safety assessment b) poor education and lack of training, especially when faced with an unusual situation, c) management pressure (real or perceived) to continue work even when safety systems were inoperable or deficient, d) poor maintenance programme or none at all, leading to a reduction in layers of safety, and non-investigated false alarms leading to persons ignoring warning systems. This combination of failures points to a lack of managerial commitment to safety.

Managerial commitment has to be stated in a written policy (which praises safe work and discourages shortcuts) and in a radiation protection programme which involves: assigning the use of sources and devices only to fully trained workers, implementing procedures and checklists for normal operation, procedures for contingency, and providing safety equipment, survey meters, maintenance and close supervision.

Regulatory authorities should prioritize their resources and devote a high level of control to those practices with a high potential for accidents i.e.: Industrial radiography, industrial and research irradiators, and radiotherapy facilities.

At the licensing stage, regulatory authorities should verify that managers are fully aware of the potential for accidents and their consequences and that this awareness is reflected in an unambiguous policy and appropriate supervision. Regulatory authorities can actively contribute to this awareness by disseminating information on real accidents, case histories and pictures of the effects of radiation from accidents.

Regulatory control of training programmes is needed for radiation protection officers and those workers in high risk practices, such as the ones discussed in this paper.

Not only radioactive sources should be subject to authorization but also radiation equipment and devices. Technical compatibility between sources and devices (for example radiography devices) is an essential part of safety.

Verification of formal compliance with regulatory requirements is necessary, but not sufficient: inspections should be targeted at detecting early warnings of degradation of safety, especially of the elements identified as critical in a systematic safety assessment (14). Early indicators are the attitude of staff with respect to safety, their understanding of their responsibilities, acquaintance with safety procedures, including emergency procedures; maintenance, (especially if repairs take a long time or whether unsafe provisional repairs are made to keep equipment operational); other signs of degradation are the replacement of trained staff by less trained staff either temporarily or permanently.

Preventing loss of source control

A specific item in the regulatory system should be the prevention of loss of control of sources. Also in this item, priorities should be given to practices with the potential to cause major accidents with "orphan" sources, such as industrial radiography and radiotherapy; a second priority should be given to sources from other practices such as nuclear gauges, which are relatively safe in operation, are not subject to frequent inspection and tend to be forgotten and to become orphan.

An obligation to notify of any temporary or permanent disuse of sources or their removal from operational use, would allow the regulatory authority to perform a closer follow up of all sources no longer in use and prevent loss of control of these sources. A national programme to search for possible lost sources should be implemented. This should include sources that existed before regulatory control was exercised.

Reporting of unusual radiation events and lost and found sources.

National regulatory requirements should include an obligation to report missing and found sources and abnormal events with radiation sources. If relevant information becomes internationally available and lessons are regularly disseminated all countries would benefit. Loss of control of sources has a world-wide dimension that needs international undertakings to increase international commitment of governments to control sources within their territories.

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