The Radiological Accident in Ventanilla

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THE RADIOLOGICAL ACCIDENT IN VENTANILLA

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The Agency's Statute was approved on 23 October 1956 by the Conference on the Statute of the IAEA held at United Nations Headquarters, New York; it entered into force on 29 July 1957. The Headquarters of the Agency are situated in Vienna. Its principal objective is "to accelerate and enlarge the contribution of atomic energy to peace, health and prosperity throughout the world".

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FOREWORD

Radioactive material can offer a wide range of benefits in the areas of medicine, research and industry throughout the world. Precautions, however, are necessary to limit the exposure of people to the radiation that is emitted. Where the activity of radioactive sources is substantial, as in the case of radiotherapy or industrial radiography sources, great care is necessary to prevent accidents that could have severe consequences. Despite the precautions taken, serious accidents involving radiation sources do occur, albeit infrequently.

A serious radiological accident occurred in Ventanilla, Peru, in February 2014. Three workers were exposed when they were conducting non-destructive testing on pipe joint welds in a chemical plant, using industrial radiography with a radioactive source of ^{192}Ir. The most exposed worker developed a severe and complex local radiation injury in the area surrounding the upper left thigh and anatomical projection of the left hip. Under the Convention on Assistance in the Case of a Nuclear Accident or Radiological Emergency, the Peruvian authorities requested assistance from the IAEA for medical support in the evaluation and treatment of the worker, and later for additional specialized follow-up treatment. The treatment of the worker is an example of successful international collaboration and assistance coordinated by the IAEA.

The IAEA thanks the experts involved in the response to this accident, especially those who participated in the IAEA Assistance Missions, provided advice on dose assessment or shared in the medical management of the most exposed worker: J.F. Bottolier-Depois of the Institute for Radiological Protection and Nuclear Safety, France; M. DiGiorgio of the Nuclear Regulatory Authority, Argentina; A. Lachos of the National Institute of Neoplastic Diseases, Peru; and S. Petrick of the Peruvian Institute of Nuclear Energy.

The IAEA is grateful to the Government of Brazil for offering to treat one of the workers involved in the accident, the Government of France for its assistance in the medical treatment of the worker, the Government of Argentina for the support with biodosimetry and the Government of Peru for its agreement to help disseminate, through this publication, the lessons identified from this accident.

The IAEA officer responsible for the preparation of this publication was E.D. Herrera Reyes of the IAEA's Incident and Emergency Centre.

EDITORIAL NOTE

CONTENTS

SUMMARY

This publication provides information for Member States about the national actions taken and the international assistance provided by the IAEA in the management of the radiological accident in Ventanilla, Peru, in 2014. It notes that, even though radiological accidents are uncommon, industrial radiography remains one of the most frequent contributors to such accidents. It also describes the responses to the accident at the national level, as well as the international assistance provided by the IAEA under the Convention on Assistance in the Case of a Nuclear Accident or Radiological Emergency (hereinafter referred to as the Assistance Convention) [1].

The radiological accident occurred in the early morning of 14 February 2014 in a chemical plant. A company was conducting non-destructive testing (NDT) on pipe joints using industrial radiography with a radioactive source of ^{192}Ir (specifically, gammagraphy). The radioactive source had a calculated activity of 1220 GBq (33 Ci) on the day of the accident. The work was being carried out 12 m above the ground floor and involved a series of actions performed by three workers.

The most exposed worker, referred to as 'Worker 1' in this publication, hung the equipment's guide tube around his neck, with its distal part and the collimator inside his left vest pocket. For unknown reasons, the pigtail containing the radioactive source did not return to the safety position on the shielded radiography equipment, but instead the source remained in the collimator, which was located in the distal part of the guide tube. Although the workers were equipped with personal dosimeters that sounded an alarm, they did not hear this alarm, reportedly due to the noisy working environment. As with other radiological accidents in the past, there are some uncertainties and inconsistencies in the workers' descriptions of the event, especially related to the exact time and duration of the exposure, the distance from the skin to the collimator, and other data that were later estimated on the basis of calculations and the clinical evolution of Worker 1.

According to the information provided by the workers, shortly after finishing work on the last pipe joints, Worker 1 left the noisy work area and then heard the alarm. The workers performed a survey with a Geiger–Müller detector. They realized that the source was not in the safety position, but had remained unshielded in the guide tube. They moved the source back into the safety position and informed their manager of the accident. A medical evaluation was arranged for them at a primary care centre, and Worker 1 was hospitalized for further evaluation.

The whole body absorbed dose estimated for Worker 1 was less than 1 Gy. The development of acute radiation syndrome (ARS) was therefore not expected,

but the absorbed dose did cause a very severe local radiation injury (LRI) to the area surrounding the upper left thigh and anatomical projection of the left hip, which evolved into tissular radionecrosis.

On 24 April 2014, the Peruvian authorities requested assistance from the IAEA in the medical assessment and treatment of Worker 1, under the Assistance Convention [1]. On 28 April 2014, the IAEA carried out its first assistance mission to Peru through the mechanism of the IAEA Response and Assistance Network (RANET), with experts from Brazil and France and a biodosimetry assessment from Argentina. The objective of the mission was to respond to the Government of Peru's request for help in dealing with this radiological emergency by means of the assessment and treatment of Worker 1.

On 9 June 2014, the Peruvian authorities again requested the assistance of the IAEA to enable the specific medical treatment of Worker 1 under the Assistance Convention [1]. The second assistance mission started on 21 July 2014, transferring Worker 1 from Peru to Brazil for treatment. The treatment was performed in Brazil with the help, through RANET, of experts from France who were cooperating with experts from Brazil and the IAEA. The treatment of the patient included dosimetry guided surgery, administration of mesenchymal stem cell (MSC) therapy, physiotherapy, hyperbaric oxygen therapy, nursing care and nutritional and psychological support, through a multidisciplinary approach. On 6 November 2014, Worker 1 was discharged and returned in good health to Peru, where medical follow-up and treatment continued as necessary.

The main factor contributing to the accident was the lack of safety and radiation protection procedures: specifically, the failure of the pigtail to return to the safety position in the radiography equipment. Other factors that contributed to the accident included the inadequate use of portable radiation detector survey meters and, possibly, inadequate use of personal alarm dosimeters.

The successful treatment of Worker 1 was achieved as a result of the significant efforts of professionals, institutions and organizations from Argentina, Brazil, France and Peru. There was a complete integration of medical efforts and mobilization of resources, coordinated by the IAEA.

As in the case of a 2013 radiological accident in Chilca, in which French experts provided assistance to medical professionals in Chile [2], the cooperation between Brazilian and French medical specialists is another excellent example of the transfer of knowledge within the international medical community. This was demonstrated through the culture of MSCs, their use as adjuvant therapy for this LRI and the dosimetry guided surgery approach used in the Ventanilla accident.

1. INTRODUCTION

1.1. BACKGROUND

This publication describes the radiological accident that occurred in Ventanilla, Peru, in February 2014, which resulted in the exposure of three workers, one of whom developed a severe LRI. It provides information about the circumstances of the accident and the responses at the national level, as well as the international assistance provided by the IAEA under the Assistance Convention [1].

Paragraph 5.93 of IAEA Safety Standards Series No. GSR Part 7, Preparedness and Response for a Nuclear or Radiological Emergency [3] states:

> "Governments and international organizations shall put in place and shall maintain arrangements to respond in a timely manner to a request made by a State, in accordance with established mechanisms and respective mandates, for assistance in preparedness and response for a nuclear or radiological emergency."

The response to this radiological accident provides a good example of international coordination under the auspices of the IAEA and the effectiveness of the mechanism established in compliance with the specific requirements of GSR Part 7 [3]. This radiological accident and similar previous events have demonstrated that failure to follow safety procedures in industrial radiography may result in serious injuries to workers and the public, or even in the death of overexposed individuals [2, 4].

1.2. OBJECTIVE

The objective of this publication is to compile and disseminate information on the radiological accident in Ventanilla. This information and the lessons identified from the accident — including its circumstances, its notification, the medical response and dose assessment, and the response at the national and international levels — are key elements that should encourage States to analyse their response procedures for radiological emergencies, and to identify any necessary actions to be implemented in order to avoid or prevent potential similar accidents.

The intended audience for this publication includes Member States' competent authorities, regulatory bodies, emergency response planners, medical and other healthcare professionals, as well as companies and workers involved in industrial radiography and other applications of ionizing radiation.

1.3. SCOPE

This publication addresses the chronology of the events and circumstances of the radiological accident in Ventanilla in February 2014. The information includes a detailed description of the international assistance provided by the IAEA, the health consequences, the dose assessment and the medical management of the affected individual. Guidance provided here, describing good practices, represents expert opinion but does not constitute recommendations made on the basis of a consensus of Member States.

1.4. STRUCTURE

This publication is based on official documents, information provided by the workers and authorities involved, and the clinical manifestation of the most exposed worker. It consists of a chronological description of events, starting in Section 2 with details on the circumstances of the accident, including information about the radioactive source and the notification of the accident. Section 3 covers the response at the national level, the initial dose assessment and the first medical actions taken, while Section 4 provides information related to the coordination of the response at the international level. Section 5 describes the dose assessment of the workers, including medical, biodosimetry and other retrospective methods applied to establish the absorbed dose of Worker 1. Section 6 discusses the medical considerations and the clinical evolution of Worker 1. A summary of the findings and conclusions concerning the management of the Ventanilla radiological accident, and the lessons to be identified from it, are provided in Sections 7 and 8, respectively.

2. THE ACCIDENT

2.1. DESCRIPTION

The radiological accident took place in a chemical plant that was under construction and situated in the district of Ventanilla, Peru, at 02:30 Peru Time

(PET)[1] on 14 February 2014. An industrial radiography company that had a valid operating licence was subcontracted by a service provider to carry out NDT at the chemical plant. The operation was carried out by three workers (identified as Worker 1, Worker 2 and Worker 3) who had valid individual licences for operating the radiography equipment. Two of the workers had also been licensed as radiation protection officers, although these licences had expired in 2013 [5].

The NDT involved industrial radiography (gammagraphy) using ^{192}Ir with an activity of 1220 GBq at the time of the accident. The specific job consisted of performing radiographs of different welded joints of pipes in the plant. Of the 15 joints to be tested, two were located at ground level and 13 at a height of approximately 12 m above the ground floor.

In order to complete the NDT in the time allotted, the workers organized their duties[2] as follows [6]:

— Worker 1 delimited the working areas, placed radiography films on the welded joints to be radiographed, fixed the position of the collimator, and moved the guide tubes and eventually the radiography equipment from one place to another.
— Worker 2 moved the radiography equipment from one place to another, initiated the exposure, monitored the duration of exposure and retracted the source using the remote control after the pre-established time had elapsed.
— Worker 3 placed the safety signs, identified the films, watched over the area at the moment of exposure and moved the radiography equipment.

To complete the assigned duties on the joints located above ground level, Worker 1 had to climb up a ladder onto various platforms to prepare the NDT, pull up the radiography equipment by a rope, put the film in place and fix the position of the collimator. Once the radiography equipment was set up, but before exposing the radioactive source to the films, Worker 1 had to climb down again to distance himself from the source and reduce his radiation exposure. When the irradiation of each joint was finished (three exposures per joint), Worker 1 disconnected the guide tube, pulled it out of the pipe towards himself and put it around his neck. For reasons still unknown, at one point during this repeated process, the pigtail with the radioactive source did not return to the safety position inside the shielded container, but remained in the distal part of the guide

[1] PET is five hours behind Universal Time Coordinated (UTC). Hereinafter, time references are made in PET.

[2] The duties described were compiled from the information provided by the workers during the first IAEA Assistance Mission.

tube connected to the collimator, which Worker 1 placed inside his vest pocket (as shown in Fig. 1).

Consequently, Worker 1 received a high local radiation dose to the area surrounding his upper left thigh and the anatomical projection of the left hip (referred to hereinafter as ‘left hip/upper thigh area’). All three workers wore personal dosimeters with sound alarms, but according to the information provided in their report to the authorities, the workers did not hear the alarm because of the noisy working environment. Walking to one of the last NDTs, from joint number 24 to joint number 39 (separated by a distance of about 25 m), Worker 1 was the first to hear the continuous sound of the personal dosimeter alarm.

When Worker 1 alerted his two colleagues, they also heard the alarm from their dosimeters and immediately initiated emergency procedures. Worker 1 requested Worker 2 and Worker 3 to get the emergency kit, the recovery container and the radiation monitor, which were located in the company van near the work site.

FIG. 1. Worker 1 showing the manner in which he placed the guide tube with the collimator into his vest pocket (photographs courtesy of IPEN [6]).

Once he received the recovery container, Worker 1 placed it over the collimator and the source was shielded for recovery. The workers then proceeded to retrieve the radioactive source, using tongs and portable shielding from the emergency kit. They connected the remote control to the source and retracted it back into its shielded safety position inside the radiography equipment. While all three workers were involved in the recovery of the source, the actual retrieval procedure was performed by Worker 2 and Worker 3, who completed it in approximately 3–5 min. The workers left the chemical plant at 03:25 on 14 February 2014.

The workers reported the event to their manager at 04:10 on 14 February 2014. The company initiated the notification process to the national authorities and arranged a primary medical evaluation for the three workers at the local San Gabriel Clinic (at 05:10 on 14 February 2014). After the medical evaluation, Worker 1 remained hospitalized for the following 72 hours. The other two workers were examined and the decision was taken to treat them as outpatients.

As in other radiological accidents, there were some uncertainties and inconsistencies in the workers' descriptions of the event, especially related to the exact time and duration of their exposure; the distance of the skin of Worker 1 from the collimator; the position of the collimator inside the vest pocket of Worker 1; and other data that were later estimated on the basis of calculations and the clinical evolution of Worker 1 (see Fig. 2).

2.2. THE DEVICE AND SOURCE INVOLVED

The device involved in the accident was a portable, lightweight source projector (camera) used for industrial applications of gamma radiography — a Sentinel Model 880 Delta, serial number D5188 [6]. It contained an ^{192}Ir source, Model T-5, serial number UJ1410, which had a certified activity of 3626 GBq as of 18 October 2013. On the day of the accident, the estimated activity was 1220 GBq [7]. The radiography equipment is shown in Fig. 3.

A collimator (see Fig. 4) is a radiation shield that is placed at the end of the guide tube to limit and direct the radiation beam to the dimensions required when the sealed source is moved into position for a radiographic exposure.

2.3. NOTIFICATION

The workers reported the accident to their manager at 04:10 on 14 February 2014. Twenty minutes later, by phone, the company initiated the notification process to the national authorities, the Technical Office of the National Authority

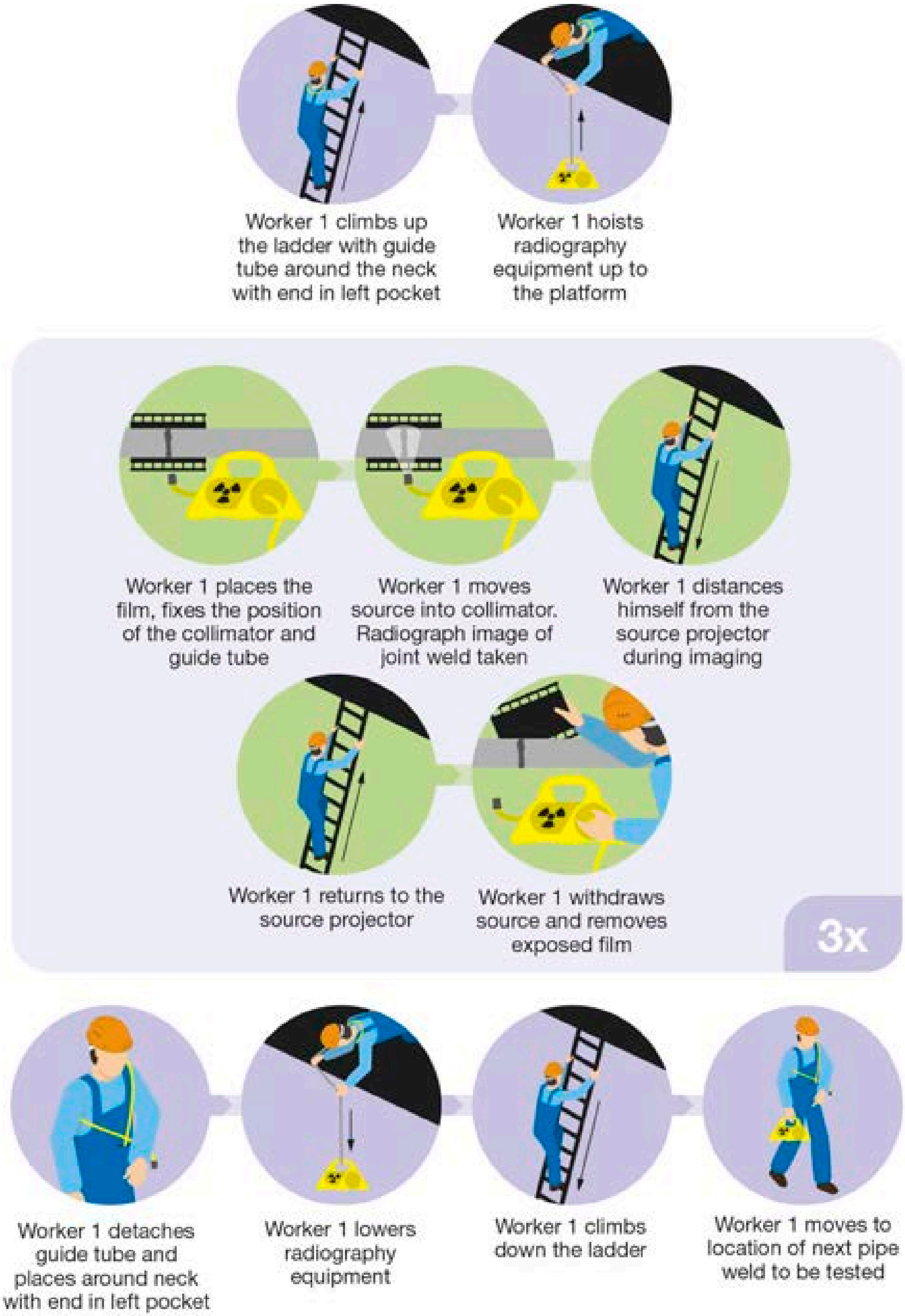

FIG. 2. Reconstruction of the accident on the premises of the chemical plant.

FIG. 3. The source projector (camera) model used in the accident [6].

FIG. 4. Parts of the radiography equipment and associated tools: yellow guide tube (left); connectors (centre); and collimator (right)[6].

(OTAN). The process was completed on the same day with the notification to the Peruvian Institute of Nuclear Energy (IPEN) [8]. These authorities initiated the first evaluation of the accident.

On 5 March 2014, the International Nuclear and Radiological Event (INES)[3] National Officer of Peru reported the radiological event to the IAEA as an INES event, using the IAEA Unified System for Information Exchange in Incidents and Emergencies (USIE)[4] [10]. Several weeks later, on 24 April 2014, the Permanent Mission of Peru to the IAEA officially requested from the IAEA the provision of assistance under the Assistance Convention [1].

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[3] INES was developed in 1990 (and has been updated several times since then) for the purpose of communicating the safety significance of events at nuclear installations [9].

[4] USIE is an IAEA web portal for the contact points of States Parties to the Assistance Convention [1] to exchange urgent information during nuclear and radiological incidents and emergencies, and for officially nominated INES National Officers to post information or events rated on INES.

3. RESPONSE AT THE NATIONAL LEVEL

3.1. INITIAL ACTIONS

The initial actions of the Peruvian national authorities consisted of the following:

— Gathering information from workers and people involved in the event;
— Conducting a reconstruction of the accident at the original location;
— Performing an evaluation and reaching a preliminary conclusion;
— Proceeding with a medical evaluation;
— Suspending the operation of the radiography firm;
— Issuing an official statement.

On Friday, 14 February 2014, two OTAN officers inspected the facilities of the radiography company, interviewed the involved workers and gathered information for a preliminary estimation of doses received by the workers, especially by Worker 1. In addition, medical specialists from IPEN and the National Institute of Neoplastic Diseases (INEN) performed an initial evaluation of Worker 1.

On Monday, 17 February 2014, IPEN officers, representatives of the company and the involved workers held a meeting to obtain further information and details about the accident, including the joints that were tested, the planned activities for that day and the work that had been carried out. They also considered the results of the dosimeter analysis [11].

The analysis, completed on 17 February 2014, of the personal optically stimulated luminescence dosimeters worn by the workers at the time of the accident showed the following effective doses [11, 12]:

— Worker 1: 62.65 mSv;
— Worker 2: 15.85 mSv;
— Worker 3: 17.00 mSv.

A reconstruction of the chronological events at the chemical plant where the accident had occurred was considered necessary, but at the beginning of their investigation OTAN officers did not obtain authorization from the management of the chemical plant to access the site. As a precautionary measure, the radiography company was asked to suspend operation until the causes of the accident had been determined and possible corrective measures could be taken.

3.2. RECONSTRUCTION OF THE ACCIDENT

On Friday, 21 February 2014, the OTAN officers were able to proceed with their regulatory duties and carry out the reconstruction of the accident, during which they were accompanied by the three workers involved [6].

The sequence of manoeuvres and actions (actions 1–9 are described later in this section) performed by Worker 1 during the early morning of the accident made it difficult to calculate the distance between the source and his body, as well as the duration and geometry of the exposure. The time and duration of the exposure, and the distance from the radioactive source were estimated from the work carried out at joint number 20. Because the last three radiography films were overexposed, a reconstruction of Worker 1's actions and measurement of the duration of these actions was necessary to better understand his exposure. The reconstruction of the scenario considered nine main actions executed by Worker 1 on the day of the accident (see also Fig. 2) [6].

3.2.1. Action 1: Ascending and descending the ladder

Worker 1 was performing NDT on a platform at a height of 12 m above the ground floor. For this, he would climb up a ladder, place the films and fix the position of the collimator at the pipe joint in question.

Once the radiography equipment was set up, and before exposing the films to the radioactive source, Worker 1 would climb down the ladder to distance himself from the source and reduce his radiation exposure. He repeated this process for each joint.

When the irradiation of each joint was finished (three exposures per joint), Worker 1 would disconnect the guide tube and hang it around his neck, placing the collimator in his left vest pocket, and climb down the ladder to go on to the next joint to be tested. To climb up and down from the platform, he wore a safety harness that limited his manoeuvres and the movement of the guide tube around his neck (see Fig. 5).

To measure the duration of each action, an operator from the NDT company who was not involved in the accident helped the authorities during the reconstruction. He was instructed to perform the different manoeuvres and actions as directed by Worker 1, bearing in mind the possibility of fatigue owing to the heavy workload at night.

The time that Worker 1 would have needed to climb up and down the platform was measured as follows:

— Time taken to climb up the ladder: 52.7 s;
— Time taken to climb down the ladder: 47.5 s.

FIG. 5. Left: Worker 3 (blue overalls) adjusting the safety harness on the operator (green overalls). Right: The operator climbing up the ladder according to the instructions given by Worker 1 (photographs courtesy of IPEN [6]).

Considering the inclined position of the worker while climbing up and down the ladder, it was estimated that the distance between the radioactive source and the skin surface of the worker's body (left flank) was on average approximately 6 cm.

3.2.2. Action 2: Moving the radiography equipment

To perform the radiography of a pipe joint, Worker 1 would hoist the radiography equipment to the platform using a rope prepared by Worker 3. Once the radiographs of that joint were finished, he would lower the radiography equipment. During these manoeuvres, Worker 1 would keep the guide tube in the position shown in Fig. 1. At the same time, Worker 3 would also carry out manoeuvres to raise and lower the radiography equipment to and from Worker 1, while Worker 1 stayed on the platform, as shown in Fig. 6.

FIG. 6. Worker 3 performs manoeuvres to raise and lower the radiography equipment while Worker 1 stays on top of the platform (photographs courtesy of IPEN [6]).

As Worker 1 would adopt an inclined position to handle the rope with the equipment, it was estimated that the collimator would have been about 8 cm from the skin of Worker 1 (left flank). This assumption was based on direct measurements and considerations concerning the weight of the collimator.

The time that it would have taken Worker 1 to raise and lower the radiography equipment, with the collimator in his left vest pocket, was measured as follows:

— Time taken to raise the radiography equipment: 19.0 s;
— Time taken to lower the radiography equipment: 37.0 s.

3.2.3. Action 3: Attaching and detaching the guide tubes

Another action to be considered in the estimated duration of the exposure of Worker 1 was the time used to attach and detach the guide tubes from the radiography equipment so that the equipment could be raised and lowered (Fig. 7). Worker 1 performed this manoeuvre with the guide tube around his neck and the collimator in his left vest pocket. According to Worker 1, these manoeuvres were carried out within approximately 60 s. The estimated distance between the collimator and the skin of Worker 1 (left flank) was approximately 8 cm.

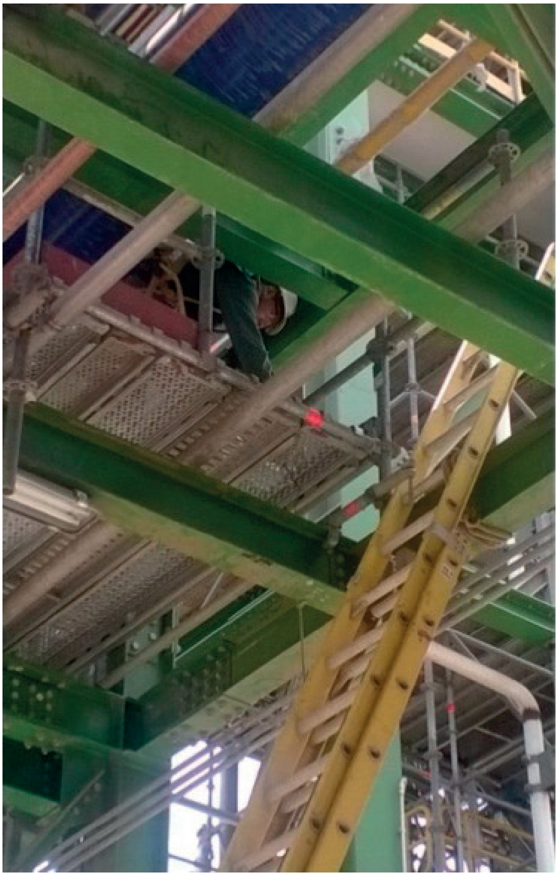

FIG. 7. Reconstruction of the manoeuvres on the platform: Connecting and disconnecting the guide tube, attaching and detaching the radiography equipment to raise or lower it (photograph courtesy of IPEN [6]).

3.2.4. Action 4: Radiography

Worker 1 took three radiographs per joint, and the average time estimated for placing a new film and fixing the position of the collimator at each joint was about 20 s (for each radiograph). The distance between the collimator and the worker's left flank was estimated to have been around 1 m.

3.2.5. Action 5: Assessing access to the next joint

When Worker 1 finished the exposures at a joint, he would climb down to the ground on the ladder and from there observe the next joint to be inspected in order to assess the difficulty of accessing it. He performed this inspection with the guide tube around his neck and the collimator in his left vest pocket. According to his statement, the time spent on this would have been approximately three minutes.

3.2.6. Action 6: Moving radiography equipment to the next joint

When on the ground level, Worker 1 would move the radiography equipment to the next joint. He also performed this manoeuvre with the guide tube around his neck and the collimator in his left vest pocket. The estimated distance between the joints that were already tested was approximately 12 m, and the time stated for moving between the joints, while carrying the radiography equipment, was about one minute.

3.2.7. Action 7: Verifying the number and location of tested joints

Once the work at joint number 24 was complete, Worker 1, while still at ground level, asked Worker 2 and Worker 3 to verify that the numbers and locations of the joints that had been tested were correct. According to the statement by Worker 1, this could have taken 12–15 min, during which time he carried the guide tube around his neck and the collimator in his left vest pocket.

3.2.8. Action 8: Moving out of the noisy area

Walking from joint 24 to joint 39 at a slow pace, Worker 1 would have covered about 25 m by the time he heard the continuous sound of the audible alarm from the dosimeter. The time it took to hear the sound was approximately 35 s. At that moment, Worker 1 put the guide tube on the ground (Fig. 8), covered the collimator with the radiography equipment (Fig. 9) and moved about 30 m away.

FIG. 8. Location where Worker 1 heard the continuous alarm sound and dropped the guide tube (photograph courtesy of IPEN [6]).

FIG. 9. The position of the yellow guide tube in this photograph shows the location where Worker 1 placed the radiography equipment over the collimator (photograph courtesy of IPEN [6]).

3.2.9. Action 9: Start of emergency actions

Emergency actions began, and Worker 1 asked Worker 2 and Worker 3 to bring the emergency kit, the recovery container and the radiation monitor, which were located in the company van. This took them 3–5 min. Worker 1 placed the recovery container over the collimator for immediate recovery. While all three workers were involved in the recovery of the source, the operation itself was performed by Worker 2 and Worker 3, and took about 3–5 min to complete.

3.2.10. Preliminary conclusion

Based on the chronology of the events described in the workers' statements, Worker 1 was more exposed than the other two workers. He stated that he was in contact with the radioactive source for approximately 20–30 min in different positions, but there was no conclusive evidence that this was in fact the duration of the exposure.

A relevant aspect considered in the reconstruction was the position of the collimator in the left vest pocket of Worker 1. It provided a wide range of local absorbed dose to the body of Worker 1, depending on the side to which the collimator had directed the radiation beam — that is, whether the estimation considered the shielded side of the collimator or the side of the exposed source (for further details, see Section 5 on dose assessment).

The first dose assessment after the reconstruction of the scenario, based on the actions described and the possible positions of the collimator in the left vest pocket of Worker 1 [6], led to the following conclusions. The local absorbed dose for Worker 1 was estimated to be between 12 and 24 Gy to the left hip/upper thigh area. The absorbed dose to the whole body for Worker 1 was estimated to be 109 mGy. The doses for Worker 2 and Worker 3 were not estimated by the authorities, since their personal dosimeters registered only 15.85 mSv and 17.0 mSv, respectively.

3.3. MEDICAL ACTIONS AT THE NATIONAL LEVEL

The medical actions performed in Peru consisted of an initial medical evaluation of the involved workers and the hospitalization of Worker 1 for the first 72 hours, including laboratory tests and initial care at the local San Gabriel Clinic. Afterwards, Worker 1 was transferred to INEN.

On the basis of the medical history, the absence of initial clinical manifestations and the subsequent results obtained from the analysis of the personal dosimeter of Worker 1, it was possible to rule out the development of

ARS in the case of Worker 1. Nevertheless, 12 hours post-exposure, he developed a local erythema on the left hip/upper thigh area, indicating a very high local absorbed dose, with the consequent possibility of developing an LRI.

At later stages, after hospitalization at INEN, Worker 1 continued to receive periodic medical follow-up as an outpatient. The medical treatment consisted of systemic antibiotics and anti-inflammatories, with topical treatment for the LRI with corticoids and triethanolamine.

The complexity of the case, the symptoms of the patient, the high absorbed local dose, the prognosis for the LRI and the tissular radionecrosis observed in Worker 1 prompted the Peruvian national authorities to request international assistance from the IAEA under the Assistance Convention [1]. The complete medical management and clinical evolution of Worker 1 are described in Section 6.

3.4. NOTIFICATION AND REQUEST FOR INTERNATIONAL ASSISTANCE

On 5 March 2014, an INES report on the overexposure of three workers during NDT industrial radiography was submitted by the INES National Officer. The report provided information on dose estimations and the clinical condition of Worker 1. Subsequent reports of the event sent through the Permanent Mission of Peru to the IAEA did not differ from the initial information. The INES National Officer reported the event to the IAEA through USIE as an INES Level 3 'serious incident' [10].

The notification contained a summary of the events, the estimated doses and the description of the ongoing investigation. Regarding Worker 1, the preliminary whole body dose estimation was less than 0.5 Gy, and the local dose estimation was 16 Gy to the left hip/upper thigh area.

On 23 April 2014, the health status of Worker 1 was communicated to the Incident and Emergency Centre (IEC) of the IAEA. The IAEA recognized the seriousness of the event and offered its good offices[5] to coordinate any required assistance to the Peruvian national authorities.

On 24 April 2014, as a result of the clinical evolution of the very severe LRI in Worker 1, the Permanent Mission of Peru officially requested assistance from the IAEA under the Assistance Convention [1] for the evaluation and treatment

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[5] An offer of good offices is a message sent to a Contact Point of an affected or potentially affected State offering IAEA services. This definition is from INTERNATIONAL ATOMIC ENERGY AGENCY, Operations Manual for Incident and Emergency Communication, EPR-IEComm 2012, IAEA, Vienna (2012).

of Worker 1. After the assistance was provided, the Peruvian authorities issued a second request for assistance from the IAEA on 9 June 2014, also under the Assistance Convention [1], requesting a specific medical treatment for the LRI of Worker 1.

4. COORDINATION OF THE RESPONSE AT THE INTERNATIONAL LEVEL

4.1. IAEA COORDINATION OF THE INTERNATIONAL ASSISTANCE

States Parties to the Assistance Convention [1] have undertaken to cooperate among themselves and with the IAEA to facilitate the timely provision of assistance in the case of a nuclear accident or radiological emergency, in order to mitigate its consequences. As part of its strategy to implement the objectives of the Assistance Convention [1], the IAEA set up a global system of mutual support that became known as RANET [13].

RANET is intended, inter alia, to strengthen the worldwide capability to provide assistance and advice in the event of nuclear or radiological emergencies, within the framework of the Assistance Convention [1]. States Parties to the Assistance Convention [1] are expected, within the limits of their capabilities and resources, to identify national assistance capabilities, which include qualified experts, equipment and materials that could be made available to assist another State. This obligation is fulfilled through registration of a State's national assistance capabilities and other resources in RANET [13].

For this accident, the request for assistance through RANET involved the medical management of Worker 1. Given the diagnosis and prognosis of the patient, a rapid response was organized by the IEC at IAEA Headquarters, in Vienna.

4.2. IAEA ASSISTANCE MISSIONS

The first request for assistance by the Peruvian national authorities was received by the IEC on 24 April 2014 for medical assistance with respect to a radiological emergency in the State.

Based on the information provided on the seriousness of the LRI in Worker 1, it was decided that an experienced medical team — comprising two specialists from France, one from Brazil and one from the IAEA — be sent to Peru from 29 April to 2 May 2014. The overall objective of this IAEA Assistance Mission was to assist the relevant national and local authorities with the medical management of the exposed individuals.

In particular, the tasks of the IAEA Assistance Mission to Peru included the following [14]:

— Assessing the medical condition of the three exposed persons;
— Assessing the radiological impact in terms of local doses and whole body doses of the three exposed persons;
— Providing advice on the medical treatment of the three exposed persons;
— Supporting dose reconstruction based on the most probable scenario of exposure;
— Providing additional recommendations for actions to be taken by the Peruvian authorities and the IAEA for responding to the radiation emergency, and gathering of relevant information for a report.

A second request for assistance was received by the IEC on 9 June 2014 for specific medical treatment for Worker 1. The IEC directed the request for assistance to relevant States Parties to the Assistance Convention [1] and, after receiving several offers, Peru accepted the offer of assistance from Brazil, with the cooperation of France. It was agreed that medical treatment would be provided by Brazilian specialists, while French specialists would provide medical expertise and consultation in the administration of the medical treatment. France offered the opportunity to transfer to Brazil a new medical protocol (medical evaluation of the patient, development of MSCs for the treatment and dosimetry reconstruction to guide the intended surgery).

This second Assistance Mission was organized in Rio de Janeiro, Brazil, commencing on 21 July and ending on 6 November 2014. It was accomplished in stages (the procedures related to each stage are detailed in Section 6) and comprised:

(1) Medical evaluation of the patient admitted to the Marcilio Dias Naval Hospital (HNMD) in Rio de Janeiro, Brazil;
(2) Medical treatment consisting of reconstructive surgery and MSC injection therapy integrated in a multidisciplinary approach treatment strategy (radiopathology consultation, reconstructive/orthopaedic surgery augmented by cell therapy and pain management therapy);
(3) Provision of any other medical treatment as necessary;
(4) Arrangements for follow-up reporting on the patient’s status after the medical treatment.

Details on the symptoms of Worker 1, the international assistance provided and the medical management performed in Brazil are provided in Section 6.

5. DOSE ASSESSMENT OF THE WORKERS

5.1. SCENARIO RECONSTRUCTION IN PERU

Scenario reconstruction was performed by the Peruvian national authorities (IPEN and OTAN), based on the actions described in Section 3.2 [6].

The estimation of local absorbed doses required the consideration of a number of calculations regarding timing and the distance between the source and the body of Worker 1. The shielding provided by the tungsten in the collimator itself also had to be considered.

The actions performed by Worker 1, the estimated time to complete each of these actions and also the distances between the collimator and the body surface (the left flank) are shown in Table 1.

The dose estimation on the reconstruction was difficult to calculate due to the inhomogeneous type of exposure. The time and distance of the exposure from the radioactive source were estimated from the work performed at joint number 20, based on the evidence of the overexposed radiography films.

To facilitate understanding of the dosimetric calculation for the reader, it is necessary to describe the guide tube, the collimator and the pigtail, which are shown in Figs 10, 11 and 12.

The dimensions of the collimator involved in the accident are shown in Fig. 11 (in cm). Note that there are two openings, one for connection with the guide tube and the other for exposure of the source (pinhole).

In the accident, the pigtail with the radioactive source was in the distal part of the guide tube, connected to the collimator. A pigtail with a radioactive source should never be touched under any circumstances. A similar pigtail (with no radioactive source) is shown in Fig. 12.

In the interview, Worker 1 was requested to reproduce the manner in which he wore the guide tube and how he inserted the collimator into his vest pocket, as shown in Fig. 13.

TABLE 1. ACTIONS PERFORMED BY WORKER 1 AND TIMES AND DISTANCES FROM THE SOURCE [6]

Action performed by Worker 1	Time to complete the action	Distance of collimator from body
Climb up the ladder	53 s	6 cm
Hoist radiography equipment up to the platform	19 s	8 cm
Attach and detach guide tubes from radiography equipment	1 min	8 cm
Place the film, fix the position of the collimator and take three radiographs per joint	1 min (20 s per radiograph)	100 cm
Lower the radiography equipment	37 s	8 cm
Climb down the ladder	48 s	6 cm
Identify next joint to be radiographed (while collimator in left vest pocket)	3 min	2 cm
Verify the number and location of the joints that have been worked on	12–15 min	2 cm
Move source projector to next joint	1 min	2 cm

FIG. 10. Left: The guide tube used during the accident, with the collimator connected. Right: A closer image of both distal parts of the guide tube, with the collimator connected to the guide tube.

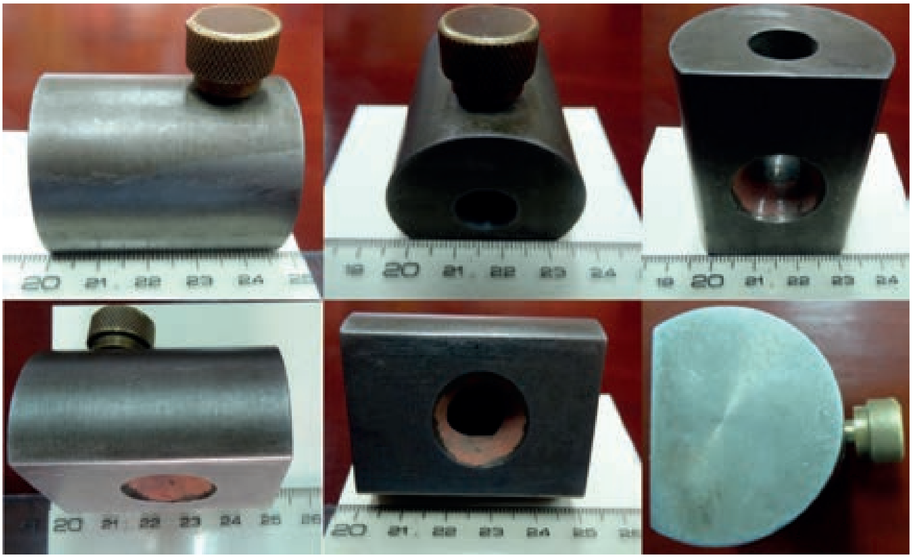

FIG. 11. Different sides and dimensions of the collimator used on the day of the accident. The centre photographs show the side for connecting the distal part of the guide tube to the collimator (top centre) and the side with the pinhole for the exposure of the source (bottom centre).

FIG. 12. A pigtail with no radioactive source.

FIG. 13. Left: Worker 1 demonstrating how he carried the guide tube around his neck. Centre: Worker 1 showing how he inserted the collimator into his vest pocket. Right: Position of the collimator in his left vest pocket.

Based on IPEN's reconstruction of the accident scenario [6], there were three positions in which the collimator could have been inside Worker 1's vest pocket. Worker 1 stated that he positioned the collimator inside the pocket with the beam pointing at himself, as shown in Fig. 14(a). In this case, the collimator would provide no shielding, the pinhole of the collimator would be directed towards the skin and the source would be almost in contact with the skin.

However, due to Worker 1's movements during the performance of his work, the collimator's position inside the vest pocket kept changing. Two other possible positions are shown in Figs 14(b) and 14(c). In Fig. 14(b), the distance between the radioactive source inside the collimator and Worker 1's skin is 1.0 cm, providing only about 3 half-value layers (HVL) of protection. In the position shown in Fig. 14(c), the distance between the radioactive source inside the collimator and the skin is 1.3 cm, which would have provided more shielding and nearly 4 HVL of protection.

In Table 2, doses are estimated with regard to the actions performed by Worker 1; the variables considered are the duration of the action and the distance and the position of the collimator with respect to the skin of the left hip/upper thigh area of Worker 1. From the reconstruction of the accident and the interviews taken by the Peruvian authorities with the involved workers, the following results were obtained:

— An exposure duration of 33 min and 39 s;
— Three possible positions of the collimator in the vest pocket of Worker 1 during the performance of his work;
— Local doses estimated at 193 Gy in the position shown in Fig. 14(a), 24 Gy in the position indicated in Fig. 14(b) and 12 Gy in the position presented in Fig. 14(c) [6].

FIG. 14. Possible positions of the collimator inside Worker 1's vest pocket in relation to his skin. The beige area at the bottom of each image represents the skin of Worker 1 in the left hip/upper thigh area.

Table 3 provides a breakdown of the possible whole body dose for Worker 1. The estimated absorbed dose to the whole body was calculated to be 109 mGy.

Dose estimations for Worker 2 and Worker 3 were not calculated by the Peruvian national authorities, instead they were based on their history, their clinical evolution and the dose reported from their personal dosimeters [15].

5.2. CLINICAL DOSE ESTIMATION

In clinical terms, Worker 1 presented early manifestations of hyperaesthesia and erythema (see Fig. 15). A very high local exposure was anticipated, and radionecrosis development was considered unavoidable (for further details on the onset of the clinical manifestations, see Section 6).

However, Worker 1 did not experience nausea, vomiting or any other possible prodromal manifestation of ARS. Also, the early haematological curve, especially the lymphocyte behaviour, made ARS unlikely (see Fig. 16). A mild transient leucocytosis was observed on the day of the exposure, which may be related to cytokine mediated inflammatory response due to the radiation exposure (see the white blood cell counts in Fig. 17).

The serum amylase presented a normal value (49 U/L, normal range 28–100 U/L) on day 1 post-exposure, suggesting that no significant cephalic exposure took place.

TABLE 2. DOSE ESTIMATIONS FOR THE LEFT HIP/UPPER THIGH AREA OF WORKER 1 [6]

Joint	Action performed by Worker 1	Time (s)	Distance (cm)	Dose rate (mGy)	Dose (mGy) Case (a)	Doses with shielding (mGy)	
						3 HVL (1.0 cm) Case (b)	4 HVL (1.3 cm) Case (c)
Joint 20	Places guide tube around neck	20	2	396 825	2 205	276	138
	Lowers equipment	37	8	24 802	255	32	16
	Descends with guide tube	47	6	44 092	576	72	36
	Time on the ground	300	2	396 825	33 069	4 133	2 067
Joint 22	Ascends with guide tube	52	6	44 092	637	80	40
	Raises equipment	19	8	24 802	131	16	8
	Placement at exposure point	60	2	396 825	6 612	827	413
	Places guide tube around neck	20	2	396 825	2 205	276	138
	Lowers equipment	37	8	24 802	255	32	16
	Descends with guide tube	47	6	44 092	576	72	36
	Time on the ground	300	2	396 825	33 069	4 134	2 067

TABLE 2. DOSE ESTIMATIONS FOR THE LEFT HIP/UPPER THIGH AREA OF WORKER 1 [6] (cont.)

Joint	Action performed by Worker 1	Time (s)	Distance (cm)	Dose rate (mGy)	Dose (mGy) Case (a)	Doses with shielding (mGy)	
						3 HVL (1.0 cm) Case (b)	4 HVL (1.3 cm) Case (c)
Joint 24	Ascends with guide tube	52	6	44 092	637	80	40
	Raises equipment	19	8	24 802	131	17	8
	Placement at exposure point	60	2	396 825	6 612	827	413
	Places guide tube around neck	20	2	396 825	2 205	276	138
	Lowers equipment	37	8	24 802	255	32	16
	Descends with guide tube	47	6	44 092	576	72	36
	Time on the ground	900	2	396 825	99 206	12 401	6 200
Joints 24–39	Route from one joint to the other	35	2	396 825	3 858	482	241
	Total	2 109 (~34 min)			193 070 (~193 Gy)	24 134 (~24 Gy)	12 067 (~12 Gy)

TABLE 3. ESTIMATION OF THE WHOLE BODY DOSE FOR WORKER 1 [6]

Joint	Action	Time (s)	Distance (cm)	Dose rate (mGy)	Dose (mGy)
Joint 20	Changing film (2 × 20 s each)	40	50	634.92	7.055
	Taking radiographs (3 × 15 s each)	45	1 000	1.59	0.020
Joint 22	Changing film (2 × 20 s each)	40	50	634.92	7.055
	Taking radiographs (3 × 15 s each)	45	1 000	1.59	0.020
Joint 24	Changing film (2 × 20 s each)	40	50	634.92	7.055
	Taking radiographs (3 × 15 s each)	45	1 200	1.10	0.014
Joints 24–39	Equipment and guide tube left on the ground	20	10	15 873.00	88.183
	Waiting for recovery equipment	300	3 000	0.176 367	0.015
				Total	109.415 (~ 0.1 Gy)

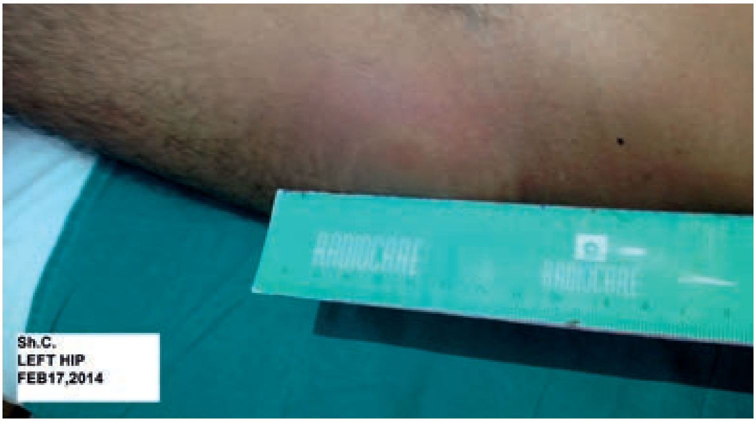

FIG. 15. Worker 1: Erythema developing on day 3 after exposure (17 February 2014) (photograph courtesy of Alberto Lachos, INEN).

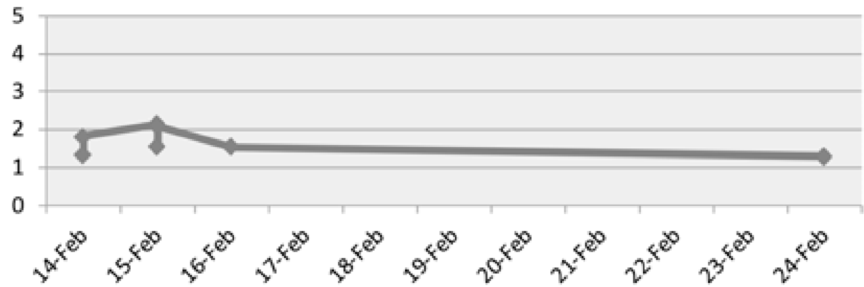

FIG. 16. Lymphocyte counts ($10^3/\mu L$) in the 10 days after exposure for Worker 1.

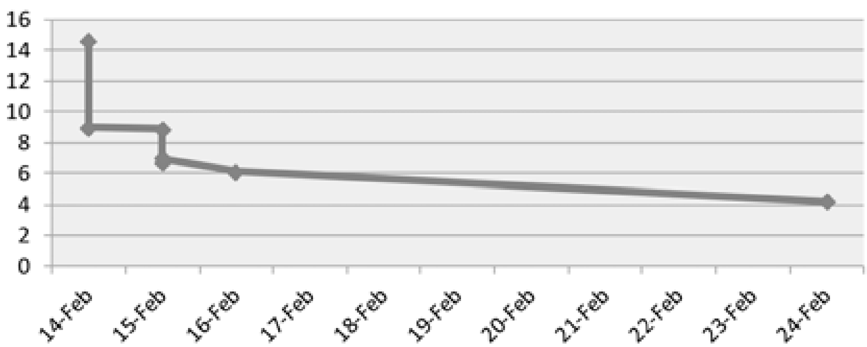

FIG. 17. White blood cell ($10^3/\mu L$) counts in the 10 days after exposure for Worker 1.

5.3. BIOLOGICAL DOSE ASSESSMENT IN ARGENTINA AND FRANCE

Chromosomal aberration analysis using dicentrics and ring assay from peripheral blood samples of persons overexposed to ionizing radiation makes it possible to estimate the absorbed doses. Biological dosimetry tests were carried out at the Nuclear Regulatory Authority (ARN) in Argentina [16] and the Institute for Radiological Protection and Nuclear Safety (IRSN) in France [17–19]. Both laboratories performed the tests in accordance with ISO 19238:2004 [20].

Dicentric chromosomes are specific biomarkers for ionizing radiation. The dose reconstruction is performed by dicentric analysis, in which the analysis of dicentric chromosomes present in peripheral blood lymphocytes is used to estimate the dose of ionizing radiation received by an individual who is suspected to have been recently and severely exposed to radiation [21]. The frequency of dicentrics and rings in individuals not exposed to ionizing radiation is 1 in 1000 lymphocytes (a range of 0–2 dicentrics/1000 lymphocytes). The lower detection limit of the technique for low linear energy transfer radiation is 0.10 Gy [21].

The blood sample from Worker 1 was received by the ARN in Argentina on 28 April 2014. From 509 lymphocytes analysed, 27 dicentric chromosomes and one centric ring were found [16]. The IRSN in France received the blood sample from Worker 1 on 3 May 2014. The analysis of 517 lymphocytes resulted in the following observations: 28 dicentric chromosomes with their associated fragments in 26 cells; one centric ring with the associated fragment in one cell; 13 isolated fragments in 13 cells; and two dicentrics without fragments in two cells [17]. In addition, blood samples from Worker 2 and Worker 3 were analysed at IRSN on 10 July 2014 [18, 19]. A summary of the whole body estimated doses in the three workers is found in Table 4.

5.4. DOSE ASSESSMENT IN FRANCE

In addition to IPEN's local body dose assessment, the IRSN reconstructed the distribution of absorbed doses by the exposed body area of Worker 1 [22]. The presence of a circular lesion located on the left hip/upper thigh area, with a central necrosis 3 cm in diameter surrounded by a moist desquamation halo, observed 2.5 months after the exposure, led to the conclusion that the dose gradient at the surface of the skin was very high. Considering the characteristics of the gamma emission of the radioactive source (^{192}Ir), it was probably located very close to the skin (2–3 cm distance), and its position was relatively unchanged during the whole exposure.

TABLE 4. DOSE ESTIMATION BASED ON BIOLOGICAL DOSIMETRY (DICENTRIC ASSAY) [16, 19]

Individual	Mean whole body dose (Gy)	Confidence interval 95%	Non-homogeneous whole body exposure	Laboratory
Worker 1	0.72	[0.38–0.96]	Yes	ARN Argentina
Worker 1	0.76	[0.51–1.06]	Yes	IRSN France
Worker 2	0.21	[0.05–0.48]	Yes	IRSN France
Worker 3	No detectable dose within the limits of sensitivity of the technique used (0.14 Gy for reference)			IRSN France

For the estimation of the local skin dose, three positions of the collimator were considered by IPEN (see Section 5.1). The position with the collimator beam pointing directly at the skin of Worker 1 led to a local skin dose of 193 Gy, whereas the two other positions resulted in local skin doses of 24 Gy and 12 Gy, respectively. The report concluded that it was most likely that the local skin dose was between 12 and 24 Gy [6].

Although the approach to the reconstruction scenario by IPEN seems to have been correct, it was agreed during the IAEA Assistance Mission in Peru that a local skin dose of about 100 Gy or even higher would be the most probable and realistic scenario for the development of radionecrosis in such a long latency period. Indeed, a local skin dose of 12 or 24 Gy was not consistent with the clinical evolution of Worker 1.

Taking this into account, the IRSN performed additional calculations to estimate the skin and in-depth tissue absorbed doses. It was extremely important to establish which structures received an absorbed dose that would lead to the development of radionecrosis. This would also be particularly helpful in guiding the treatment plan, especially the surgical procedure.

The hypotheses used in the consideration of the IRSN calculations were the following:

— The collimator beam was pointing directly at the skin during the exposure (see Fig. 14(a)).
— Considering the size of the visible necrosis area (3 cm in diameter at the moment of the reconstruction) and the geometry of the collimator (60° conical aperture), the source–skin distance was established to be 2.5 cm. This distance was slightly larger than that used in the IPEN calculations.
— The exposure time during this sequence was set to 1715 s, according to the IPEN report.
— According to the IPEN report, two additional positions were considered. The source–skin distance was set to:
    • 6 cm (exposure time: 245 s);
    • 8 cm (exposure time: 149 s).

The scenarios with distances of 6 cm and 8 cm contributed less than 2% to the total dose.

The calculations were performed using the radiation–material interaction MCNPX Monte Carlo computer code. The source was a cylindrical ^{192}Ir source measuring 1 mm in radius and 2 mm in height, enclosed in a steel cylinder measuring 2 mm in thickness and 6 mm in height. The source holder was left in a 4 HVL metal collimator. The source activity at the time of the accident was 1220 GBq (33 Ci). The source, the source holder and the collimator were modelled. The thigh was modelled by a cylinder composed of soft tissue like material (Fig. 18).

The absorbed dose at the area of necrosis (3 cm in diameter) was estimated at 50 Gy. This value is directly affected by some uncertainty regarding the distance between the source and the skin.

The estimated in-depth doses are given in Table 5. It can be seen that the local skin dose (at the centre of the necrosis area) is lower than that calculated by IPEN because of the different source–skin distances. The threshold dose for necrosis development (20–25 Gy) was estimated to be 2 cm in depth. The absorbed dose to the muscle next to the lesion was estimated to be between 25 Gy (entrance) and 13 Gy (posterior muscular border). The absorbed dose to the part of the femur located next to the lesion was estimated to be 5 Gy (see Fig. 19).

Considering the clinical signs and the different scenarios established by IPEN, the most likely situation is that the collimator beam was pointing directly at the skin of Worker 1, as shown in Fig. 14(a).

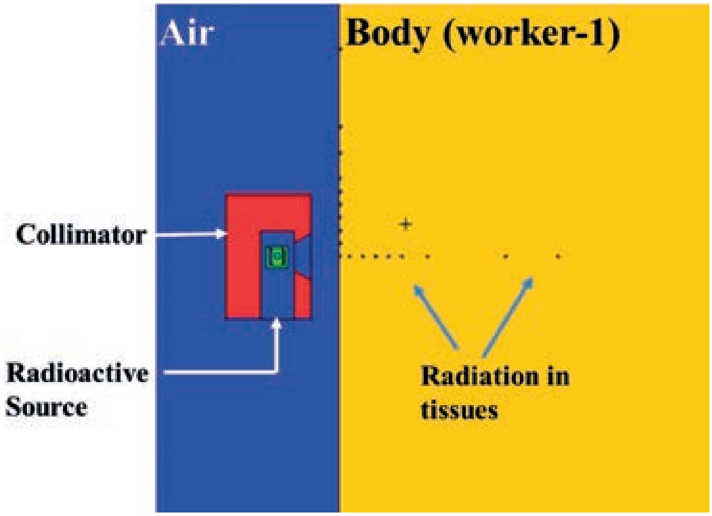

FIG. 18. Modelling of the thigh at 1 cm from the entrance of the collimator [22].

TABLE 5. ESTIMATED IN-DEPTH ABSORBED DOSES [22]

Depth in tissues (cm)	Absorbed dose (Gy)
0	81
0.5	60
1	43
1.5	32
2	25
2.5	19
3.5	13
6.5	5
8.5	3

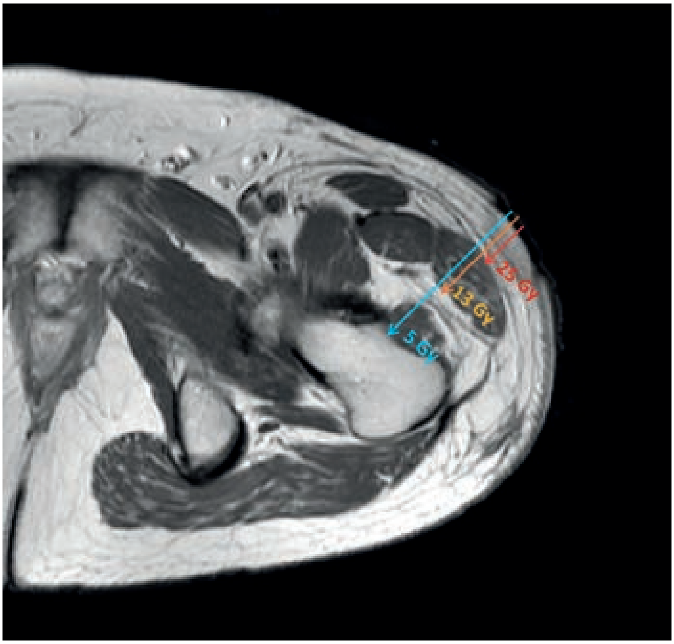

FIG. 19. In-depth absorbed doses reported on a magnetic resonance imaging cross-section of the thigh (3 March 2014) (image courtesy of IRSN [22]).

6. MEDICAL CONSIDERATIONS

6.1. INITIAL MANIFESTATIONS OF WORKER 1

A description of the accident is found in Section 2, where the exposure of Worker 1 is detailed. The following paragraphs give a chronological summary of the evolution of the LRI, clinical manifestations of the patient and medical actions performed:

— Worker 1: Male, 29 years old at the time of the accident;
— Past medical history: No relevant findings; non-smoker;
— Profession: Engineer, industrial radiographer.

On 14 February 2014 (the accident occurred at 02:30), the following actions took place [6]:

— At 05:10, after the workers had reported the accident, the company arranged for their evaluation at the local clinic, a primary healthcare centre. Worker 1 was hospitalized at this centre for the following 72 h. Worker 2 and Worker 3, after the first medical examination, continued as outpatients for medical follow-up.
— At 08:00, Worker 1 noticed some redness and hyperaesthesia in the area around his left hip/upper thigh. The initial haematological tests showed mild leucocytosis (increased count of leucocytes) and transient granulocytosis (increased count of granulocytes). Lymphocyte values were normal [23].
— At 13:00, an officer from OTAN interviewed Worker 1 to obtain further information related to the accident.
— At 17:00, medical staff from IPEN and INEN evaluated the patient. He had not shown any signs of nausea, vomiting or diarrhoea since the estimated time of the accident. The physicians observed an increased local temperature and a small erythema on his left hip/upper thigh area.

The medical staff from IPEN suggested that a serum amylase blood test and a sperm count (semen analysis) be performed. The medical staff from IPEN also advised the healthcare staff at the clinic on the management of irradiated patients. Figures 20 and 21 show the affected area of Worker 1 on the day of the accident and the first day after his exposure.

FIG. 20. Photograph from the day of the accident (14 February 2017) (photograph courtesy of A. Lachos, INEN [24]).

FIG. 21. Photograph from the first day after the exposure (15 February 2017) (photograph courtesy of A. Lachos, INEN [24]).

On 17 February 2014, physicians from IPEN and INEN evaluated the patient [23, 24]. There was significant oedema (swelling) on the left hip/upper thigh area, with a diameter of 10 cm, associated with local pain. The haemogram and serum amylase were in the normal range, which supported the hypothesis that the dose to the whole body was lower than 1 Gy. Dressing of the lesion was performed and oral and topical anti-inflammatories were prescribed (topical triethanolamine and corticoids)[6]. There were no abnormalities in the lymphocyte count rate after 48 hours.

On 20 February 2014, a spermogram showed morphological alterations that cannot be attributable to the radiation exposure [24].

On 22 February 2014, the erythema had a diameter of 8 cm, was associated with pain, and had a more intense redness in its middle.

On 26 February 2014 (see Fig. 22), the lesion evolved with a slight brown pigmentation and the diameter reduced to 7.5 cm. However, the pain and the local temperature increased. On this day, an ultrasound of the lesion was performed, demonstrating oedema on the skin and subcutaneous tissues, with no evidence of necrosis [25].

On 27 February 2014 (see Fig. 23), the lesion started to ulcerate in its centre, surrounded by oedema of 5 cm. The pain level increased, especially in the centre of the lesion [24].

On 3 March 2014, magnetic resonance imaging (MRI) showed an inflammatory process of the skin and subcutaneous tissues, with no alterations of the muscular fascia or underlying muscular tissues.

On 8 March 2014, the ulcer increased in size, reaching a diameter of 6 cm, with severe oedema and a higher pain level. Antibiotics were administered, in addition to topical corticoids and triethanolamine.

On 10 March 2014 (see Fig. 24), a necrotic area in the centre of the lesion, ulceration, oedema and erythema could be observed.

On 13 March 2014 (see Fig. 25), the lesion evolved with a central hyperpigmentation, surrounded by a yellow coloured halo. Significant oedema and signs of necrosis in the central area of the lesion could be observed. A new ultrasound was performed in the left hip/upper thigh area, showing significant oedema on the skin and muscular fascia, associated with mild local muscular oedema.

On 14 March 2014, a new ipsilateral erythema appeared in the left lower abdominal area. This was in line with the different positions adopted by the patient during the NDT on the day of the accident.

On 19 March 2014 (see Fig. 26), the necrotic area in the centre of the lesion, ulceration, oedema and erythema persisted. The erythema in the abdominal area can also be observed in Figs 26–29.

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[6] Triethanolamine water based emulsion is used for the dressing and management of superficial wounds, minor abrasions, dermal ulcers, donor sites, first and second degree burns, including sunburns, and radiation dermatitis.

FIG. 22. Evolution of the local radiation injury, 12 days after the accident (26 February 2014) (photograph courtesy of A. Lachos, INEN).

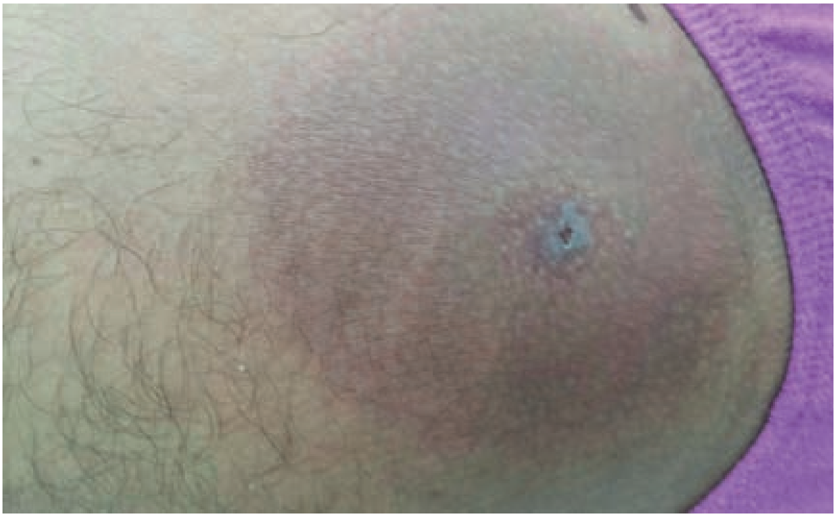

FIG. 23. Evolution of the local radiation injury, 13 days after the accident (27 February 2014): Ulceration in the centre of the lesion, the point with the highest absorbed dose (photograph courtesy of A. Lachos, INEN).

FIG. 24. Evolution of the local radiation injury, 24 days after the accident (10 March 2014): A necrotic area in the centre of the lesion, ulceration, oedema and erythema (photograph courtesy of A. Lachos, INEN).

FIG. 25. Evolution of the local radiation injury, 27 days after the accident (13 March 2014): A necrotic area in the centre of the lesion, ulceration, oedema and erythema can be observed (photograph courtesy of A. Lachos, INEN).

On 20 March 2014, the necrotic area persisted, and the inflammatory reaction of the LRI continued to progress. The patient was treated with Biafine[7]

[7] Biafine is a water based emulsion formulated for the dressing and management of superficial wounds.

FIG. 26. Evolution of the local radiation injury, 33 days after the accident (19 March 2014) (photograph courtesy of A. Lachos, INEN).

and local steroids injected in the lesion. The medical staff from IPEN suggested considering surgery and cellular therapy.

On 7 April 2014 (see Fig. 27), the necrotic area of ulceration of the lesion kept progressing, increasing in size [25]. Local management of the wounds was performed concurrently with oral medication for pain (opioids). The patient was treated as an outpatient.

In Figs 27 and 28, the evolution of the LRI after more than 50 days can be observed, showing a large ulceration that comprised approximately one third of the upper left thigh and the anatomical projection of the left hip, with necrotic tissue in the centre of the lesion. Figure 28 shows how the hypopigmentation and dyschromia of the skin in the left abdominal flank changed in the three days between the two photographs.

The further evolution of the LRI is shown in Figs 29 and 30. A marked inflammation process, central necrosis and ulcerative process of the lesion, surrounded by hypopigmentation of the skin, can be observed. Seventy days after the accident, the inflammation measured about 14 cm in diameter, and the central necrosis had a diameter of approximately 5 cm (see Fig. 30).

FIG. 27. Evolution of the local radiation injury, 52 days after the accident (7 April 2014), showing a local procedure for the cleaning of the wound. The evolution of the desquamated lesion in the abdominal area can also be observed (photograph courtesy of A. Lachos, INEN).

FIG. 28. Evolution of the local radiation injury, 55 days after the accident (10 April 2014): A big ulcer with a necrotic area in the centre of the lesion, hyperaemia and moist desquamation. The changes in pigmentation of the skin can be observed on the thigh and in the abdominal area (hypopigmentation/hyperpigmentation) (photograph courtesy of G. Mendoza, IPEN).

FIG. 29. Evolution of the local radiation injury, 66 days after the accident (21 April 2014) (photograph courtesy of G. Mendoza, IPEN).

FIG. 30. Evolution of the local radiation injury, 70 days after the accident (25 April 2014) (photograph courtesy of A. Lachos, INEN).

6.2. RECOMMENDATIONS BY THE IAEA ASSISTANCE MISSION TO PERU

Worker 1 continued to receive treatment in Peru, but because of the adverse evolution of the LRI, the Peruvian authorities requested international assistance from the IAEA for the medical evaluation of the patient (see Section 4). In response, an IAEA Assistance Mission was sent to Lima, Peru, from 29 April to 2 May 2014 [14].

After the Assistance Mission team arrived in Lima, it interviewed the workers, consulted the national authorities and performed a medical examination of Worker 1.

During the medical evaluation, the experts graded the patient's pain using the numerical rating scale (NRS)[8], as follows: spontaneous pain 9–10/10 NRS; under the use of 25–50 mg tramadol per day (opioid medication), approximately 5/10 NRS.

The patient mentioned, on 13 March 2014, the appearance of an erythema and pruritus and dyschromia on the left forearm and left flank on the abdomen, which were confirmed by the Assistance Mission experts on 30 April 2014 (see Figs 31 and 32).

On 30 April 2014, 76 days after exposure, the size of the lesion was 10 cm in diameter, with a central area of necrosis 5 cm in diameter (see Fig. 33). The function of the left hip joint was preserved without pain during passive mobilization. Active mobilization increased pain. The patient presented difficulties standing up and walking and adopted an antialgic position.

Figure 33 shows the clinical status of the LRI on the first day of the IAEA Assistance Mission to Peru. The most recent MRI available was one month old (Fig. 34). When the evolution of the LRI is compared with the condition shown on the MRI, it can be observed that the ulcer affected mainly the adipose tissues and reached the fascia muscularis with no involvement of muscular tissues. For an adequate evaluation, a new MRI was requested in order to be able to compare the evolution since the previous images had been taken.

The Assistance Mission team observed that Worker 1 had developed a severe and painful LRI. In view of the severity of the lesion (extensive radionecrosis), the experts recommended a surgical procedure combined with autologous cell therapy as the only reliable approach [14]. A blood sample from the patient was obtained for a second biological dosimetry, which was performed by the IRSN in France [17].

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[8] In an NRS for pain assessment, patients are asked to circle a number between 0 and 10, 0 and 20, or 0 and 100 that best describes their pain intensity. Zero usually represents 'no pain at all', whereas the upper limit represents 'the worst pain ever possible' [26].

FIG. 31. Left forearm of Worker 1 in two different photographs showing slight depigmentation (dyschromia). Initially, a dry desquamation was reported (30 April 2014) (photographs courtesy of INEN).

FIG. 32. Left abdominal area of Worker 1 showing depigmentation. Initially, a dry desquamation was reported (30 April 2014).

FIG. 33. Worker 1, 76 days after exposure; lesion in the left upper thigh and inguinal area (30 April 2014).

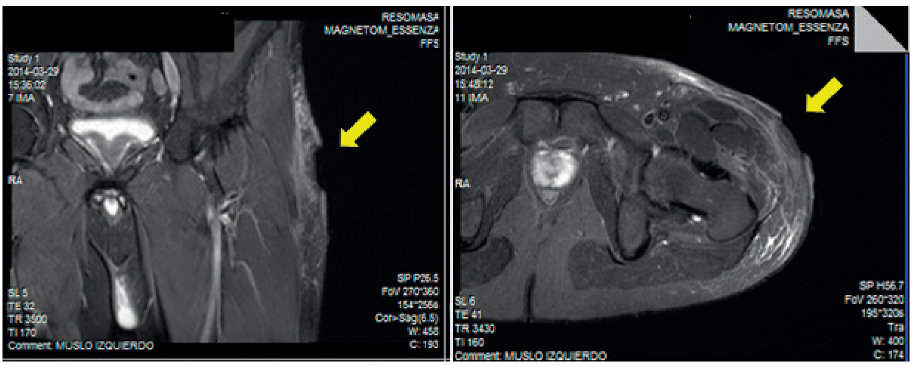

FIG. 34. Second magnetic resonance imaging of Worker 1 (29 March 2014). Yellow arrows show the lesion; the muscular plane is respected (images courtesy of INEN).

6.3. TREATMENT AT THE MARCILIO DIAS NAVAL HOSPITAL

After extensive arrangements, the patient was admitted to the HNMD in Rio de Janeiro, Brazil, on 21 July 2014, 157 days after the accident. Figure 35 shows the condition of the lesion at that time.

6.3.1. Initial general evaluation

The patient was jointly and thoroughly examined by teams from the plastic surgery and nuclear medicine departments, as well as others including the haematology, orthopaedics, nutrition and dietetic services, physiotherapy

FIG. 35. View of the lesion on admission to the Marcilio Dias Naval Hospital (photograph courtesy of HNMD).

and psychology departments. A comprehensive evaluation was ordered, including biochemistry, bone scintigraphy, thermography and another MRI. The thermography of the left thigh and pelvis showed a large central area of necrosis (Fig. 36). The patient was also evaluated by the pain management clinic, and it was decided to begin treating with gabapentin and continue with the administration of tramadol (an opioid).

The bone scintigraphy (Fig. 37) showed no bone injury; the MRI identified an infiltration and oedema in the muscle and muscle interstitium of the proximal third of the thigh. The patient began physiotherapy, medical nutritional therapy and received psychological support, which continued throughout his stay at HNMD. To aid with psychological support, the hospital permitted the patient's spouse to stay with him during his hospitalization.

The nutritional evaluation of the patient showed a normal body mass index of 22.4. In order to assist in the surgical wound healing process, a hypercaloric and hyperproteic diet was initiated and fractionated six times a day. Protein nutritional supplements were administered three times a day.

At the early stages of the hospitalization, the patient exhibited a functional limitation of his left leg and an antialgic posture. This condition was addressed by means of continued physiotherapy support.

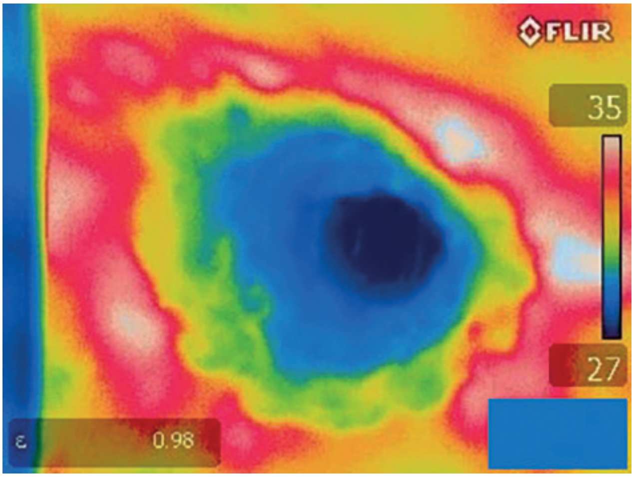

FIG. 36. Thermography of left thigh on admission to Marcilio Dias Naval Hospital (image courtesy of HNMD).

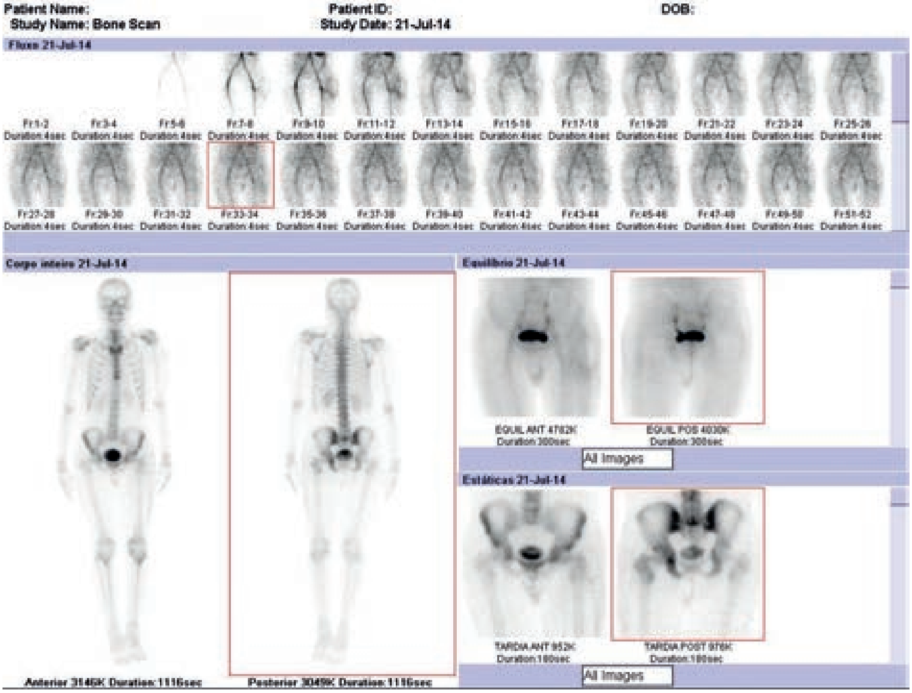

FIG. 37. Bone scintigraphy in three phases with no abnormalities (images courtesy of HNMD).

6.3.2. Management of the local radiation injury

The surgery team evaluated the lesion and decided to continue using dressings with silver sulfadiazine 1% daily until the day of the surgery. On 23 July 2014, upon the request of the IAEA Assistance Mission team, a myelogram with bone marrow aspiration for MSC culture was obtained (Fig. 38).

On 6 August 2014, the best approach for the treatment of Worker 1 was discussed by HNMD staff, experts from the IAEA and the Brazilian National Cancer Institute (INCA) in Rio de Janeiro. Two options were possible: a split thickness skin graft (option 1) or a free flap (option 2). Both of these would also involve simultaneous, and three subsequent, injections of MSCs, cultured following the protocol of the Centre de Transfusion Sanguine des Armées (CTSA) at Percy Military Hospital in Clamart, France. The transfer of this MSC culture protocol was processed at INCA.

On 7 August 2014, preparations for the surgery based on the clinical observation and the dose assessment were carried out (Fig. 39). The surgery was successfully performed on the same day, involving full resection of the

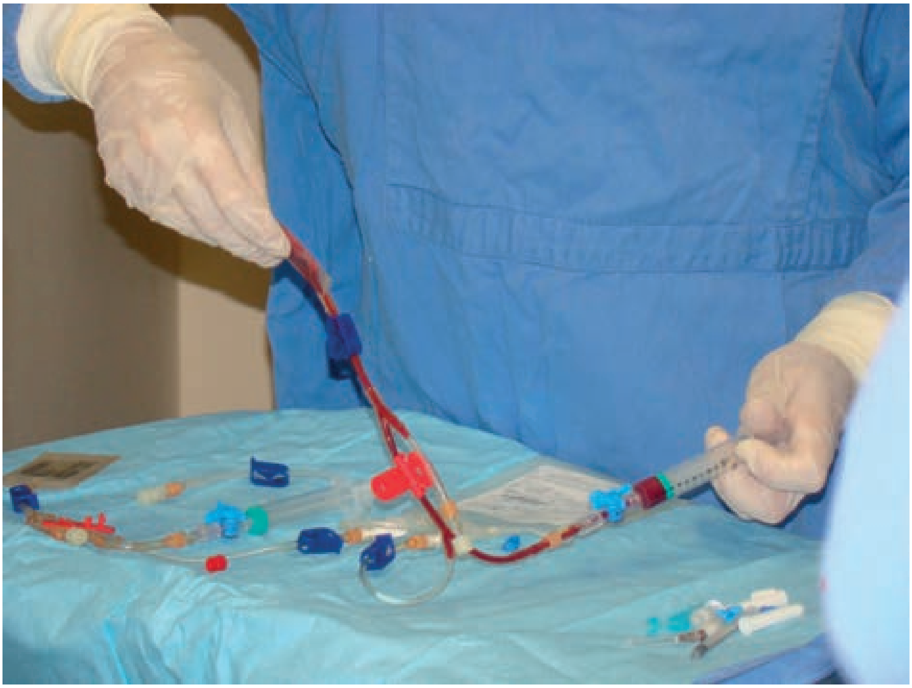

FIG. 38. Bone marrow collection for mesenchymal stem cell culture (photograph courtesy of HNMD).

necrosis up to the muscular plane (see Fig. 40), the first injection of MSCs with the assessment of the IAEA Assistance Mission team (see Fig. 41) and a skin autograft (see Fig. 42). The next three MSC administrations were carried out once weekly, with the last one on 28 August 2014. A new thermography image and a comparison with the aspect of the lesion after the first surgery is shown in Fig. 43.

FIG. 39. The local radiation injury of Worker 1 before surgery measuring 14 cm × 9 cm (7 August 2014). A central necrotic area and a hyperaemic area of 1.5 cm around the lesion can be observed (photograph courtesy of HNMD).

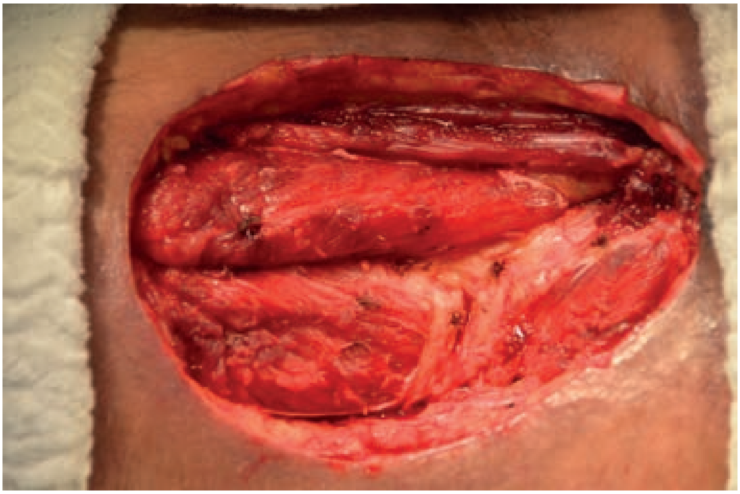

FIG. 40. Viable muscular layer underlying the necrotic area during the surgery (photograph courtesy of HNMD).

FIG. 41. First injection of MSCs (photograph courtesy of HNMD).

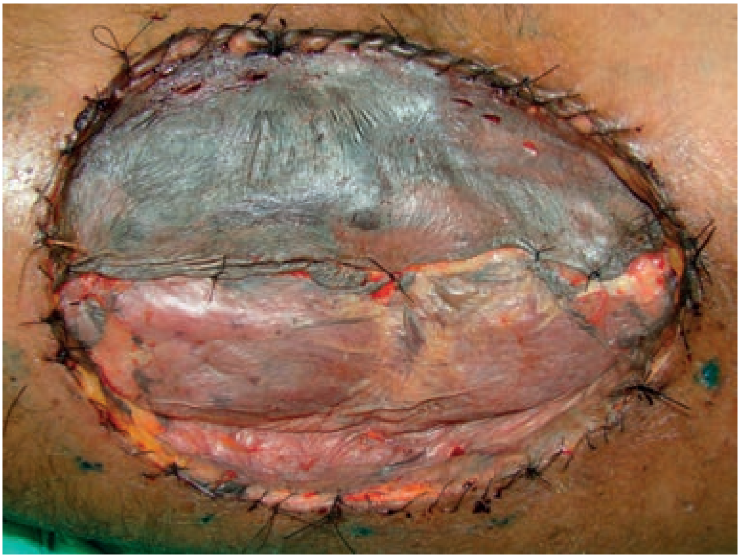

FIG. 42. Evolution of the LRI after the surgery (14 August 2014) (photograph courtesy of HNMD).

FIG. 43. LRI after the first surgery and respective thermography image. When compared with Figs 35 and 36, necrosis is not observable after the first surgery (photograph and image courtesy of HNMD).

The patient's surgical wound presented a small area where the skin graft did not work. Hyperbaric oxygen therapy (HBOT) sessions commenced on 3 September 2014, contributing to an improvement of tissue granulation and clinical results for this case. In total, 28 sessions of HBOT were administered during the entire period of hospitalization, which may have alleviated the pain and reduced the need for opioids. It was decided to continue the HBOT and to perform another skin graft on the area where the loss of the first graft had occurred.

On 20 September 2014, the patient presented vomiting and abdominal pain. Acute appendicitis was diagnosed, and a video laparoscopic appendectomy was successfully performed. This intercurrence delayed the second surgery that was scheduled.

On 26 September 2014, the second surgery was performed, which consisted of a split thickness graft (see Fig. 44). The integration of the skin graft was complete, and HBOT continued.

On 23 October 2014, another bone scintigraphy showed normal metabolic activity in the femur and pelvic areas.

On 4 November 2014, a new thermography was performed, which showed no ischemic area in the left thigh (see Fig. 45). The integration of the skin graft was complete, and the patient was discharged from HNMD in Brazil on 6 November 2014 in a good condition to continue follow-up in Peru (Fig. 46).

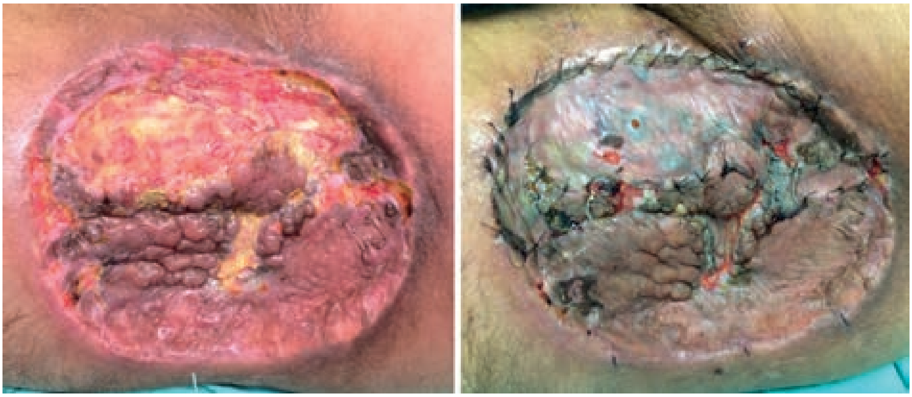

FIG. 44. Worker 1's local radiation injury before (left) and after (right) the second surgery (photographs courtesy of HNMD).

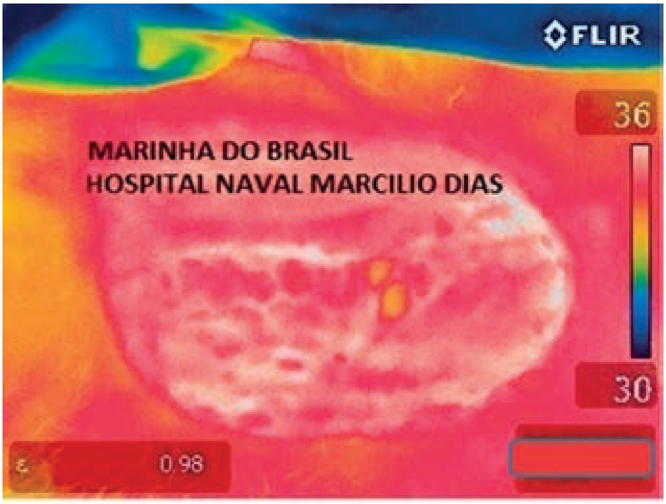

FIG. 45. Thermography image on discharge from Marcilio Dias Naval Hospital (photograph courtesy of HNMD).

6.4. MEDICAL FOLLOW-UP IN PERU

The patient continued with medical follow-up in Peru after his return from Brazil, and no new episodes of pain or ulceration of the skin occurred. He is in good medical condition, with no evidence of recurrences within the three years following the accident. The lesion as of March 2017 is shown in Fig. 47.

FIG. 46. Graft aspect on discharge from Marcilio Dias Naval Hospital (photograph courtesy of HNMD).

FIG. 47. View of the operated area during medical follow-up in Peru in March 2017 (photograph courtesy of A. Lachos, INEN).

6.5. UTILIZATION OF MESENCHYMAL STEM CELLS

MSCs are characteristically multipotent cells obtainable from bone marrow or alternatively from other non-marrow tissues, such as umbilical cord and adipose tissues. The main effect of MSCs is to deliver paracrine factors, such as anti-inflammatory cytokines and growth factors, and promote the healing of injured tissues. In dosimetry guided surgery, MSCs are injected at different points in the surgical area, and thereafter again in a number of sessions [27].

MSCs are located in stem cell niches that represent a biological structure in which various types of stromal cells — osteoblasts, adipocytes, endothelial cells and haematopoietic stem cells — cooperate for haematopoiesis development through cytokine and chemokine production and cell–cell interaction.

The role of cytokines, chemokines and growth factors produced by MSCs is crucial for well orchestrated haematopoiesis regulation. MSCs produce a large number of cytokines, growth factors and chemokines that participate in the recruitment of macrophages and endothelial cells to improve wound healing. In addition to their multipotent properties, MSCs are very sensitive to the environment and produce paracrine factors in response to environmental stimulation. Through the secretion of paracrine factors, it has been extensively demonstrated that MSCs could exhibit immunomodulatory, antiapoptotic, proangiogenic, antiscarring activities that could be of interest for tissue repair purposes [28].

MSCs have been used in severe LRI cases, such as those related to the industrial radiography accidents in Nueva Aldea (in 2005) [29]; Dakar (in 2006); Francisco de Orellana (in 2009); Turmero (in 2010); and Chilca (in 2012–2013) [2]; as well as the radiotherapy accident in Epinal (2007). These experiences were the basis for the use of MSCs in the treatment of Worker 1.

6.5.1. Procedures

The complete transfer of the MSC culture procedure was facilitated by the IAEA Assistance Mission. MSCs were cultured following the protocol of the CTSA [30]. The transfer of this MSC culture protocol was carried out at INCA and required four weeks of training.

Approximately 50 mL of the patient's bone marrow was harvested on 23 July 2014 by intraosseous aspiration of the posterior iliac crest, using a bone marrow aspiration needle and citrate phosphate dextrose adenine as the anticoagulant, and collected into a special bone marrow bag (BM1). Harvested cells were conditioned in refrigerated bags and transported to a cell processing facility at INCA as part of the IAEA Assistance Mission.

In the cell processing laboratory, bone marrow samples were taken for cell counting and immunophenotyping for CD45 leukocyte cell markers. After this, 2.5×10^8 CD45 negative cells were seeded in four clinical grade, closed culture devices, using 150 mL of complete medium composed of α-medium (135 mL), heparin (60 µL), ciprofloxacin (0.75 mL of a solution of 2 mg/mL) and 24 mL of human platelet lysate (in line with the CTSA protocol and the technique of Schallmoser [31, 32]). Due to technical limitations, allogenic platelets were used instead of autologous ones.

Cells were cultivated in a restricted area, at 37°C, under 5% CO_2 and in an environment with more than 80% humidity. After two days of culture, all mediums were replaced by completely fresh mediums. Cells were cultivated for five more days, and on 30 July 2014 another total medium change was performed, in line with the CTSA protocol.

On 7 August 2014, cells were harvested from CellSTACK culture chambers using human trypsin, put in suspension and quantified. Four more CellSTACK cultures were grown (BM1 passage 1) at a cell density of 4000 cells/cm^2 (total cell number 5.0×10^6). These cells were cultivated under the same conditions for seven more days, in line with the CTSA protocol.

The remaining cells were maintained in suspension, conditioned in refrigerated bags and sent to HNMD for the first set of surgical injections. The injections were made into the borders of the graft, in small amounts of 100–500 µL (injection number 1). On the same day, a new bone marrow aspiration was performed in order to cultivate a second batch of cells for injection (BM2). As with the BM1 cells, four CellSTACK cultures were plated and incubated for two days. On 9 August 2014, the medium was changed for a fresh one, in keeping with the CTSA protocol.

On 14 August 2014, BM1 passage 1 cells were harvested using trypsin and all cells were taken for injection at the HNMD surgical centre (injection number 2), under the supervision of the IAEA Assistance Mission team. Meanwhile, BM2 cells underwent another complete medium change at the laboratory.

On 21 August 2014, BM2 cells were harvested with trypsin and, similarly, four new CellSTACK cultures were plated (BM2 passage 1) for another expansion, while the remaining cells were injected into the patient's graft (injection number 3), with the guidance of the IAEA Assistance Mission team.

On 28 August 2014, BM2 passage 1 cells were finally harvested with trypsin, and all cells were injected, as before, into the borders of the graft (injection number 4), under the observation of the IAEA Assistance Mission team.

6.5.2. Product quality control

Cell quantification: According to the CTSA protocol, all cells in suspension for plating, replanting or injection were quantified using a haemocytometer (Neubauer chamber). Table 6 shows the number of cells in each of the injections performed.

Microbiological contamination: At each medium change, microbiological tests were performed using common haemoculture medium flasks (BD BACTEK). All tests were negative.

Viability assay: All cells harvested for plating, replanting and injection were assayed for cell viability using the trypan blue dye exclusion test. All samples had over 99% viability.

MSC phenotype: Each injection batch was assayed by flow cytometry using surface cell markers CD90, CD105, CD73, CD45, CD34, CD19, CD14 and HLA-DR. Table 7 summarizes the results for each injection performed.

TABLE 6. NUMBER OF EXPANDED CELLS COLLECTED FOR EACH INJECTION

	Injection 1	Injection 2	Injection 3	Injection 4
Total cells	1.23×10^8	1.67×10^8	1.92×10^8	1.11×10^8
Doses injected	15	15	19	11

TABLE 7. SURFACE CELL MARKERS OF MSCs

	Injection 1	Injection 2	Injection 3	Injection 4
CD90	99.29	99.84	99.66	99.62
CD105	99.31	99.78	99.69	99.43
CD73	99.23	99.74	99.67	99.41
CD45	5	3.34	2.95	0.92
CD34	14.01	4.19	1.34	0
CD19	0.40	0.84	0.60	0.21
CD14	3.25	1.36	0.18	0.35
HLA-DR	15.58	55.5	24.76	37.55

7. FINDINGS AND CONCLUSIONS

The radiological accident sequence can be broadly divided into five phases for analysis.

7.1. PHASE 1: EXPOSURE

The initial phase started at 02:30 on 14 February 2014 during the work of the three gamma radiography workers, when the radioactive source became disconnected, did not return to the safety position and remained in the guide tube (instead of being retracted to its safety position). The workers did not realize this and continued their radiography tasks.

The workers were wearing personal dosimeters with alarms that would give a warning sound if the source remained outside the shielding. They did not hear the sound of the alarm because of the noise from motors and other machines in the area where the work was performed.

Worker 1 stated that he had been in contact with the radioactive source for 20–30 min, but it is not certain that this was the actual duration of the exposure. He also said that he had experienced no early symptoms, but that 12 hours after the exposure, he started to notice reddening in the area most exposed to the radiation.

The factors contributing to the accident include the following:

— Radiation protection procedures were not strictly followed.
— There may have been a problem with the radiography equipment.
— A portable radiation detector was not in use during the NDT.
— The personal alarm dosimeters may have been used inappropriately.

7.2. PHASE 2: IDENTIFICATION AND RECOVERY

According to Worker 1, the area where the radiography was carried out was too noisy, which rendered the audible alarm practically useless. Once he was en route from joint 22 to joint 39 (a distance of about 50 m), he began to gradually leave the noisy area. When he was about 25 m from joint 39, he noticed the sound of the personal dosimeter, alerted his co-workers and initiated the recovery of the source [6].

The recovery of the source was performed by Worker 2 and Worker 3 in approximately 3–5 min. According to the workers' statements, they tried to direct the source from the guide tube into the recovery container, but they noted that the source remained exposed. Faced with this, they managed to get the source out of the radiography equipment, put it on the ground and covered it with the recovery container. They proceeded to retrieve the radioactive source using tongs and portable shielding from the emergency kit. They connected the remote control to the source and retracted it back into its shielding in the radiography equipment at 03:25 on 14 February 2014 [6].

Safety culture and radioprotection procedures are essential elements of reducing the possibility of accidents [33]. In most accidents related to industrial radiography, it is inattention to safety rules and inadequate adherence to radioprotection principles and procedures that lead to radiological emergencies, with health consequences for the workers involved and sometimes also for the public.

7.3. PHASE 3: NOTIFICATION

The workers reported the accident to their manager at 04:10 on 14 February 2014. The company initiated the notification process to OTAN, and the process was completed with a notification to IPEN on the same day.

On 5 March 2014, the INES National Officer reported the radiological accident through USIE to the IAEA. The IAEA requested further information from the Peruvian national authorities because of the risk of a possible overexposure accident with potential health consequences for any of the involved workers. It was not until 23 April 2014 that the health status of Worker 1 was communicated to the IEC. The IAEA, recognizing the seriousness of the event, offered its good offices for coordinating any assistance required by the Peruvian national authorities. On 24 April 2014, the Permanent Mission of Peru officially requested the provision of medical assistance from the IAEA for the handling of the radiological accident.

Even though the notification process was adequate, there was a significant delay between the accident and the communication of the health status of Worker 1. Previous experiences have demonstrated that the initiation of early medical interventions can reduce the morbidity of patients with LRIs. An expedited medical assessment and early medical actions are necessary for these patients. Once the seriousness of the medical situation was recognized, fast action was taken to notify the IAEA and request international medical assistance through its good offices.

7.4. PHASE 4: INTERNATIONAL ASSISTANCE

The following is the chronology of the international assistance in response to the accident:

- First request for assistance from the IAEA by the Peruvian national authorities received by the IEC on 24 April 2014;
- First IAEA Assistance Mission to Peru from 29 April to 2 May 2014 (two experts from France, one expert from Brazil and one expert from the IAEA);
- Second request for assistance from the IAEA by the Peruvian national authorities received by the IEC on 9 June 2014;
- Second IAEA Assistance Mission to Brazil, from 21 July to 6 November 2014 (four experts from France and one expert from the IAEA).

7.5. PHASE 5: TREATMENT

The following is the chronology of treatment for Worker 1:

- Admission of patient to HNMD on 21 July 2014;
- Transfer of the culture protocol from Percy Military Hospital/IRSN, France, to HNMD/INCA, Brazil;
- Medical management at HNMD with support from the IAEA Assistance Mission team included medical evaluation, the first skin graft and MSC injection (on 7 August 2014); MSC injections (on 14, 21 and 28 August 2014); HBOT (from 3 September to 31 October 2014); appendectomy (on 20 September 2014); and a second skin graft (on 26 September 2014);
- MSC development by INCA, under the guidance of CTSA, from 23 July to 28 August 2014 (including two bone marrow aspirations);
- Discharge of the patient from HNMD on 6 November 2014.

8. LESSONS TO BE IDENTIFIED

A number of the lessons to be identified are not unique to this accident but are worth reiterating in this publication (the IAEA has collected lessons identified from other accidents in industrial radiography in Refs [33, 34]). This section will examine four main aspects to facilitate the identification of these lessons.

8.1. OPERATING ORGANIZATION

The operating organization is responsible for the possession and use of industrial radiographic sources and devices. This includes their operation in accordance with regulatory authority regulations, permits and authorizations or appropriate international safety standards [33]. The primary responsibility for radiation safety lies with the licensee. A safety culture needs to be in place, fostered and maintained by management and followed by the workers. The licensee needs to ensure that all appropriate procedures are observed without exception.

Specific device related training and supervised hands-on experience need to be provided, including the use of radiographic equipment, survey meters, remote handling tools and personal dosimeters. The absence of a portable radiation detector during radiography operations contributed decisively to the accident, and its consequences, in Ventanilla.

Safe operation of industrial radiography depends on the proper implementation of radiation protection and safety, such as the regular use of alarm dosimeters and dose rate meters. Radiation protection and safety in industrial radiography, especially on-site radiography, rely strongly on human intervention and the correct implementation of procedures. Persons performing such work have high demands placed on them, and they must, therefore, be fully trained and qualified. Employers need to provide suitable and adequate human resources and appropriate training in protection and safety. Periodic retraining can help to ensure that the required degree of competence is maintained. Overload and time pressure may hinder safety, and these issues need to be appropriately addressed.

On-site safety in industrial radiography depends mainly on the radiographers' knowledge and skills, and the correct implementation of procedures. Preventive maintenance programmes may reveal technical incompatibilities or problems that can be corrected in time and eliminate possible causes of mishaps.

8.2. NATIONAL AUTHORITIES

On the basis of the evaluation of this (and other) accidents, the regulatory body needs to review the technical and administrative requirements and procedures for workers, equipment and training. Additional requirements to cover gaps that could potentially exist need be introduced.

All the equipment that is in use needs to be maintained according to the prescribed standards, as defined by the regulatory authority and in conjunction with the manufacturer's recommendations. It is important to investigate the malfunction, or the operational and technical failure that was the root cause of this accident (the radioactive source became disconnected and did not return to the safety position, but instead remained in the guide tube).

Problems were faced when Worker 1 had to be transferred abroad for highly specialized treatment. There was no medical coverage for the patient by health insurance. It is essential that licensees be encouraged by national authorities to arrange for suitable medical insurance coverage for their employees with regard to accidents in the workplace, as this will allow specialized treatment outside the State whenever necessary.

National authorities also need to ensure that sufficient resources are readily accessible to cover emergencies. Expertise on biodosimetry was available within the State, but local preparation of cultures from the biosamples could not be performed. It is advisable that operational capabilities for basic biodosimetry are available.

The reconstruction of the accident and dose assessments performed in Peru were useful for the initial evaluation of the case. National authorities always have the mandate to access the facilities where a radiological emergency occurred.

IPEN used USIE to report the accident on an INES event reporting form to provide the information on the accident to the IEC. It also promptly responded to the IAEA's offer of assistance by quickly making a formal request for advice on dose assessment and medical management. The use of USIE to report this accident facilitated the exchange of information, and expedited the actions to complete the Assistance Mission that was requested.

8.3. INTERNATIONAL COOPERATION

Early clinical manifestations (erythema, oedema and blistering), within hours or a few days in the case of a local radiation exposure, indicate the development of a severe LRI (radionecrosis). If international cooperation is anticipated in such a circumstance, it is appropriate that the notification and request for assistance are initiated as early as possible in order not to jeopardize the success of the treatment. Coordinated actions between national authorities and international assistance in the early accident phase might significantly reduce the consequences of an accident or even prevent them.

As in the case of the radiological accident in Ventanilla, the IAEA, upon request, can provide assistance to Member States in radiological emergencies, within the framework of the Assistance Convention [1]. The governments of all

States in which radiation sources are used are invited to accede to the Assistance Convention [1].

National authorities are encouraged to share information about radiation emergencies with the IAEA and with other States to help prevent or mitigate the consequences of such accidents in the future. As in several other responses to radiological emergencies, the involvement of RANET in the response process was essential for the appropriate treatment and successful recovery of the patient. The effective treatment of the patient was possible because of significant efforts by professionals and institutions from Argentina, Brazil, France, Peru and the IAEA. The efficient integration of efforts and the mobilization of resources was coordinated by the IAEA.

Under the Assistance Action Plan organized by the IAEA, experts from France transferred to their Brazilian colleagues the technical knowledge for the medical management of LRIs involving dosimetry guided surgery combined with MSC injection. While in this particular case it greatly benefited the affected patient, the thorough understanding and perfection of this medical procedure requires extensive experience. Therefore, further systematic training needs to be given to the Brazilian specialists in the application of these techniques.

The cooperation between French and Brazilian medical experts with regard to the culture of MSCs and their use as an adjuvant therapy for the LRI is an excellent example of technical knowledge transfer within the international medical community.

8.4. MEDICAL COMMUNITY

The decision to transfer the patient from Peru to Brazil for specialized medical treatment significantly contributed to his recovery. When a patient is transferred abroad, the different environment, culture and language can have a significant emotional impact. The extensive psychological support and counselling that was provided positively contributed to the general management of the patient. In this particular case, the presence of the patient’s spouse throughout his treatment in Brazil reduced the psychological burden experienced by the patient.

Early dosimetry guided surgery and MSC therapy before the development of radionecrosis would have significantly reduced the morbidity of the lesion (pain, emotional distress, infection, surgical difficulties, duration of hospitalization, sequels, etc.). Unfortunately, this was not possible, as the patient was referred to HNMD with an already established radionecrosis in his left hip/upper thigh area.

The combination of reconstructive surgery and MSC therapy, even with an established radionecrosis, proved to be a valuable method for the management of this condition. An accurate in-depth dose reconstruction, with identification of the tissues and structures that have incurred doses potentially leading to radionecrosis, is paramount for dosimetry guided surgery. Concomitant therapies involving HBOT, physiotherapy and nutritional support contributed to the favourable treatment outcome and highlight the importance of a multidisciplinary and integrated approach to severe cases of LRI.

A recurrent issue in the treatment of patients has been the economic aspect. Frequently, the affected workers have no insurance or their health insurance does not cover the expenses involved in this kind of treatment. If they do have medical coverage, it often does not provide support for treatment abroad. This administrative gap needs to be bridged promptly during radiation emergencies. In many cases, this represents an issue affecting the hospitalization of patients abroad. In this particular case, it was a factor in the discussion and decision about transferring the patient. The treatment abroad was provided at no cost to the patient or the national authorities, but it needs to be emphasized that the costs involved are significant and that they need to be covered during emergencies. It is important that this situation be clarified for Member States.

After three years, according to the information received from the medical team responsible for the follow-up of Worker 1 and the Peruvian authorities, the patient is in good health, with no recurrence of injury in the area of the lesion and no functional or other consequences reported. It is important in such situations that patients receive strictly organized medical follow-up as part of the overall medical management of these cases.

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ABBREVIATIONS

ARN	Nuclear Regulatory Authority (Argentina)
ARS	acute radiation syndrome
BM	bone marrow
CTSA	Centre de Transfusion Sanguine des Armées (France)
HBOT	hyperbaric oxygen therapy
HNMD	Marcilio Dias Naval Hospital (Brazil)
HVL	half-value layers
IEC	Incident and Emergency Centre
INCA	Brazilian National Cancer Institute
INEN	National Institute of Neoplastic Diseases (Peru)
INES	International Nuclear and Radiological Event Scale
IPEN	Peruvian Institute of Nuclear Energy
IRSN	Institute for Radiological Protection and Nuclear Safety
ISO	International Organization for Standardization
LRI	local radiation injury
MRI	magnetic resonance imaging
MSCs	mesenchymal stem cells
NDT	non-destructive testing
NRS	numerical rating scale
OTAN	Technical Office of the National Authority (Peru)
RANET	Response and Assistance Network
USIE	Unified System for Information Exchange in Incidents and Emergencies

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