# The Radiological Accident in Chilca

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# FOREWORD

The use of radioactive materials offers a wide range of benefits throughout the world in medicine, research and industry. However, precautions are necessary to control and limit the exposure of people to the radiation emitted. When highly radioactive material is involved, as in the case of industrial radiography or radiotherapy sources, extreme care needs to be taken to prevent accidents that could have severe consequences. Nevertheless, in spite of precautions being taken, serious accidents involving radiation sources do occur. When the IAEA coordinates assistance after being notified of an accident, a follow-up review is conducted to give an account of the entire event. This review is intended to assist organizations that are responsible for radiation protection, source safety, and emergency preparedness and response to identify the lessons that can be learned to prevent similar accidents.

A serious radiological accident occurred in Peru around midnight on 11 January 2012 during non-destructive testing in the district of Chilca, in the Cañete Province of Lima. An iridium-192 source in a radiography camera used to test pipeline joints became stuck inside the guide tube, resulting in three workers being overexposed to ionizing radiation. Under the Convention on Assistance in the Case of a Nuclear Accident or Radiological Emergency (the Assistance Convention), the Peruvian authorities requested assistance from the IAEA to advise on the dose assessment and medical management of those involved in the accident. On the basis of the advice given by an international assistance mission team, the Peruvian authorities made another request under the Assistance Convention for medical treatment of the worker with the most severe radiation injuries. The treatment was completed in May 2012. In December 2012, this person developed other skin lesions, accompanied by erythema, oedema and pain. A third request for assistance was made by Peru, and an offer was made and accepted for the patient to be treated in Chile between July and September 2013.

The IAEA wishes to thank all the experts and professionals involved, in particular, the experts from France who participated in all the international assistance missions, provided advice on dose assessment and medical management, and later treated the most exposed worker. The IAEA also wishes to thank the Government of France for offering to treat the patient in 2012, the Government of the United States of America for providing the financial resources required for treatment in France and the Government of Chile for the treatment of the patient in 2013.

The IAEA is grateful to the Government of Peru for its permission to disseminate, through this report, the valuable lessons identified from this accident. In addition, the IAEA expresses its gratitude to the Peruvian Institute

of Nuclear Energy and the Government of France for their assistance in the preparation of this report.

The IAEA officers responsible for the preparation of this publication were E.D. Herrera Reyes and M. Krishnamachari of the IAEA's Incident and Emergency Centre.

*EDITORIAL NOTE*

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# 1. INTRODUCTION

## 1.1. BACKGROUND

Industrial radiography is commonly used to detect defects in the weld joints of pipes and piping equipment. This non-destructive testing (NDT) technique detects defects using gamma radiation to penetrate components without damaging them. The equipment is generally portable and ideally suited to carrying out NDT in remote and often difficult conditions. Iridium-192 is ideal for gamma radiography, but other radionuclides can also be used depending on the characteristics of the object material. At the time of the accident, there were nearly one hundred gamma radiography sources in use in Peru.

The accident occurred during the late night hours of 11 January 2012 and the early morning hours of the next day. A Peruvian NDT company was carrying out operations in the district of Chilca, located in the Cañete Province of Lima. Three workers made a total of 97 radiography exposures over a period of about 2.5 h but did not verify whether the source was back inside the camera after each exposure. It was after completion of their tasks that one of the workers noticed that the source was not inside the camera but instead was stuck inside the guide tube. Realizing the seriousness of the situation, the worker informed the radiation protection officer (RPO) of the NDT company, who with the help of another worker, recovered the source and safely returned it to its normal location inside the camera. After about 3 h, the workers who had performed the radiography developed symptoms that included vomiting and fatigue. Three days after the accident, the company notified the national regulatory authority, the Peruvian Institute of Nuclear Energy (IPEN). IPEN conducted an investigation and recommended that the three workers be admitted to hospital. A formal request for assistance was sent from IPEN to the IAEA on 20 January 2012 under the Convention on Assistance in the Case of a Nuclear Accident or Radiological Emergency (the Assistance Convention) for dose reconstruction and medical advice. The IAEA received a second request from IPEN on 1 February 2012 under the same convention for the medical treatment of the worker who had been most severely exposed during the accident. This request was followed by a third, this time for medical assistance after this worker experienced a recurrence of symptoms; this third mission was completed in September 2013.

## 1.2. OBJECTIVE

Since 1988, the IAEA has provided support and assistance under the Assistance Convention and, when feasible, has developed follow-up reports. Several such reports have been published, such as those on the accidents in, chronologically, El Salvador [1], Israel [2], Belarus [3], Viet Nam [4], Peru [5], Panama [6], the Islamic Republic of Iran [7], and the Plurinational State of Bolivia [8]. The findings and conclusions in these publications have provided an objective basis for learning lessons to improve safety and emergency preparedness and response arrangements.

Similar to the accident discussed in this publication, previous accidents involving industrial radiography sources have occurred in Yanango, Peru [5], Gilan, Islamic Republic of Iran [7], and Cochabamba, the Plurinational State of Bolivia [8]. As early as 1998, the IAEA published a review of accidents in industrial radiography [9], and annex E to the United Nations Scientific Committee on the Effects of Atomic Radiation Report to the General Assembly in 2000 pointed out that "most of the accidents occurred in the industrial use of radiation and most of them involved industrial radiography sources" [10].

The objective of this report is to compile and disseminate information about (a) the circumstances that led to the accident in Chilca, (b) its initial handling by the national authorities and their request for assistance from the IAEA, (c) the response of the IAEA and (d) the work done with regard to the dose assessment and medical treatment of the three workers. This publication seeks to help Member States identify similar or precursor situations and take the necessary actions to either prevent accidents from occurring or mitigate the effects of radiation injuries in a timely manner.

The information in this publication is intended for use by competent authorities, regulatory bodies, emergency response planners, first response organizations and a broad range of specialists, including medical specialists, physicists and persons responsible for radiation protection, as well as facilities that use radioactive sources.

## 1.3. SCOPE

This publication gives an account of the events leading up to and following the accident, as well as the response actions taken. It describes in detail the methods and results of dose assessments and how these complemented the medical evaluations. It also describes the medical management of those involved

in the accident, including diagnosis and treatment details for the most exposed person. The publication ends with the findings, conclusions and lessons to be learned from this accident.

## 1.4. STRUCTURE

Information about the regulatory framework in Peru is provided in Section 2, which also includes details of the radiography camera and equipment involved in the accident. An account of the reported events leading to the accident, the recovery of the source, the identification of the accident and the reporting to IPEN is given in Section 3. Section 4 presents an overview of IPEN's initial response to the accident, the subsequent responses of the IAEA through the Response and Assistance Network (RANET) [11], and the assistance provided by other international organizations and Member States. Assistance included a first international assistance mission to Peru to provide advice and assistance on dose reconstruction, preliminary dose assessment and the strategy for medical treatment; a second international assistance mission to facilitate medical treatment in France of the most severely exposed worker; and a third international assistance mission to provide additional treatment in Chile for the same patient. Section 5 describes the preliminary dose assessment by the international assistance mission team and its recommendations for more accurate assessment. Section 6 discusses the team's preliminary medical diagnoses based on medical symptoms and the classification of the severity of patient lesions based on the available medical data. Section 7 outlines the medical recommendations from the international assistance mission to Peru, and Section 8 discusses the results from various methods of dose reconstruction, such as biological and electron paramagnetic resonance (EPR) dosimetry and computer simulations. Section 9 details the actual medical management of the affected workers in Peru, as well as the subsequent medical treatment of the most severely exposed patient in France and Chile, which took place during the second and third international assistance missions. Conclusions and lessons to be learned for different stakeholders are presented in Section 10. Appendices I–VI contain details of the Peruvian safety regulations, the chronology of activities of the international assistance mission team to Peru, reports on local radiation injury (LRI) and haematological manifestations, the results from biological dosimetry tests, and the sequence of events starting with December 2012 and leading to the treatment of the most severely exposed person in Chile in 2013.

# 2. BACKGROUND INFORMATION

## 2.1. REGULATORY FRAMEWORK

The legal framework and regulatory infrastructure in Peru with regard to radiation protection and the safety and security of radiation sources are described in this section.

### 2.1.1. Organization

IPEN is a government organization under the Ministry of Energy and Mines and is responsible for regulatory functions and activities related to the development, research and promotion of peaceful uses of nuclear technology.

The regulatory responsibilities of IPEN include:

(a) Authorization for the use of radiation sources;
(b) Regulatory inspections and enforcement activities for radiation safety in nuclear installations and during radiological practices;
(c) Approval of regulations;
(d) Maintenance of the national registry of radiation sources;
(e) Safeguarding of nuclear material;
(f) Security of radiation sources.

The regulatory functions of IPEN are carried out through the Technical Office of the National Authority, which reports directly to the President of IPEN. The Technical Office has two departments, the Department for Authorization and the Department for Control.

### 2.1.2. Legislative and legal framework for radiation safety

Under National Law 28028, the Law for Regulation of Ionizing Radiation Sources, IPEN is empowered as the national regulatory authority to carry out regulation and control with regard to radiation and nuclear safety, security and safeguards in Peru. Under this law, Supreme Decree 039-2008-EM establishes the regime for the authorization, inspection and enforcement of radiation safety [12]. The requirements related to radiation safety have been provided under the Radiation Safety Regulation, which was issued through Supreme Decree 009-97-EM and is based on the recommendations from the International Commission on Radiological Protection (Publication 60) [13] and the IAEA

(IAEA Safety Standards Series No. GSR Part 3, Radiation Protection and Safety of Radiation Sources: International Basic Safety Standards) [14].

The Supreme Decree 039-2008-EM establishes the categorization of various practices depending on the radiation risk involved. This supreme decree provides for a mechanism of enforcement and penalties. Various penalties have been set, and these penalties can range, depending on the event, from fines to the closure of the facility or installation.

There are also specific rules issued by IPEN with regard to safety in teletherapy, nuclear medicine, diagnostic X ray and industrial radiography. Industrial radiography is rated as a category A activity under IPEN's regulations, the highest regulatory level in Peru. Regulations require a licence to be issued for radiographic operations. Industrial radiography is specifically regulated by IPEN's rule IR.001.2009, entitled Radiation Safety Requirements for Industrial Radiography (in Spanish). This rule establishes for licensees the requirements related to safety of equipment, operational prerequisites, occupational exposure limits, public exposure limits, transport conditions, security requirements and emergency preparedness [15].

Appendix I lists, among other items, Peruvian national regulations, Peruvian national decrees and the safety standards issued by IPEN.

## 2.2. RADIATION APPLICATIONS IN PERU

The applications of radiation sources under IPEN regulatory administration at the time of the accident (January 2012) are listed in Table 1. There were about 3860 users of radiation sources in the country, 85% of which were medical and dental X ray applications.

IPEN authorizes specific organizations or companies to perform radiation applications and also authorizes qualified personnel to work in such organizations. The details of the number of organizations and qualified personnel authorized (as of January 2012) by IPEN to perform various applications of radiation sources are shown in Table 2. The total number of permits issued to individuals to work in facilities carrying a higher risk (e.g. industrial radiography) was 4381.

TABLE 1. FACILITIES UNDER THE ADMINISTRATION OF IPEN (JANUARY 2012)[a]

| Facility type | Number |
|---|---|
| Brachytherapy | 7 |
| Dental X ray | 1502 |
| Gamma irradiators | 4 |
| Import of radiation sources | 43 |
| Industrial radiography | 36 |
| Maintenance of radiation equipment | 21 |
| Medical X ray | 1763 |
| Nuclear gauges | 136 |
| Nuclear medicine | 43 |
| Radioactive waste management | 1 |
| Radioimmunoassay | 11 |
| Radioisotope production | 2 |
| Research and teaching | 11 |
| Teletherapy | 19 |
| Veterinary X ray | 15 |
| Well logging | 11 |
| X ray equipment sale | 203 |
| X ray fluorescence | 11 |
| X ray scanning for security purposes | 21 |
| Total | 3860 |

[a] This detailed information was provided by IPEN.

TABLE 2. ORGANIZATIONS AND AUTHORIZED OPERATORS IN PERU BY INDUSTRY SECTOR

| | Industrial | Medical | Other radiation related services | Government (IPEN) | Total |
|---|---|---|---|---|---|
| Organizations | 244 | 1302 | 233 | 5 | 1784 |
| Operators (staff) | 1051 | 2932 | 361 | 37 | 4381 |

## 2.3. LICENSING AND REVIEW PROCESS

### 2.3.1. Scope

The primary radiation safety regulations are applicable to all workers who carry out activities involving radiation sources. The regulations require that users notify IPEN of all activities involving radiation sources and request an authorization to carry out those activities. Authorizations are required for facilities and for individuals who would operate or handle radiation sources. Depending on the radiation practice, authorization from IPEN could consist of the simple registration of a practice, or it might require the issuance of an operating licence and a formal authorization to carry out a particular activity or perform a specific service [15].

### 2.3.2. Application for licence and its issue

The licensing process for operating a radiography camera begins with the submission of an application to IPEN, which must include all the technical information and details to prove that regulatory requirements are being met. The technical information includes a description of the installation and its radiation sources, radiation safety measures, organizational procedures, security provisions and measures, and emergency response plans. The information is assessed by the Technical Office of the National Authority, and an inspection is performed to verify and validate the information provided. Once it is determined that all the technical requirements pertaining to radiation safety are in compliance, the operating licence is granted. If the technical requirements are not met, the applicant is required to correct the identified deficiencies within a specified time frame. The licence also includes the specific conditions and scope of the activity,

such as the authorized location, the authorized equipment (camera, including manufacturer, model and serial number), the authorized source (radionuclide and maximum activity), the operational requirements, the emergency preparedness and response requirements, the transport requirements, the security provisions and the responsibilities relating to disposal of the source. In addition, a licensee is required to apply separately for a specific authorization to import any source [15], including sources to replace an $^{192}$Ir source.

### 2.3.3. Qualification of personnel

The staff members who operate the radiography camera and those who carry out radiation protection functions are required to have individual licences from IPEN. Personnel applying for individual licences should have the following qualifications:

(a) Radiography camera operators must have completed primary education, received a formal 20 h training course on radiation protection and have experience in the manipulation of a radiography camera under the supervision of a licensed worker. The applicants must also pass a qualification examination administered by IPEN. Licensed operators have to undergo a refresher training course every three years to revalidate their licences.
(b) RPOs must have completed a high school level education, received a formal 40 h training course on radiation protection and have at least six months' experience in industrial radiography operations or one year's experience in the radiation protection of sealed radioactive sources. The applicant must also pass a qualification examination administered by IPEN. RPOs have to undergo a refresher training course every three years to revalidate their licences [15].

### 2.3.4. Periodic inspections

Industrial radiography facilities are subject to annual inspections by IPEN, but the frequency of inspections is increased if IPEN considers it necessary. These inspections cover (a) the procedures that are in place to control operational exposures, (b) the monitoring programme, (c) the safety of sources during storage, (d) the procedures to ensure safety during transport, (e) the safety of equipment and radioactive sources, (f) operational procedures and (g) emergency response procedures. The findings of the inspection are conveyed to the users, and the licensee is required to take corrective actions within a stipulated time

frame to address any shortcomings. If these corrective actions are not taken, penalties are imposed on the licensee.

### 2.3.5. Renewal and revalidation of licences

The licences for industrial radiography have to be revalidated every three years. The application for revalidation is submitted to the Technical Office of the National Authority as a declaration of fulfilment of all the conditions and restrictions of the licence. The revalidation process includes an assessment of the licensee's history of complying with regulatory requirements and an inspection of the facility. Subject to all the conditions being met, the licence is revalidated for a further period of three years.

## 2.4. PROCEDURE FOR RADIOGRAPHY OPERATIONS

IPEN's regulations [15] for radiography operations require that:

(a) An operational radiological manual defining procedures for routine operations and emergencies for the specific facility or practice has been approved by IPEN;
(b) A calibrated ionizing radiation detector be used whenever the unit is in operation;
(c) The crew in the field include at least one operator and one RPO, each with a valid licence;
(d) Personal dosimeters, alarm dosimeters and direct reading dosimeters be available to all personnel involved in the operation;
(e) The radiography projector be assembled and arranged by the licensed operator;
(f) The area where the radiography is taking place be designated as a controlled area, with access restricted to only the authorized radiographer and assistant(s).

## 2.5. DEVICE AND SOURCE INVOLVED IN THE ACCIDENT

The device involved in the accident was a radiography camera unit manufactured by SPEC as Model SPECT 2T, Series 1016, containing an $^{192}$Ir source, which had a certified activity of 4366 GBq as of 23 December 2011 and an estimated activity of 3653 GBq on 12 January 2012. A short description of the camera, the associated equipment and the collimator is given below.

The container (projector) of the camera (Fig. 1) houses the source and devices to connect the remote control and the guide tube.

The camera has a remote control, which allows the source to be exposed or to be retracted to its safe position inside the projector. The remote control comprises a crank, a conductor cable, protection tubes and an attachment to the projector. A female connector in the conductor cable connects it to a male connector (pigtail) on the radioactive source.

The guide tube guides the source from the projector to the point of exposure. This tube has an exposure tip, which is placed in a collimator (Fig. 2) to limit the exposure in areas other than the target area.

There is an accompanying tool kit (Fig. 3), which contains the tools and equipment necessary to operate the camera.


*FIG. 1. The radiography camera involved in the accident.*

*FIG. 2. Collimator used during radiography of the pipes.*

*FIG. 3. Kit of equipment and tools associated with the camera.*

# 3. THE ACCIDENT

This section describes the circumstances that led to the accident, how it occurred and how it was noticed. The sequence of events was established on the basis of interviews with five exposed workers, interviews with the licensee and discussions with IPEN.

## 3.1. CIRCUMSTANCES OF THE ACCIDENT

### 3.1.1. Location and timing

The accident occurred late in the night of 11 January 2012 and during the early hours of 12 January 2012 at an electricity power plant in Chilca, Cañete, about 60 km south of Lima. Welding of different pipes was in progress, and a Peruvian company was carrying out an NDT examination to assess the quality of the weld joints. The NDT operation using the equipment described in Section 2.5 was planned to be carried out during the late night hours of 11 January 2012.

The operation was scheduled after normal working hours to reduce the possibility of exposure of personnel not engaged in NDT operations.

### 3.1.2. Details of the work being carried out

The work being carried out was the radiographic examination of pipes with diameters of 2, 3 and 4 in (5.1, 7.6 and 10.2 cm, respectively). Each of the 2 in (5.1 cm) pipes required two exposures; the other two required three exposures each. Consequently, there were two set-ups for this work. In the first set-up (referred to as 'area A', shown in Figs 4 and 5), the 2 in (5.1 cm) pipes were taken to the area, and in the second set-up (referred to as 'area B', shown in Figs 4 and 6), the radiography camera was taken to the location of the 3 and 4 in (7.6 and 10.2 cm) pipes.

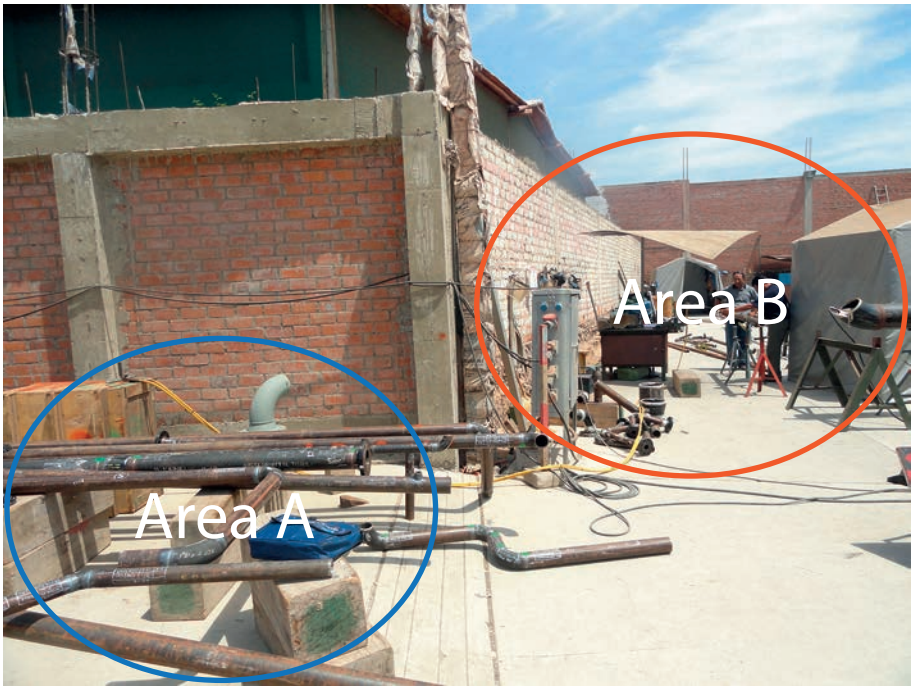


*FIG. 4. Working areas A and B.*

*FIG. 5. Set-up for the test of the 2 in (5.1 cm) pipes, area A.*

*FIG. 6. Set-up for the test of the 3 and 4 in (7.6 and 10.2 cm) pipes, area B.*

### 3.1.3. General arrangement of work and workplace

The work was carried out by assistants led by an authorized radiography camera operator (Worker 1). The RPO was not present when the work was carried out. The company provided the workers with a kit that included a set of tools and equipment for operational and personal safety. However, the two assistants, Co-worker 1 and Co-worker 2, left their personal dosimeters in the transportation vehicle; thus, Worker 1 was the only worker wearing a personal dosimeter. None of the workers used alarming dosimeters or direct reading dosimeters.

Worker 1 was responsible for carrying out the radiography and was assisted by Co-worker 1 and Co-worker 2. Co-worker 1 had the task of passing the films to Worker 1; Co-worker 2 was to codify the films and pass them to Co-worker 1. There was a portable monitor (Geiger–Müller) to measure background radiation in the area. This portable monitor was switched on and left on the floor to verify that the source had left the camera. According to Worker 1, the reading of this monitor was about 50 μSv/h when operations began. This reading was verified by Worker 1 and by both assistants from time to time when the exposures were being made. The objective of having this monitor in operation appears to have been only to verify that the source had left the camera and not to verify whether the source had returned after every exposure.

The radiographic camera was assembled and arranged by Co-worker 1. The camera not having been assembled by the authorized camera operator could have led to the wrong connection of the male and female connectors, as was revealed in the investigation.

## 3.2. HOW THE ACCIDENT OCCURRED

### 3.2.1. Overview

In total, 97 exposures were made by Worker 1 during a period of about 2.5 h, until operations ended at 02:20 on 12 January 2012. Worker 1 switched on the radiation monitor, launched the source and verified that the source had left the camera, but did not check the dose rates after each operation when the source was supposed to have returned to its safe position. The radiation monitor remained close to Co-worker 2 and was continuously showing the same reading of 50 μSv/h. The radiation monitor was never used to check whether the radioactive source had returned safely to the projector and was not used to monitor the area.

### 3.2.2. Radiography of the 2 in (5.1 cm) pipes

The radiography of the 2 in (5.1 cm) pipes was carried out first. Before each exposure, Worker 1 approached a table, as shown in Fig. 5, to align the source with the pipe joint to ensure the correct placement of the films. This operation was carried out at an average distance of 20 cm from the guide tube, and it is estimated that a total of about 80 min was spent at the table during the radiography of all these pipes. During these operations, Worker 1 touched the end of the guide tube at least ten times to align it correctly, and he would have spent almost 10 s in this position. On some occasions, he also lowered his head to watch the position of the end of the guide tube.

Information collected from the three workers indicated that, on each occasion, Co-worker 1 was near Worker 1 for about 20 s, after which Co-worker 1 would move away to a distance of about 15 m. Similarly, Co-worker 2 was also in close proximity to Worker 1 on 20 occasions, spending about 20 s there each time.

After the radiography of the 2 in (5.1 cm) pipes was complete, the radiography camera, tools and radiation monitor were taken to area B. Dose rates in the area were not checked during this process.

### 3.2.3. Radiography of the 3 and 4 in (7.6 and 10.2 cm) pipes

Before each exposure, Worker 1 would put the films around the pipe and then attach the guide tube to the pipe (see Fig. 6). During this work, Worker 1 would have spent some 50 min at a distance of about 20 cm from the guide tube. In these operations, Worker 1 manipulated the guide tube and the collimator. After completion of this work, when the planned activities had been carried out, Worker 1 dismantled the radiography equipment. Upon removal of the guide tube, Worker 1 noticed that the pigtail was not visible, and he realized that the source was not back in the camera. He used the detector to confirm this and verified that the area dose rate monitor (which had been switched on at the start of operation) was still indicating a reading of 50 μSv/h, even though the source was supposed to be in a safe position. He concluded that the source was stuck somewhere inside the guide tube. Realizing the seriousness of the situation, Worker 1 informed (via telephone) the company's RPO, who came to the scene accompanied by another worker (Worker 2). In an operation lasting about 1 min, the RPO and Worker 2 used the standard procedure for safely removing the stuck source from the guide tube and returning it to its place inside the camera.

### 3.3. INITIAL SYMPTOMS AND NOTIFICATION OF IPEN

At 02:30 on 12 January 2012, soon after the completion of the radiography work, Worker 1 vomited three times. Over the next 2 h, Worker 1 continued to vomit (ten times). At about 03:00, Co-worker 1 experienced fatigue, and at about 05:00, Co-worker 2 complained of dizziness. Worker 1 was taken to a local medical service in Chilca at 06:00 and, after intravenous hydration, was sent home on the presumption that he had a gastric problem. Around this time, Co-worker 1 vomited several times. All three workers were sent by the company to a private clinic, where it was concluded that their situation was stable and that they could return home.

The company conducted an investigation and processed some of the films exposed during the radiography. It was determined that the films had been overexposed for some reason. On 15 January 2012, an erythema appeared on the left hand index finger of Worker 1. The company then realized that the workers had been overexposed to radiation and telephoned IPEN to inform the organization about the accident.

The chronological sequence of the above events is summarized in Table 3.

## 4. THE RESPONSE

This section details the response by various organizations at different levels after the accident was reported to IPEN. The response of IPEN and other national organizations is described and is followed by information on the response at the international level.

### 4.1. RESPONSE AT THE NATIONAL LEVEL

In addition to IPEN, other national organizations played an important role in the response to the accident. These organizations included the Ministry of Foreign Affairs of the Government of Peru, the Permanent Representative of Peru to the IAEA and the National Institute of Neoplastic Diseases (INEN); the three workers who had been overexposed were admitted to INEN on 17 January 2012.

Soon after IPEN received the accident report from the radiographic company on 16 January 2012, it initiated a prompt investigation and made an assessment of the doses the workers would have received based on their statements.

TABLE 3. KEY EVENTS LEADING TO THE ACCIDENT AND THE NOTIFICATION OF IPEN

| Day | Date (Time) | Event(s) | Person/organization involved | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | Worker 1 | Co-worker 1 | Co-worker 2 | RPO | Worker 2 | Hospital | IPEN |
| 0 * | 11 Jan. 2012 (23:20) | The radiography camera is taken from the company's Chilca office to the location (5 min away) where the NDT is to be conducted. Co-worker 1 prepares the equipment. | x | x | x | | | | |
| 0/1 | 11 Jan. 2012 (23:32) to 12 Jan. 2012 (02:15) | Worker 1 carries out 97 radiographic exposures using the camera. | x | x | x | | | | |
| 1 | 12 Jan. 2012 (02:20) | Soon after dismantling the equipment, Worker 1 notices that the source is not in the camera and verifies that the area dose rate monitor (which had been switched on at the start of operations) is still indicating half of its scale (50 μSv/h), even though the source is supposed to be in a safe position. Recognizing the seriousness of the situation, he leaves the area and communicates the situation to the RPO. | x | | | x | | | |
| 1 | 12 Jan. 2012 (02:30) | The RPO and Worker 2 arrive at the scene and recover the source. They carry out the operation with a 2 m long clip and ensure that each of them is in the area for a period of 30 s or less. The recovery job is completed in about 1 min. | | | | x | x | | |

TABLE 3. KEY EVENTS LEADING TO THE ACCIDENT AND THE NOTIFICATION OF IPEN (cont.)

| Day | Date (Time) | Event(s) | Person/organization involved | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | Worker 1 | Co-worker 1 | Co-worker 2 | RPO | Worker 2 | Hospital | IPEN |
| 1 | 12 Jan. 2012 (02:30–05:00) | Worker 1 vomits three times and about 2 h later exhibits severe vomiting (ten times).<br>Co-worker 1 exhibits fatigue; Co-worker 2 exhibits dizziness. | x | x | x | | | | |
| 1 | 12 Jan. 2012 (06:00–07:00) | Worker 1 is taken to a medical facility and given intravenous hydration. He is sent home on the presumption that he has a gastric problem to be treated at home.<br>Co-worker 1 vomits several times. | x | x | | | | x | |
| 1 | 12 Jan. 2012 (09:00) | The company takes the three workers to a clinic for a medical check; it is concluded that they are all in a stable condition and that they can be sent back to their homes in Lima.<br>The company refers the affected persons to another clinic, and their blood counts are within normal ranges. | x | x | x | | | x | |
| 1 | 12 Jan. 2012 | The company initiates a parallel investigation into the event but is not able to gather much information.<br>Some of the films used in the assays are processed (the first and the last three), and it is confirmed that they have been overexposed.<br>Several possible reasons are considered for the overexposure. | | | | x | x | | |

TABLE 3. KEY EVENTS LEADING TO THE ACCIDENT AND THE NOTIFICATION OF IPEN (cont.)

| Day | Date (Time) | Event(s) | Person/organization involved | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | Worker 1 | Co-worker 1 | Co-worker 2 | RPO | Worker 2 | Hospital | IPEN |
| 4 | 15 Jan. 2012 | Worker 1 exhibits erythema on the index finger of his left hand. The company realizes that the three workers have been exposed to high radiation levels and that the source remained in the guide tube throughout the whole operation. In the evening, the company notifies IPEN by telephone about the incident. | x | | | | | | x |
| 5 | 16 Jan. 2012 | IPEN receives formal communication from the company (RPO), including details of the accident. | | | | x | | | x |

* Used as day 0 throughout this publication.

The InLight optically stimulated luminescence dosimeter of Worker 1 was sent for reading by the dosimetric service company. This initial dose assessment indicated high levels of exposure (about 7 Gy to the whole body) for Worker 1. For the two co-workers, estimates made with the help of numerical models indicated exposure levels in the range of 1 Gy. On 17 January 2012, IPEN recommended that the patients be sent to INEN for medical evaluation. A more detailed reconstruction of the events that led to the accident was made at the accident site, with the help of the workers involved. From the reconstruction, it appeared that, while some of the preliminary assessments would need to be revised, the dose estimates still indicated severe radiation exposures. After the collection of more details of the accident, a message was posted by IPEN on the IAEA Unified System for Information Exchange in Incidents and Emergencies web system on 19 January 2012. The IAEA's Incident and Emergency Centre (IEC) immediately reacted and, on the same day, offered the IAEA's good offices. The chronology of actions taken at the national level, up to the arrival of the IAEA international assistance mission, is summarized in Table 4.

## 4.2. IAEA RESPONSE AND INTERNATIONAL ASSISTANCE

On 19 January 2012, the IAEA's IEC received a communication from Peru reporting the accident and, on the same day, the IEC formally offered its good offices to the competent authority in Peru, IPEN, for any assistance it might need in responding to the accident. On the next day, 20 January 2012, a formal request for assistance under the Assistance Convention was made by Peru to the IEC, which immediately initiated the process of organizing an international assistance mission involving the IAEA RANET. During this period, the IEC communicated and stayed in contact with RANET counterparts and other counterparts from the World Health Organization and the Pan American Health Organization.

TABLE 4. CHRONOLOGY OF ACTIONS AT NATIONAL LEVEL

| Date | Action |
|---|---|
| 15 Jan. 2012 | IPEN is notified of the accident. |
| 16 Jan. 2012 | The formal report of the accident is received by IPEN, and emergency actions are initiated. |
| 17 Jan. 2012 | Statements about what happened are obtained by IPEN from the affected workers, the RPO and the manager of the company. |
| | Exposures are estimated by interviewing affected workers. |
| | The first medical examination of the workers is conducted by the IPEN physician. |
| | IPEN recommends to the company that the affected workers be admitted to INEN for medical evaluation. |
| 19 Jan. 2012 | Information on the accident is reported to the IAEA's IEC through the Unified System for Information Exchange in Incidents and Emergencies. |
| | IPEN receives an offer of good offices from the IAEA for any assistance in responding to the accident. |
| 20 Jan. 2012 | IPEN requests the dosimetry service provider to repeat the reading of Worker 1's InLight optically stimulated luminescence dosimeter to confirm the results. The dose report is confirmed. |
| | IPEN submits an official request for assistance to the IAEA under the Assistance Convention. |
| 21 Jan. 2012 | IPEN performs an on-site reconstruction of the accident. Workers 1 and 2, Co-workers 1 and 2, the RPO and INEN specialists participate in this effort. The mean whole body dose to Worker 1 (the most exposed worker) is assessed to be about 4.4 Gy. |
| 22 Jan. 2012 | IPEN receives an IAEA international assistance mission. |

### 4.2.1. First IAEA international assistance mission to Peru

The IAEA's IEC prepared an assistance action plan for dose assessment support and medical advice. The IAEA international assistance mission to Peru had the following objectives:

(a) Assess the medical condition of the persons who had been overexposed to radiation.
(b) Assess the radiological impact in terms of local doses and whole body doses of these persons.
(c) Provide medical advice for treatment.
(d) Provide support for dose reconstruction based on the most probable exposure scenario.
(e) Recommend additional actions to be taken by Peru and the IAEA in responding to the radiation emergency.
(f) Gather information for a possible report to be published.

The international assistance mission team was composed of two medical experts from France, one from the Institute for Radiological Protection and Nuclear Safety (IRSN), Fontenay-aux-Roses, and the other from the Hôpital d'instruction des armées Percy (HIA Percy), Clamart. An expert from the IAEA's IEC was the assistance mission leader.

The team arrived in Lima on 22 January 2012, met with the officials of IPEN and visited the workers in the INEN hospital to assist with continuing medical evaluations. After discussions and agreements with IPEN and INEN personnel, contacts with the IRSN in France were initiated to carry out biological dose assessments as a complementary evaluation to the assessments already being made in Peru. IPEN developed a presentation on preliminary dose reconstruction data. The first phase of the mission ended with the French expert from the HIA Percy leaving for France with the biological samples on 23 January 2012. The other two team members continued to assess the most severely exposed worker (Worker 1) and reconstructed the events leading to the accident. These tasks involved obtaining more accurate data from IPEN officials and INEN physicians, evaluating the results of Worker 1's personal dosimeter and performing a more detailed reconstruction of the accident scenario.

After a final medical debriefing on 25 January 2012, the mission drafted its conclusions and recommendations about the medical issues involved, emphasizing the possibility that it might be necessary to transfer Worker 1 for very specialized treatment. The mission members departed from Lima on 26 January 2012.

A detailed chronology of the international assistance mission team's activities during this period is given in Appendix II.

### 4.2.2. Second IAEA international assistance mission for medical treatment of Worker 1 in France

Although the IAEA's international assistance mission team completed its task and left Peru on 26 January 2012, the team continued to follow developments in the health of the three workers who were under treatment in Peru. It became clear that Worker 1 had the worst prognosis and would need specialized treatment. Urgent steps were needed to transfer him to a specialized centre with state of the art capabilities for the treatment of a severe LRI. On 1 February 2012, the IAEA's IEC received a formal request from IPEN for assistance with the medical treatment of Worker 1 "in a hospital having a high level of knowledge and experience in the treatment of irradiated victims combining haematological resuscitation and combined plastic surgery to autologous human grade stem cell injection".

The IAEA's IEC initiated immediate actions in response to this formal request for assistance. Member States with the required medical treatment facilities and expertise in this field were asked to convey their availability to provide the medical treatment. Also, a request sent to all competent authorities in Member States asked their counterparts to consider providing financial support for the medical treatment. On 2 February 2012, an offer of assistance was received from the HIA Percy in France. A request was sent by the IEC to the competent authorities of Member States, under the Assistance Convention, inviting them to provide financial support for the treatment.

The World Health Organization expressed its interest in following up on and supporting the activities of the IAEA's IEC related to the offer of assistance to Peru. On 3 February 2012, the Government of the United States of America (USA) offered financial support for the medical treatment of Worker 1. On the basis of the various responses and offers received by the IEC, including the offer of financial support received from the USA, the Government of Peru decided to accept France's offer of medical treatment. The IEC immediately prepared the second assistance action plan, defining the treatment to be undertaken and detailing the financial arrangements with regard to the expenses to be borne by the IAEA and the Governments of France, Peru and the USA. The plan was put into operation on the same day (3 February 2012). Worker 1 and a doctor from IPEN arrived at the HIA Percy on 6 February 2012, where the patient's treatment commenced without delay.

The medical experts in France kept the IAEA's IEC regularly informed about progress in the treatment of the patient. By mid-May 2012, his treatment

was complete, and he returned to Peru. With this, the second international assistance mission of the IAEA's IEC was concluded.

### 4.2.3. Third IAEA international assistance mission for medical treatment of Worker 1 in Chile

In November 2012, it was reported that Worker 1 had experienced slight pain in both hands and, over the next month, there was noticeable retraction of the grafted skin. In late January 2013, the Peruvian doctors discussed the health status of the patient with medical staff from the IAEA's IEC and from France. The deteriorating health of the patient led to a teleconference in mid-May 2013, and a third request for assistance was received from Peru on 18 May 2013. On the basis of this request, the IEC approached several Member States for assistance to Peru, and a positive response was received from Chile on 20 June 2013. The objectives of a third assistance action plan, designed by the IAEA's IEC, included a medical evaluation of the patient's condition, reconstructive surgery and cell therapy (mesenchymal stem cells (MSCs) or MSC injections) and other treatment as necessary, and the establishment of an arrangement for follow-up reporting on the medical treatment that was being administered. The Mutual de Seguridad Hospital in Santiago, in cooperation with the Stem Cells Laboratory of Del Desarrollo University and with the Chilean Nuclear Energy Commission, offered to carry out the treatment free of cost. To meet the objectives of the mission, the Government of France provided the services of an expert medical team composed of doctors from the IRSN and the HIA Percy. The IAEA's IEC organized and took the lead in the development of the international assistance mission, which was composed of medical experts from the IRSN, the HIA Percy and the IEC.

The international assistance mission met in Chile on 27 and 28 June 2013 and — after a detailed review of the infrastructure, an assessment of medical capabilities and a meeting with the healthcare professionals involved — the team recommended a strategy for the treatment of the patient in Chile. In mid-July 2013, Worker 1 travelled to Chile for several days to undergo a medical evaluation. A blood sample was taken for cytogenetic biological dosimetry, and bone marrow and platelet samples were taken to facilitate the cultivation of MSCs. The medical expert from the HIA Percy also went to Chile at this time to oversee the procedures. Worker 1 returned to Chile on 4 August 2013 and was admitted to the Mutual de Seguridad Hospital. On behalf of the international assistance mission team, two medical experts from the HIA Percy and the medical expert from the IAEA's IEC also arrived in Chile. After reviewing the medical condition of Worker 1, the experts decided on the course of treatment. On 7 August 2013, two procedures were carried out: a second bone marrow collection procedure

and amputation surgery on the affected fingers of both hands. These procedures were followed by four MSC injections, the last on 6 September 2013. At this point, the medical condition of Worker 1 was stable and satisfactory. He was experiencing no pain, and the wounds had healed. It was recommended that a medical follow-up be performed every three months for the first year, with annual medical follow-ups to be carried out for at least ten years. With this, the third international assistance mission of the IAEA concluded.

# 5. PRELIMINARY DOSE ASSESSMENT

## 5.1. INITIAL DOSE ASSESSMENT

### 5.1.1. Preliminary reconstruction and assessment by Peruvian experts

Soon after IPEN was notified about the accident, an interview was held with the five affected workers (Worker 1, Co-worker 1, Co-worker 2, the RPO and Worker 2). Present at the meeting were, among others, three technical personnel and the physician of IPEN. A first estimate of the dose concluded that Worker 1 had received about 50 Gy on his left hand index finger and about a 4.6 Gy whole body dose. The personal dosimeter used by Worker 1 indicated a whole body dose of about 7 Gy, but this was considered improbable taking into account the clinical manifestations (symptoms and haematological indicators) that would have presented if that had been the case. The whole body doses were estimated to be 1 Gy for Co-worker 1 and less than 1 Gy for Co-worker 2.

Subsequently, IPEN undertook a more detailed reconstruction analysis of the events on the basis of the affected workers' descriptions of what had happened and the data that were available. A preliminary reconstruction of events was made to compute the dose assessment. This reconstruction was based on the following information about the activities performed by each of the five workers:

(a) Worker 1. Worker 1 performed the set-up for all the radiography tests, which included moving the guide tube and holding it at a distance of about 10 cm from its end. To align the guide tube with the film, Worker 1 would put his left hand index finger in to the open side of the collimator and touch the (presumably empty) guide tube.
(b) Co-worker 1. According to the information provided by all the workers, Co-worker 1 assisted Worker 1 with the set-up of three to five exposures. During this process, he touched the guide tube with his hand approximately

10 cm from the end of the tube, where the source is likely to have been located. The estimated time for this operation was 30 s. On two other occasions, when the exposures were made, his relative position was estimated to have been 1 m from the source.

(c) Co-worker 2. According to information provided by all the workers, Co-worker 2 was most of the time behind the walls around the corner next to the location where the NDT was being conducted. Co-worker 2 assisted Worker 1 in setting up 10–15 exposures and, in the process, his relative position with respect to the source was about 2 m. It was estimated that, on each of these occasions, he would have been in that position for 10 s.

(d) RPO and Worker 2. When called to the scene, these two workers were aware that the source was stuck inside the guide tube, and they observed the necessary precautions to recover the source in a safe manner. The RPO ensured that both of them were 2 m or further from the source, and that they were exposed for no more than 30 s. They completed the task of recovery and returned the source to a safe location in about 1 min.

### 5.1.2. Preliminary assessment with the assistance of international experts

Soon after its arrival, the international assistance mission team requested a visit to the accident site to reconstruct the sequence of events and the most probable accident scenario to facilitate the dose assessment. However, because of some practical difficulties, this could not be arranged. IPEN explained that a visit to the NDT company's site was problematic because of the short time available for making the necessary arrangements. IPEN added that it had carried out a detailed in situ reconstruction of the event a few days earlier, on 21 January 2012. IPEN emphasized that the careful reconstruction of events and the collection of data had taken into consideration different possible scenarios and the available data on the source, the camera and the tools used.

While evaluating the dose assessment, in addition to the duration or number of each of the radiographic activities, other possible contributing factors were considered by the international assistance mission team. One factor was the time spent by workers entering or leaving the work site and the time spent in the safe location behind a wall. The time estimate for this purpose, based on the reconstruction, was 25 s for a round trip (from the safe area to the work area and back). If this time estimate, the worst case scenario of the beam being focused in the direction of the workers, and attenuation due to the wall thickness of the pipe were all taken into consideration, the dose estimate for the time spent entering or leaving the site was 1 mGy. This dose was considered too low for practical purposes and was not included in the dose estimate for the workers during this event.

The more important factor was the time during which the three workers (Worker 1, Co-worker 1 and Co-worker 2) adjusted the camera and guide tube. On the basis of the information collected, this time was accounted for in the original plan for the set-up of each exposure.

On the basis of these factors, the international assistance mission team made preliminary estimations of the doses received by the workers according to where the source was expected to have been located at the time of the accident. The estimates for Co-worker 1, Co-worker 2, the RPO and Worker 2 are shown in Table 5. The assessments also took into consideration the estimates made by IPEN and INEN. Since Worker 1 was identified as the most severely exposed person, more detailed estimates were computed for him (Table 6) than for the other affected workers.

TABLE 5. PRELIMINARY DOSE RANGE ESTIMATED FOR CO-WORKER 1, CO-WORKER 2, RPO AND WORKER 2

| Type of dose | Co-worker 1 | Co-worker 2 | RPO | Worker 2 |
|---|---|---|---|---|
| Equivalent dose to the most exposed hand | No verifiable/ credible values | No verifiable/ credible values | Not relevant | Not relevant |
| Whole body dose (Gy) | 0.3 | 0.15 | 0.001 | 0.001 |

TABLE 6. PRELIMINARY DOSE RANGE ESTIMATED FOR WORKER 1

| Type of dose | Dose (Gy) |
|---|---|
| Equivalent dose to the left index finger | 40.0–44.6 |
| Equivalent dose to the right hand (area close to the second hole of the collimator) | 6.2 |
| Equivalent dose to the lens | 0.07–1.02 |
| Equivalent dose to the gonads | 0.07–1.17 |
| Whole body dose | 1.49–4.14 |

It was evident to the international assistance mission team that Worker 1, Co-worker 1 and Co-worker 2 all had whole body or partial body exposures, especially in the hands. The diagnoses and prognoses for the severity of the damage required an accurate follow-up of the clinical manifestations, laboratory results and biological dosimetric information.

It was difficult to reconstruct the exposure scenario because of the confusion, uncertainties and different versions of the sequence and timing of events described by the workers. Consequently, the international assistance mission team concluded that biological dosimetric investigations and other complementary strategies were essential for an adequate evaluation of the patients.

### 5.2. STRATEGY RECOMMENDED FOR MORE ACCURATE DOSE ASSESSMENT

The strategy recommended by the international assistance mission team to more accurately assess the dose received, and its heterogeneity, was based on three complementary approaches: biological dosimetry (based on cytogenetics), physical dosimetry (such as EPR) and dosimetric reconstruction with computer simulation.

As a first step, the team proceeded with biological dosimetry for all five workers, which involved blood samples being collected and sent to the IRSN in France. This step was taken in parallel with the analysis of the blood samples carried out by the Peruvian laboratory. With regard to physical dosimetry, samples of tooth enamel, fingernails and toenails from Worker 1 (the most severely affected person) were sent to France. The objective was to analyse these samples with the EPR technique and to compare the doses with data obtained from biological dosimetry and individual passive dosimetry.

## 6. CLINICAL MANIFESTATIONS AND PRELIMINARY DIAGNOSES

In addition to conducting a preliminary dose assessment, the international assistance mission team performed a preliminary assessment of the medical status of the three overexposed workers. The preliminary dose assessment was based on the various clinical signs and symptoms as a function of time, the description

of the accident scenario and the timing of the various events according to the histories of the exposures. The assessment enabled a reasonable diagnosis for the three patients, who were classified in accordance with the Medical Treatment Protocols for Radiation Accident Victims (METREPOL) system. The nomenclature used under this classification system is as follows:

— N: neurovascular.
— H: haematological.
— C: cutaneous.
— G: gastrointestinal.

Depending on the clinical findings, the above aspects are evaluated on a scale of 1 to 4, with the minimum severity rated as 1 and the maximum rated as 4. The classification will change over time, depending on the clinical evolution and the degree of severity of each affected aspect.

## 6.1. PRODROMAL MANIFESTATIONS

Local medical staff recorded the prodromal manifestations (early symptoms and signs of the onset of any disease) of the workers. The international assistance mission team interviewed the workers for the first time on day 11 after the accident (i.e. the day of the arrival of the first international assistance mission in Peru), when it carried out an anamnesis (detailed medical history of events and symptoms related to a clinical condition, as related by the patient to the physician) and a detailed physical examination of Worker 1, Co-worker 1 and Co-worker 2. This information is given in Table 7.

The international assistance mission team noted that, although the lymphocyte counts were obtained 24 h after the accident for Worker 1, Co-worker 1 and Co-worker 2, it was difficult to interpret the results because there were no baseline data and because new samples were not taken until 48 h after the accident. The values of the blood count obtained 24 h after the exposure were within the normal range. The team also noted that Worker 1 and Co-worker 1 developed initial mild clinical signs and symptoms that could be considered compatible with the prodromal manifestation of acute radiation syndrome (ARS). Although the character of the exposures was protracted, the systemic manifestations, such as the time of the onset of vomiting and the absence of fever, in particular, suggested a whole body dose of around 2 Gy for Worker 1 and less than 1–2 Gy for Co-worker 1.

TABLE 7. SYMPTOMS OF THE AFFECTED PERSONS RECORDED BY THE INTERNATIONAL ASSISTANCE MISSION TEAM

| Clinical manifestation | Worker 1 | Co-worker 1 | Co-worker 2 |
|---|---|---|---|
| Nausea | No | Yes | Mild |
| Vomiting | First vomiting after 3 h (three times)<br>Second vomiting after 5 h (ten times) | First vomiting after 6 h 30 min (twice)<br>Second vomiting after 6 h 40 min (three times)<br>Third vomiting after 7 h 30 min (three times) | No |
| Anorexia | Yes, after 9 h | Yes, after 2 d | No |
| Fatigue | Yes | Yes, after 3 h 30 min | No |
| Fever | No | No | No |
| Headache | Yes, after 4 h | No | No |
| Hypotension | No | No | No |
| Diarrhoea | No | No | No |
| Erythema | Yes, on index finger of left hand (day 4) | No | No |
| Lymphocyte count[a] (24 h after accident) | $2.10 \times 10^9$/L | $3.1 \times 10^9$/L | $2.55 \times 10^9$/L |

**Note:** All time durations consider the radiography work to have begun at 23:30 on 11 January 2012 and to have ended at 02:30 on 12 January 2012.

[a] Lymphocyte count can be expressed in $\times 10^9$ (Giga) per litre, which can also be written as 'G/L'; the normal range for this laboratory was $1.5 \times 10^9$/L to $3.5 \times 10^9$/L.

## 6.2. CUTANEOUS MANIFESTATIONS

An LRI can occur after radiation induced damage to the skin and underlying tissues (i.e. muscle and bone). It is mainly caused by the loss of basal cells of the epidermis and microvascular endothelial cells, combined with severe inflammatory reaction of the skin and underlying muscles that are responsible for the typical clinical signs and symptoms of an LRI. An LRI generally develops in three phases, beginning with a prodromal phase characterized by erythema and pain, followed by an often asymptomatic latent phase that can take two to three weeks, depending on the dose received locally and the volume of the irradiated tissues. An LRI can further progress with symptoms and lesions, such as painful moist desquamation and necrosis of the skin and underlying tissues. Depending on the dose received locally and the volume of irradiated tissue, the time of onset of these manifestations may vary from hours to days or weeks after exposure. Daily follow-up of the lesion is required for a long period after the exposure.

Meticulous inspection of the skin of all three affected workers on day 11 indicated that Worker 1 had a severe LRI on both hands and the other two workers had also developed symptoms of LRIs during the prodromal phase, indicating significant overexposure to radiation. It was also concluded that all three workers faced a high risk of localized radionecrosis. Additional information related to LRIs for the three affected workers up to day 19 is given in Appendix III.

## 6.3. HAEMATOLOGICAL MANIFESTATIONS

Haematological ARS can occur after radiation induced damage to the haematopoietic tissue in the bone marrow. It is mainly caused by the compromise of multiple cell lineages, resulting in the typical haematological manifestations of ARS in a person with whole body exposure, when the dose threshold of 1 Gy is exceeded. Generally, after radiation exposure of the whole or a significant part of the body, lymphopoiesis, granulopoiesis, thrombopoiesis and erythropoiesis can develop with different degrees of severity. Granulocytopenia results in a risk of infection, and thrombocytopenia gives rise to a risk of bleeding. Daily blood counts are required for follow-up of the exposed person. A detailed report on ARS (haematological manifestations) exhibited by the three affected workers is presented in Appendix IV, and a summary of the findings is given is the following subsections.

### 6.3.1. Worker 1

The clinical manifestations of this patient were compatible with:

(a) The physical dose reconstruction that estimated a whole body exposure of 1–2 Gy;
(b) The biological dosimetry that estimated a dose of 1.86 Gy combined with high heterogeneity (the upper part of the body having received doses that ranged from 2.5 to 3.5 Gy);
(c) The EPR dosimetry to the teeth that estimated a dose of 3 and 4 Gy, and the EPR dosimetry of the fingernails and toenails, which also confirmed the significant heterogeneity of the exposure.

It was concluded that Worker 1 had experienced mild haematological ARS. On day 14, he was classified as degree 3 on the METREPOL scale. The fact that this patient received an estimated dose of 4 Gy to the upper part of his body suggested that he had a high risk of aplasia within the following 10 d.

### 6.3.2. Co-worker 1

The information provided by Co-worker 1 contained several uncertainties, but it was observed that his clinical evolution was compatible with an incurred whole body dose of 0.45 Gy, estimated through biological dosimetry, and was not contradicted by the dose reconstruction, which indicated an exposure of 0.3 Gy.

It was concluded that Co-worker 1 had developed mild haematological ARS. On day 14, he was classified as degree 2 on the METREPOL scale. Given that he had received a dose estimated at 0.45 Gy, the possibility of any severe bone marrow damage was excluded. However, a follow-up of the blood count twice a week for a month thereafter was recommended.

### 6.3.3. Co-worker 2

The clinical manifestations of this patient were compatible with the biological dosimetry, which estimated a dose of 0.75 Gy. The dose reconstruction estimated an exposure of 0.15 Gy.

It was concluded that Co-worker 2 had developed mild haematological ARS. On day 14, he was classified as degree 2 on the METREPOL scale. Given that he had received a dose estimated at 0.75 Gy, the possibility of any severe bone marrow damage was excluded. However, a follow-up of the blood count twice a week for a month thereafter was recommended.

### 6.4. CLINICAL CONCLUSIONS: CLASSIFICATION OF THE SEVERITY OF LESIONS

The preliminary dose assessment was based on the various clinical signs and symptoms as a function of time, the description of the accident scenario and the timing of the various events derived from the histories of exposures. The assessment enabled a reasonable diagnosis for the three workers.

The three affected workers were graded using the METREPOL classification on day 14 after the accident (25 January 2012), and the results are shown in Table 8 (day 0 taken as 11 January 2012).

TABLE 8. METREPOL CLASSIFICATION (ON DAY 14) OF THE SEVERITY OF THE RADIATION INDUCED INJURIES TO THE THREE AFFECTED WORKERS

| Affected person | Grading of severity on day 14 (25 January 2012), METREPOL classification system |
|---|---|
| Worker 1 | N2 H3 C4 G0 |
| Co-worker 1 | N1 H2 C3 G0 |
| Co-worker 2 | N0 H2 C1 G0 |

## 7. MEDICAL RECOMMENDATIONS AT THE CONCLUSION OF THE INTERNATIONAL ASSISTANCE MISSION TO PERU

At the conclusion of its mission to Peru, the international assistance mission team made recommendations with respect to all five workers involved in the accident. These recommendations follow.

### 7.1. WORKER 1

This person was the most severely exposed to radiation during the accident. He received a significantly heterogeneous whole body dose of 1.8 Gy (with 75% of the body having received a dose in the range of 4 Gy), as well as doses ranging from 20 to 50 Gy to the extremities of both hands. The patient was graded

N2 H3 C4 G0 as of day 14 after the accident. It was expected that he could experience progressive and severe bone marrow failure (aplasia) in the next 10 d, combined with severe radionecrosis of several fingers of both hands, with a high risk of tissue radionecrosis of both hands. On the basis of this information, the international assistance mission team made the following recommendations:

(a) IPEN and the medical staff in charge of Worker 1 should formally request, as soon as possible, assistance from the IAEA under the Assistance Convention for specialized medical treatment of this patient.
(b) Worker 1 should be transferred by the first week of February 2012 to a hospital with facilities for (a) surgery; (b) intensive care medicine in haematology, equipped with a state of the art isolation system such as high efficiency particulate air filtration; and (c) stem cell therapy in a unit approved by the appropriate national authority.
(c) The strategy for the treatment of this person would be complex and could include supportive therapy (blood and platelet transfusion) and stimulation therapy using a combination of cytokines, including granulocyte colony stimulating factor and erythropoietin in the case of bone marrow aplasia. If necessitated by the clinical conditions, this treatment would be combined with treatment for severe radiation necrosis of distal extremities, including skin autograft, which in turn would be combined with ex vivo expanded autologous or allogenic human clinical grade MSC injections.
(d) As an additional precaution, a spermogram should be carried out within a month and repeated after six months. Lens opacities should also be checked after six months, and the evaluation should be repeated after a year.
(e) Since the prognosis for this patient was guarded, it was suggested to the Peruvian authorities that it would be prudent for them to immediately initiate a request for international medical assistance so that, if the patient's clinical condition deteriorated, specialized treatment could be arranged with minimal delay. It was recognized that facilities for such treatment were not available at the time in Peru.

### 7.2. CO-WORKER 1

On day 14 after the accident, on the basis of the various symptoms and signs that the patient had developed since exposure, he was graded N1 H2 C3 G0. The observed clinical and laboratory manifestations conformed to the estimated dose received. Although the risk of severe haematological compromise was excluded, this patient was considered to be at high risk of developing a severe LRI on both

hands within a few weeks. The international assistance mission team made the following recommendations:

(a) The superficial lesions of the hands, which had recently developed, should be managed in the following days or weeks with non-compressed fat dressing and Biafine. Severe pain should be periodically controlled with topical steroid therapy (dexamethasone). If the lesion deteriorated, a decision would have to be made on other actions. This could be through a consultation between the medical group in charge of the patient in Peru and the members of the international assistance mission team.
(b) A haematological survey should be conducted twice a week over the following month.
(c) EPR dosimetry of the fingernails should be used to confirm the prognosis for radiological injury.
(d) As an additional precaution, a spermogram should be carried out within a month and repeated after six months. Lens opacities should also be checked after six months, and the evaluation should be repeated after a year.

### 7.3. CO-WORKER 2

On day 14 after the accident, on the basis of the symptoms and signs that the patient developed since exposure, he was graded N0 H2 C1 G0. The observed clinical and laboratory manifestations conformed to the estimated dose exposures. Although the risk of severe haematological compromise was excluded, this person was considered to be at high risk of developing a severe LRI on his right hand within a few weeks. The international assistance mission team made the following recommendations:

(a) The superficial lesions of the hands, which had just developed, should be managed in the following few days or weeks with non-compressed fat dressing and Biafine. Severe pain should be periodically controlled with topical steroid therapy (dexamethasone). If the condition of the lesion deteriorated, a decision would have to be made on other actions through a consultation between the medical group in charge of the patient in Peru and the members of the international assistance mission team.
(b) A haematological survey should be conducted twice a week over the following month.
(c) EPR dosimetry of the fingernails should be used to confirm the prognosis for radiological injury.

(d) As an additional precaution, a spermogram should be carried out within a month and repeated after six months. Lens opacities should also be checked after six months, and the evaluation should be repeated after a year.

### 7.4. RADIATION PROTECTION OFFICER AND WORKER 2

The international assistance mission team concluded that, of the five workers involved in the accident, the radiation doses received by these two workers were below the threshold for any deterministic effect. This determination was based on a reconstruction of events. In view of this, the international assistance mission team did not recommend any specific follow-up actions for the RPO and Worker 2. However, as a precautionary measure, their blood samples were taken for analysis. Subsequent results confirmed the international assistance mission team's hypothesis.

## 8. DOSE RECONSTRUCTION: BIOLOGICAL AND ELECTRON PARAMAGNETIC RESONANCE DOSIMETRY, COMPUTER SIMULATION

### 8.1. BIOLOGICAL DOSIMETRY ON SAMPLES OF ALL FIVE WORKERS

#### 8.1.1. Overview of the biological dosimetry technique

Exposing a cell to ionizing radiation can cause breaks in the chromosomes in the nucleus. Within the nucleus, broken chromosomes can reattach incorrectly, creating a chromosome aberration. The frequency of aberrations is related to the nature of the radiation source, the intensity of the radiation and the dose rate. Chromosomal aberrations that are induced from a whole body exposure to radiation can be counted by placing the cells in a culture and observing them during their first division at the metaphase stage. The method used is to culture lymphocytes for 48 h to induce their division. Then, the division is blocked by colchicine in the first stage of the metaphase. These cells are then spread on glass slides, stained and observed under a microscope at high magnification. The counting of chromosomal aberrations is performed visually on hundreds of metaphases (usually 500) by at least two operators.

It is possible to use reference dose effect calibration curves to arrive at the dose received by the patient. The reference curve is obtained by counting dicentric

and centric rings in blood samples exposed in vitro to homogeneous and acute gamma radiation from a $^{60}$Co source with a dose rate of 0.5 Gy/min. However, the direct relationship between dicentric frequency and the dose received by an individual may vary according to the quality of the radiation and the dose rate.

### 8.1.2. Biological dosimetry carried out by the IRSN

The biological dosimetry test was carried out at the IRSN in accordance with the International Organization for Standardization standard 19238:2004 [16]. Dicentric chromosomes are specific biomarkers for ionizing radiation, but only some radiomimetic drugs are able to produce dicentric chromosomes. The dose reconstructions were carried out using 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.

The blood samples arrived at the IRSN within 24 h of being taken from the affected persons; that is, on 24 January 2012 (corresponding to day 13). The culture of lymphocytes was performed on the same day. The dose response curve used for mathematical interpolation was obtained by scoring dicentric and ring chromosomes in blood samples exposed in vitro to uniform and acute gamma irradiation from a $^{60}$Co source with a dose rate of 0.5 Gy/min. The coefficients of the reference curve (linear quadratic $Y = c + \alpha D + \beta D^2$) were $\alpha = 0.0338 \pm 0.01008$, $\beta = 0.0536 \pm 0.0010$ and $c = 0.00443 \pm 0.00039$, where $Y$ is the frequency of dicentric and ring chromosomes and $D$ is the dose of ionizing radiation.

The results of the biological dosimetry tests are summarized in Table 9.

TABLE 9. DOSE ESTIMATION BASED ON BIOLOGICAL DOSIMETRY

| Person | Whole body dose (Gy) | Confidence interval | Partial body irradiation |
|---|---|---|---|
| Worker 1 | 1.86 | 1.56–2.20 | Yes |
| Co-worker 1 | 0.45 | 0.23–0.75 | Could not be determined |
| Co-worker 2 | 0.75 | 0.50–1.06 | Could not be determined |
| RPO | Below detection limit | n.a.[a] | Could not be determined |
| Worker 2 | Below detection limit | n.a.[a] | Could not be determined |

**Note:** Data courtesy of the IRSN.

[a] n.a.: not applicable.

Additional technical information on biological dosimetry results with respect to the five workers whose samples were tested is given in Appendix V.

## 8.2. RESULTS FROM ELECTRON PARAMAGNETIC RESONANCE DOSIMETRY ON WORKER 1, CO-WORKER 1 AND CO-WORKER 2

### 8.2.1. Overview of the electron paramagnetic resonance technique

The EPR technique is a spectroscopic method based on analysis of the absorption of a microwave by unpaired electrons placed in a magnetic field. The interaction between ionizing radiation and the atoms and molecules composing the material generates excitation and ionization phenomena leading to the formation of free radicals. The quantity of such induced free radicals is proportional to the dose received in the sample material. A wide range of materials can be analysed with this technique. Such materials could include biological samples from the body of the exposed person (teeth, bones or nails) or materials worn by the person (e.g. mineral glass from mobile phones).

### 8.2.2. Rationale for electron paramagnetic resonance analysis

In addition to localized irradiation to the hands, whole body irradiation also had to be taken into consideration because of the scenario and the topology of the accident. EPR analysis can provide relevant information for both aspects of such radiation exposures. While analysis of fingernails and bone samples from the phalanx would yield information on localized irradiation to the hands, an analysis of tooth enamel would provide evidence of whole body irradiation. Furthermore, as regards whole body radiation exposure, the dose estimated from EPR measurements of teeth mini-biopsies can provide information on the level of heterogeneity of dose distribution in the body in comparison with data available from biological dosimetry and measurements from a passive dosimeter worn by the affected person.

It is difficult to estimate a dose distribution for localized irradiation to the hands based on calculations, mainly because of the strong dose gradient from the short distance between the source and the skin of the hands. Until recently, estimates of dose to the hands and fingers were based only on clinical manifestations or on EPR spectroscopy analysis after amputation and the collection of bone tissue. Developments at the IRSN in EPR dosimetry on nails and in the use of high frequency EPR for quantitative measurement have made it possible to estimate the dose received by each finger.

### 8.2.3. Dose estimation procedure

For the calcified tissues (tooth enamel and bone), the doses were estimated using the additive dose method. In this method, the sample is postirradiated with several known doses; by this process, its sensitivity to the dose specific to the studied sample is obtained. The dose from the accident is determined by applying the dose sensitivity coefficient to the amplitude of the radio induced signals before the post-irradiation protocol. The post-irradiation was performed with a $^{60}$Co irradiator at the IRSN. The calibration of the EPR signal intensity was carried out relative to kerma in the tissue. For nails, the classical dose additive method with back-extrapolation could not be applied, since the stable component of the radio induced EPR signals had a saturation behaviour for doses on the order of several tens of grays. The doses were determined relative to the dose required to saturate each sample. For any individual, the saturation dose is the same for all the nails. Therefore, assessing the dose required to saturate each clipping by post-irradiation is a way to estimate the dose received during the accident. If the dose required to saturate a given sample is equal to the saturation determined for the person's nails, the dose is null. If the dose required to saturate is lower than the reference saturation dose, the difference between the two is the dose received by the sample. The reference saturation dose for a person's nails is determined by post-irradiation on nails that have not been exposed during the accident (e.g. the toenails) or based on an average value from other individuals.

### 8.2.4. Description of samples and electron paramagnetic resonance settings

The clippings of the fingernails and toenails of Worker 1, Co-worker 1 and Co-worker 2 were received at the IRSN on 25 January 2012. In addition, for Worker 1, two tooth enamel mini-biopsies (3.5 mg for tooth 17 and 6.9 mg for tooth 26) were received on 27 January 2012. Several weeks later, after the amputation of the distal phalanx of the left index finger of this worker, the bone was also collected (Fig. 7). From the phalanx, four mini-biopsies were collected at different locations on the bone and were analysed using EPR spectroscopy. The dose estimation on the bone collected after amputation was performed at the request of the medical team at HIA Percy to help determine whether a second amputation would be required.

The EPR measurements were performed with a high frequency spectrometer (Q-band, 34 GHz), which is well adapted for the measurement of low mass samples (a few milligrams). Each nail clipping was independently analysed to estimate a dose for each fingernail or toenail. This EPR technique enables the estimation of dose (on the mini-biopsies of enamel) even in the low dose

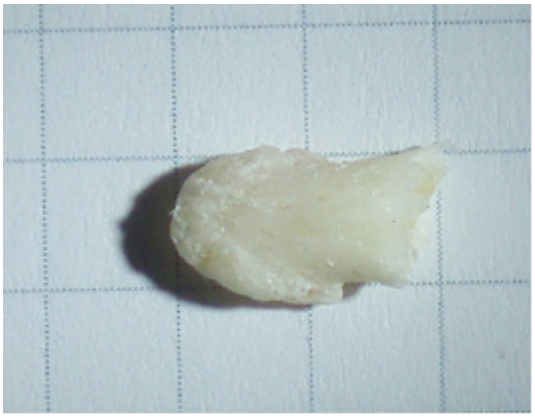

*FIG. 7. The amputated distal phalanx of the left index finger of Worker 1. (Courtesy of the IRSN.)*

region (<1 Gy). A minimum of ten independent EPR spectrums were recorded to evaluate the EPR signal amplitude.

### 8.2.5. Results of electron paramagnetic resonance dosimetry

*8.2.5.1. Electron paramagnetic resonance results on tooth enamel (Worker 1)*

An example of the dose additive method application is given in Fig. 8 for a mini-biopsy from tooth 17. The mean dose measured on tooth enamel mini-biopsies was 3.3 ± 0.2 Gy for tooth 26 and 5.9 ± 0.4 Gy for tooth 17 in terms of kerma in the tissue (Fig. 9). The average dose value was 4.6 Gy. These results also show the presence of a lateral dose gradient, with a higher dose in the right part of the jaw.

*8.2.5.2. Electron paramagnetic resonance results on nails (Worker 1, Co-worker 1 and Co-worker 2)*

The dose to the fingernails was estimated to have ranged from about 10 Gy to more than 50 Gy. Figures 10–12 show the distribution of the dose on the fingernails as measured using the EPR technique for Worker 1, Co-worker 1 and Co-worker 2. The margin of error was estimated to be about 10 Gy for these data. Results are given in terms of kerma in the tissue. The dose to the toenails of Worker 1 was estimated to be lower than 10 Gy. This estimated dose was consistent with the hypothesis that the source was inside the collimator between radiography exposures.

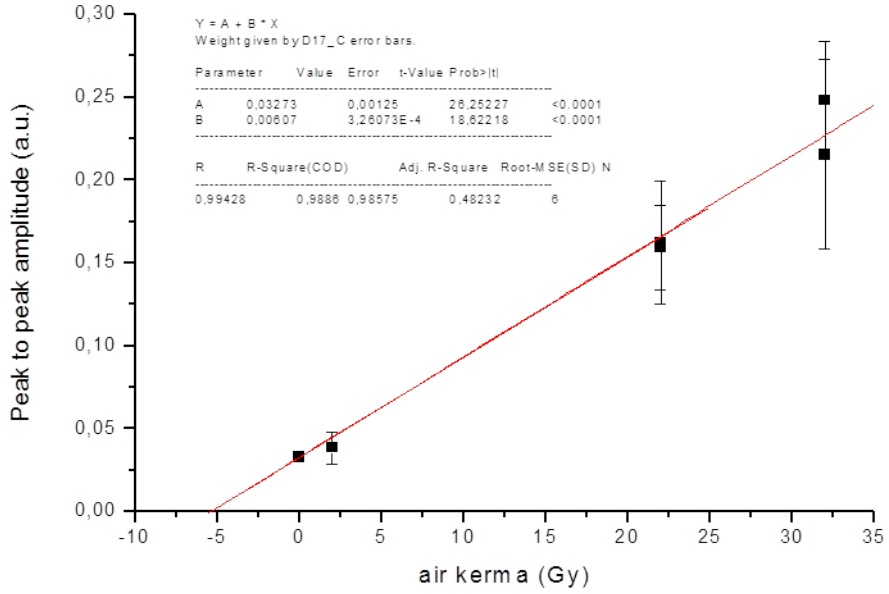


*FIG. 8. Screenshot of graphical representation of the dose additive method performed on a mini-biopsy from tooth 17. The post-irradiation was performed in terms of air kerma. The error bars are the standard deviation on ten independent electron paramagnetic resonance measurements. (Courtesy of the IRSN.)*

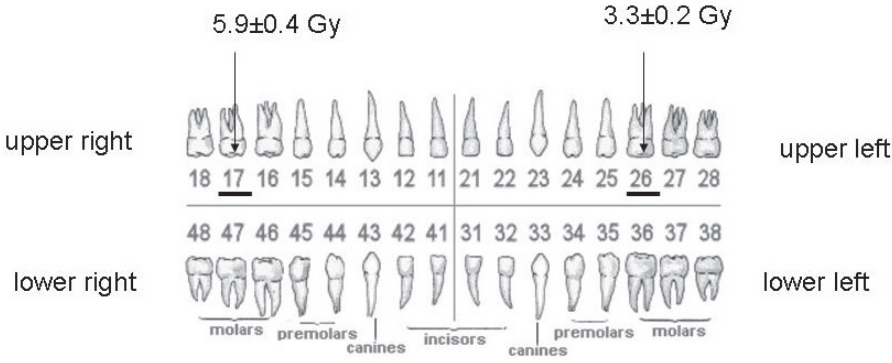


*FIG. 9. Localization of the tooth enamel mini-biopsies, with two digit tooth numbering (Courtesy of the IRSN.)*

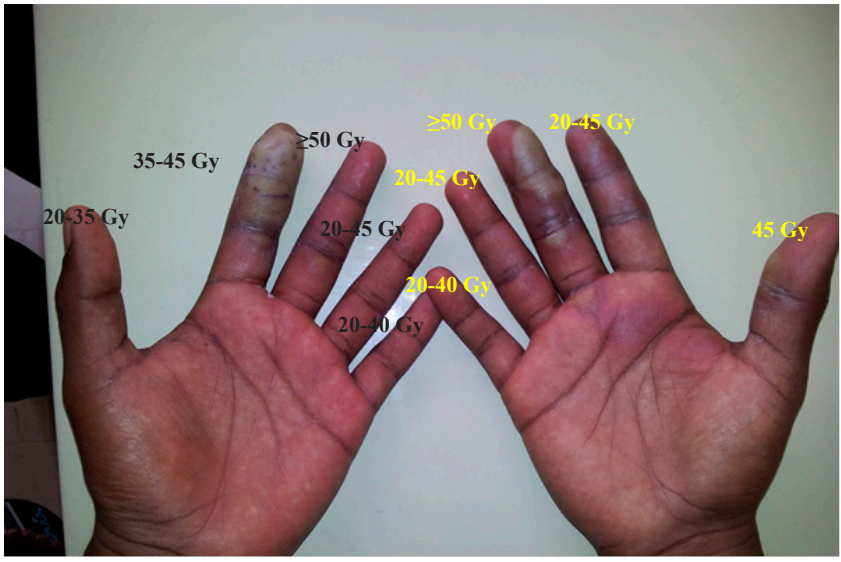


*FIG. 10. Dose measured by electron paramagnetic resonance spectroscopy on fingernails for Worker 1. (Courtesy of the IRSN.)*

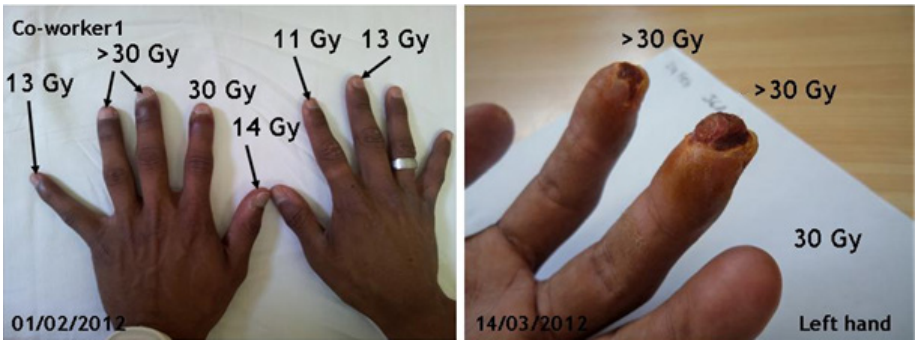


*FIG. 11. Dose measured by electron paramagnetic resonance spectroscopy on fingernails for Co-worker 1. (Courtesy of the IRSN.)*

### *8.2.5.3. Electron paramagnetic resonance results on bone (Worker 1)*

Several mini-biopsies were collected from the first phalanx of the left index finger of Worker 1 to map the distribution of the dose in the bone phalanx. An example of the dose additive method application is given in Fig. 13 for one of the

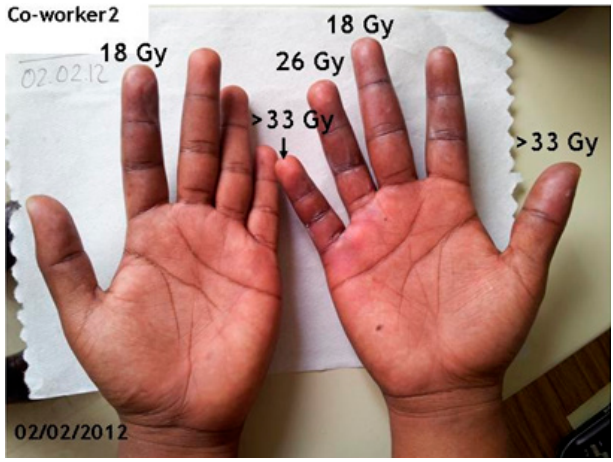


*FIG. 12. Dose measured by electron paramagnetic resonance spectroscopy on fingernails for Co-worker 2. (Courtesy of the IRSN.)*

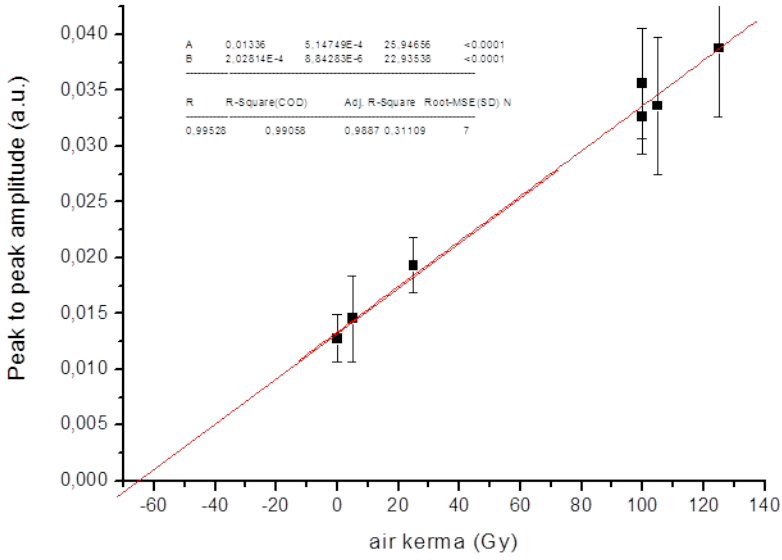


*FIG. 13. Screenshot of graphical representation of the dose additive method performed on a bone mini-biopsy from the distal phalanx of the left index finger. The post-irradiation was performed in terms of air kerma. The error bars are the standard deviation on ten independent electron paramagnetic resonance measurements. (Courtesy of the IRSN.)*

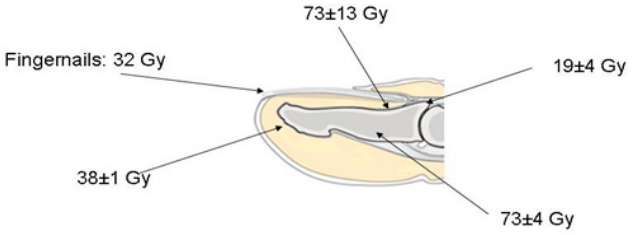


*FIG. 14. Dose estimated from bone mini-biopsies using electron paramagnetic resonance spectroscopy on the distal phalanx of the left index finger of Worker 1. Doses are expressed in terms of tissue kerma. (Courtesy of the IRSN.)*

bone mini-biopsies. The results of the corresponding EPR dosimetry are shown in Fig. 14. Results are given in terms of kerma in the tissue. A significant dose gradient is observed along the proximal–distal axis, with a maximum found in the area corresponding to the first lesion. The dose profile indicates that most of the dose was certainly delivered when the finger was in contact with the collimator during its positioning by Worker 1. The dose delivered to the tissue and the skin, in relation to the dose to the bone, was probably higher than that estimated by calculation (see the description of dose assessment by calculation). The dose at the edge of the cuts is lower (19 Gy) than the limit of necrosis dose for bone and tissue, which was estimated at around 25 Gy; this finding indicated that an additional amputation was not necessary. Moreover, good agreement was found between the dose to the fingernails and the dose on the bone biopsy located close to the nails. The difference observed between the dose to the bone and the dose to the nails was consistent with the observed dose gradient.

## 8.3. DOSE ASSESSMENT FOR WORKER 1: COMPUTER SIMULATION

### 8.3.1. Description of the scenario and modelling

The principle of dosimetric reconstruction of a radiological accident using numerical simulations is to model the source and the person (or a portion of the body of the person) exposed to radiation and to calculate the dose absorbed in different parts of the body using a Monte Carlo computer code based on the interaction of radiation with materials. In this instance, the code MCNPX (Monte Carlo *N*-Particle Extended) was used.

Taking into consideration the testimony of the workers involved, as well as clinical observations, it was obvious that the dose received by Worker 1 was very high and heterogeneous with respect to the whole body and the hands. In

view of this, it was necessary to consider the overall scenario as one involving a global exposure in the vicinity of the source for several hours and a localized severe exposure from the fingers being in contact with the collimator for a very short time. In practical terms, the dose to the whole body was mainly caused by the global exposure, and the dose to the hands was a result of the combination of both global and local exposures. In this context, two exposure configurations were considered for the calculations:

(1) Global exposure configuration. This configuration assumed that Worker 1 was in the vicinity of the source at distances ranging from 40 to 100 cm. The dose distribution to the whole body was calculated using an anthropomorphic phantom, positioning the source at the level of the chest between 40 and 100 cm (see Fig. 15). The hands were assumed to be located about 20 cm from the source.
(2) Localized exposure configuration. This configuration assumed that there was contact between the source in its holder inside the collimator and the left index finger of Worker 1 for about 10 s. The dose distribution was calculated within the finger placed in contact with the source holder (Fig. 16).

The source was modelled as a cylindrical $^{192}$Ir source measuring 1 mm in radius and 2 mm in height, enclosed in a steel cylinder with a thickness of 2 mm and height of 6 mm. Its activity at the time of the accident was assumed to have been 3653 GBq.

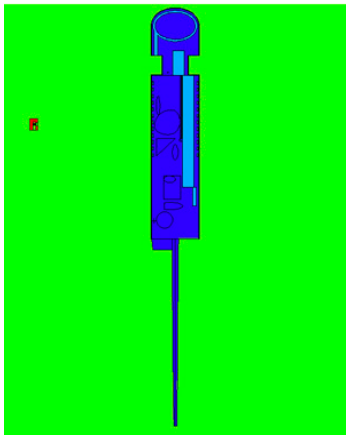

*FIG. 15. Modelling of the whole body configuration with the source at the level of the chest. (Courtesy of the IRSN.)*

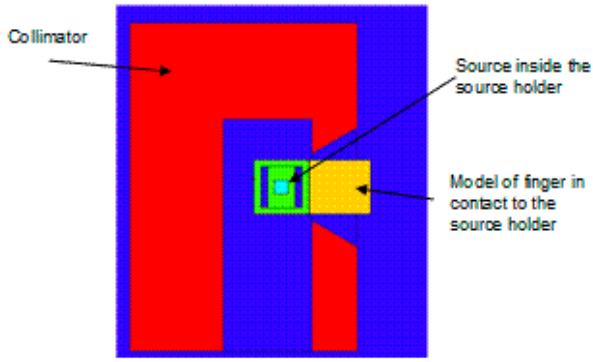


*FIG. 16. Modelling of the finger in contact with the source holder inside the collimator. (Courtesy of the IRSN.)*

### 8.3.2. Results from computer simulated dose reconstruction

The calculations for whole body exposure indicated that the mean distance of 40 cm between Worker 1 and the source was consistent with the 2.5 h scenario and with the dosimetric data results at the whole body level and at the hands, as obtained by measurements. The computed and measured values are given in Table 10. With regard to local exposure to the hands and fingers, the dose at the tip of the left index finger, which was in contact with the source holder, was computed to have been 35 Gy.

TABLE 10. COMPARISON OF DOSE ASSESSMENTS FOR WORKER 1 BETWEEN VALUES COMPUTED THROUGH COMPUTER SIMULATION AND THOSE MEASURED THROUGH OTHER METHODS

| Dose assessment | Mean trunk dose (Gy) | Tooth (Gy) | Chest[a] (Gy) | Hands (Gy) |
|---|---|---|---|---|
| Measurement | 2.5–3.5[b] | 4.6[c] | 6.0–7.0[d] | ~25[e] (nails) |
| Calculations (whole body exposure) | 2.8 | 3.2 | 6.0 | 20.0 (hands) |

**Note:** Data courtesy of the IRSN.

[a] Location of the individual passive dosimeter.

[b] Biological dosimetry for 75% of the body.

[c] EPR dosimetry; average of both teeth.

[d] Individual passive dosimeter; data provided by dosimetry laboratory in Peru.

[e] EPR dosimetry; average among nails (total dose: global + localized irradiations).

## 8.4. CONCLUSIONS FROM BIOLOGICAL DOSIMETRY AND ELECTRON PARAMAGNETIC RESONANCE DOSIMETRY

### 8.4.1. Worker 1

The results showed that, in addition to the localized irradiation to the hands, the whole body dose was fairly high. A comparison of the different techniques (cytogenetic, EPR and Monte Carlo calculations) indicated that the whole body dose distribution was heterogeneous. The dose levels to the whole body were consistent with the observed clinical and laboratory findings (see Section 6). The biological dosimetry indicated a mean whole body dose of 1.86 Gy, with 75% of the body being exposed in the range of 2.5 to 3.5 Gy. These numbers are considered consistent with the average dose in the body of 2.8 Gy calculated with Monte Carlo simulations and with the local dose of 4.6 Gy estimated by the EPR study on tooth enamel and the preliminary dose estimation. The EPR data on tooth enamel showed that there was a strong lateral gradient (left–right) that could not be taken into account in the calculations.

With regard to the hands of Worker 1, the EPR dosimetry on the fingernails indicated an average dose of around 25 Gy. The dose could have been higher locally, depending on the manner in which the source was manipulated. Because of the handling of the source and the strong dose gradient induced, the dose found in the fingernails could not always be directly related to the dose to the tissue of the finger. In fact, EPR dosimetry showed a very heterogeneous dose distribution in the bone of the distal phalanx of the left index finger. The maximum dose found in the bone (73 Gy) was in the axis of the first lesion that appeared (see Fig. 14). In the other biopsies performed on this bone, the doses did not exceed 38 Gy. Thus, the total dose to the left index finger at the level of the lesion, taking into consideration the effects of distance and attenuation by tissue, is likely to have exceeded 70 Gy, which was the dose initially estimated before the amputation and the bone analysis. The chronological sequence of the accident, in which the finger was in contact with the aperture of the collimator, was the main contributor to the dose delivered in the skin area of the first lesion. These data indicated that the duration for which the left index finger was in contact with the collimator aperture was longer than initially assessed.

### 8.4.2. Co-worker 1

The biological dosimetry indicated a mean whole body dose of 0.45 Gy. With regard to the exposure of the hands, the development of clinical signs (see Section 6) showed that Co-worker 1 had also manipulated the source and the collimator. Consequently, it was felt that the same approach adopted for Worker 1

should be applied to estimating the dose received by Co-worker 1 (i.e. the total dose to the hands would be attributable to the irradiation at a distance plus an additional dose attributable to the manipulation of the source at close quarters). On the basis of this assumption, which was based on EPR, the irradiation dose was found to be lower on average than that for Worker 1. Nevertheless, as shown in Fig. 11, the tops of the two fingers with the highest dose to the nails (>30 Gy) belatedly developed lesions. When the EPR data and the clinical signs were taken into account, the conclusion was that the average level of radiation on the left hand was higher than that on the right hand.

### 8.4.3. Co-worker 2

The biological dosimetry indicated a mean whole body dose of 0.75 Gy for Co-worker 2, which was higher than that for Co-worker 1. EPR data on the nail samples showed that Co-worker 2 had also manipulated the collimator. The clinical signs that developed later confirmed this hypothesis. The average dose on the fingers seemed to be lower than for Worker 1 and Co-worker 1. Two fingernails received a dose of at least 33 Gy (see Fig. 12). The EPR data and the type and time of appearance of the skin lesions suggested that the right hand had been exposed to a much higher level of radiation than the left hand had been.

### 8.4.4. Radiation protection officer and Worker 2

It was concluded that for the RPO and Worker 2, the total dose to the hands would have been be attributable to exposure at a distance plus an additional dose from the manipulation of the source at close quarters.

## 9. MEDICAL MANAGEMENT OF THE EXPOSED PATIENTS

This section provides details of the medical management of the exposed workers. Worker 1 was treated initially in Peru and later transferred to hospitals in France and Chile for specialized procedures.

## 9.1. INITIAL MEDICAL MANAGEMENT IN PERU

On the basis of the preliminary dose assessments, IPEN advised that the three exposed workers should be admitted to a local hospital. Consequently, they were hospitalized at INEN on the evening of 17 January 2012 (day 6). Although the results of the blood counts of Co-worker 1 and Co-worker 2 were in the normal range, those for Worker 1 indicated significant variations in the blood, suggesting at that time the possibility of an ARS haematological type.

The skin manifestations of Worker 1 were treated with dexamethasone intravenously (4 mg every 8 h) and ketoprofen orally (100 mg every 12 h). It was suggested that INEN take blood samples for biological dosimetry to be performed through the Latin American Biodosimetry Network (a regional assistance network) and take bone marrow aspirates from the iliac crest and the sternum. On 5 February 2012 (day 25), Worker 1 was transferred to France. He was admitted on 7 February 2012 (day 27) to the HIA Percy.

Co-worker 1 and Co-worker 2 underwent a medical evaluation and were given symptomatic treatment. Both were discharged on 24 January 2012 (day 13), with the recommendation that they be followed up with as outpatients. Around 7 February 2012 (day 27), both of them exhibited symptoms that required medical treatment. Co-worker 1 developed blisters on his left index finger, left thumb, and third fingers (both hands) and was treated with topical betamethasone and Biafine. Co-worker 2 developed painful blisters on distal phalanges of both hands. He was treated with topical betamethasone and Biafine, with good results. On 24 February 2012 (day 44), Co-worker 1 developed ulcers in distal phalanges of the left hand third and index fingers, which were again treated with Biafine, with good results.

## 9.2. TREATMENT OF WORKER 1 IN FRANCE

The medical management of Worker 1 in France was provided by the HIA Percy jointly with the IRSN. Worker 1 (27 years old) was hospitalized on 7 February 2012 (day 27) and displayed a combination of radiation induced aplasia and LRI on his hands. It was decided to first address the radiation induced aplasia and then the LRI, while waiting for the production of human grade MSCs.

### 9.2.1. Medical management of radiation induced aplasia

For the treatment of the radiation induced aplasia, the patient was hospitalized in the Department of Haematology at the HIA Percy. He had been exposed to a total body irradiation of 1.86 Gy, with 75% of his body having

been exposed to doses in the range of 2.5 to 3.5 Gy. Some areas of his body had been exposed to higher doses, such as his head (4.6 Gy) and his hands (25 Gy), with a 'hot spot' of 73 Gy in his distal left index finger. In view of the highly heterogeneous and protracted radiation exposure, residual haematopoiesis was expected. In fact, the patient suffered from mild radiation induced aplasia, with spontaneous and progressive recovery starting from day 25 for platelets (the minimum of 98 000/mm$^3$ × 10$^3$/μL was reached on day 27) and from day 35 for neutrophils (the lowest count of 1059/mm$^3$ was reached on day 41) (Figs 17 and 18). The normal value for platelets and neutrophils is expected to be more than 150 000/mm$^3$ and 2000/mm$^3$, respectively. Complete haematopoietic recovery

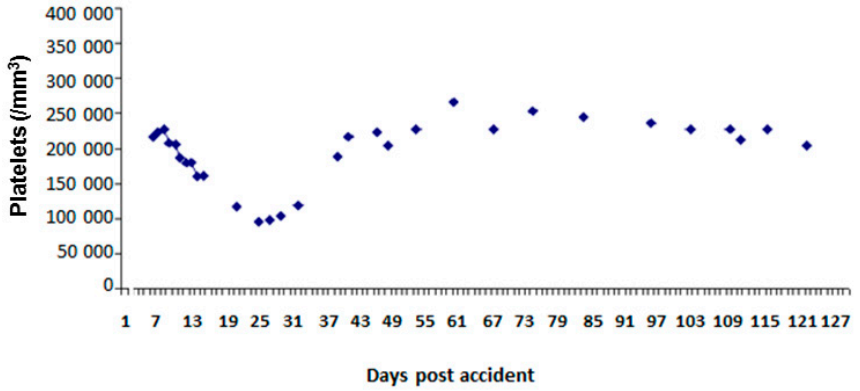


*FIG. 17. Platelet counts of Worker 1 (HIA Percy–IRSN data).*

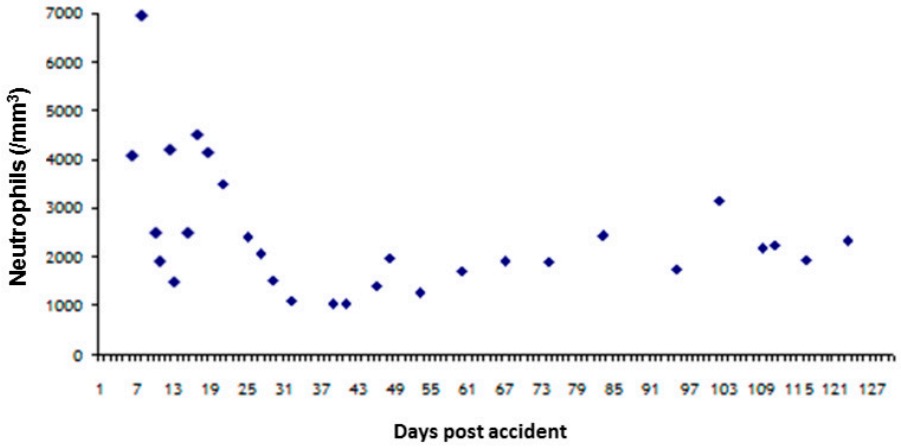


*FIG. 18. Neutrophil counts of Worker 1 (IPEN and HIA Percy–IRSN data).*

was obtained on day 60 for platelets and on day 80 for neutrophils. Consequently, this patient, who had suffered from a mild thrombocytopenia and neutropenia, recovered spontaneously without any specific treatment.

### 9.2.2. Medical management of the local radiation injury

For the treatment of the LRI, the patient was hospitalized in the Department of Plastic Surgery of the HIA Percy. The dose received locally on the hands was roughly 25 Gy. The radiation exposure was heterogeneous (see Fig. 10), ranging from 18 Gy to the left thumb to more than 38 Gy to the left middle finger, and from 23 Gy to the annular to more than 38 Gy to the index finger of the right hand. A maximum dose of 73 Gy was measured on a bone biopsy on the last phalanx of the left hand index finger, and the dose gradient was very sharp (Fig. 14).

It was decided that the patient would receive a full thickness skin autograft in combination with a local allogenic MSC injection. This procedure was preferred because the patient had received a total body exposure of 1.86 Gy, with significant dose exposure to the bone marrow (2.5–3.5 Gy) to produce non-qualified MSCs. The bone marrow of the brother of Worker 1 was collected at the HIA Percy after an iliac crest puncture on 14 February 2012 (day 34). The main challenge in MSC transplantation is to ensure that the cultured cells retain their quality and their differentiation potential during the growth process. To treat a tissue injury using cell therapy, the number of cells required can be very high. To be of therapeutic use, the cells that are produced must retain normal function, differentiation pattern and regulation during culture. MSCs have been described as multipotent progenitor cells that differentiate into osteocytes, chondrocytes, adipocytes and stromal cells. Their ability to differentiate according to multiple lineage characteristics is also preserved during the growth process. In this instance, human grade MSCs were produced by the Centre de transfusion sanguine des armées 'Jean Julien', Clamart, France. The stem cell unit and the stem cell production procedures had to undergo approval, authorization and certification by the French National Security Agency of Medicines and Health Products.

Five successive local MSC injections were required for the complete healing of the wounds on both hands of Worker 1, resulting in excellent functional recovery (Table 11 and Fig. 19). MSC injections significantly reduced the period of hospitalization to three months, and the wounds were stabilized by day 124 (Fig. 20). Worker 1 completed a hand rehabilitation programme from a physiotherapist that involved mobilization of the different interphalangeal articulations and exercises for finger rehabilitation to gain complete flexibility. Hand function also improved. Pain rapidly disappeared after the MSC injections. An inflammatory biomarker, C-reactive protein, was used to evaluate the

therapeutic efficiency of the MSC, and the C-reactive values' returned to normal (1 mg/mL) at the end of the treatment.

A blister on the extremity of the distal phalanx of the left hand index finger was observed in the days following irradiation, and the prognosis was not encouraging with regard to the rapid progression of the lesion and the dose of 73 Gy as estimated by EPR dosimetry (see Fig. 14). It was considered very likely that radionecrosis was developing on this hot spot; hence a two step local surgery was conducted. The first step was partial surgical amputation of the distal part of the phalanx, and the second was the complete disarticulation of the distal phalanx. The progression of the necrosis towards the intermediary phalanx was halted, and the prognosis was good, considering the 19 Gy dose estimated by EPR on the intermediary phalanx and the satisfactory and complete wound healing process (Figs 19 and 20).

TABLE 11. STEM CELL PRODUCTION AND INJECTION SCHEDULE

| Number of days post-irradiation | Date | Details of treatment |
|---|---|---|
| 27 | 07 Feb. 2012 | Patient (Worker 1) hospitalized at the HIA Percy. |
| 29 | 09 Feb. 2012 | Multidisciplinary medical staff (IRSN and HIA Percy) evaluate and make a decision on the strategy for treatment. A medical doctor from Peru is also present at this discussion. |
| 34 | 14 Feb. 2012 | Bone marrow puncture conducted on the brother of the patient. |
| 48 | 28 Feb. 2012 | First MSC injection ($34 \times 10^6$ cells) conducted. |
| 51 | 02 Mar. 2012 | Second MSC injection ($50 \times 10^6$ cells) conducted. |
| 57 | 08 Mar. 2012 | Third MSC injection ($40 \times 10^6$ cells) conducted. |
| 64 | 15 Mar. 2012 | Fourth MSC injection ($22 \times 10^6$ cells) conducted. |
| 79 | 30 Mar. 2012 | Fifth MSC injection ($206 \times 10^6$ cells) conducted. |

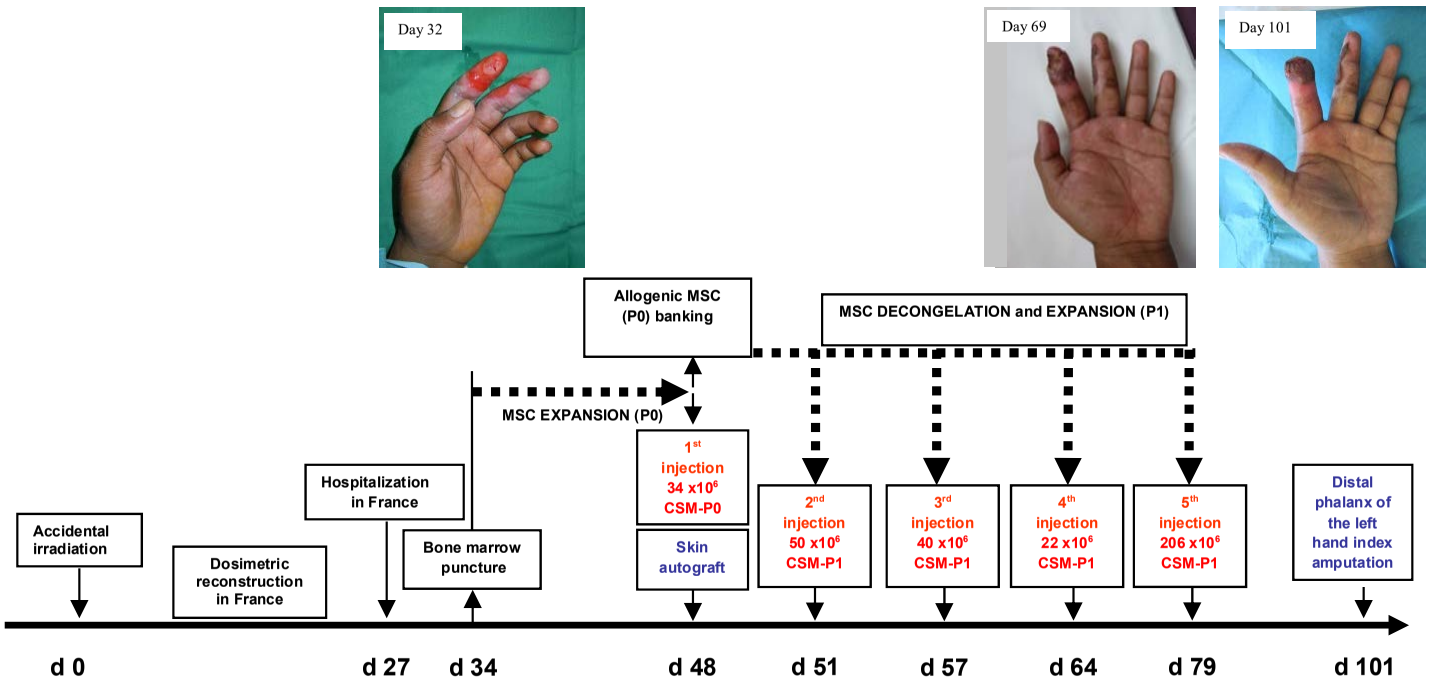


*FIG. 19. Clinical procedure, including skin autograft, local allogenic mesenchymal stem cell injection and one phalanx amputation. CSM — culture of stem cells. (Courtesy of HIA Percy–IRSN.)*

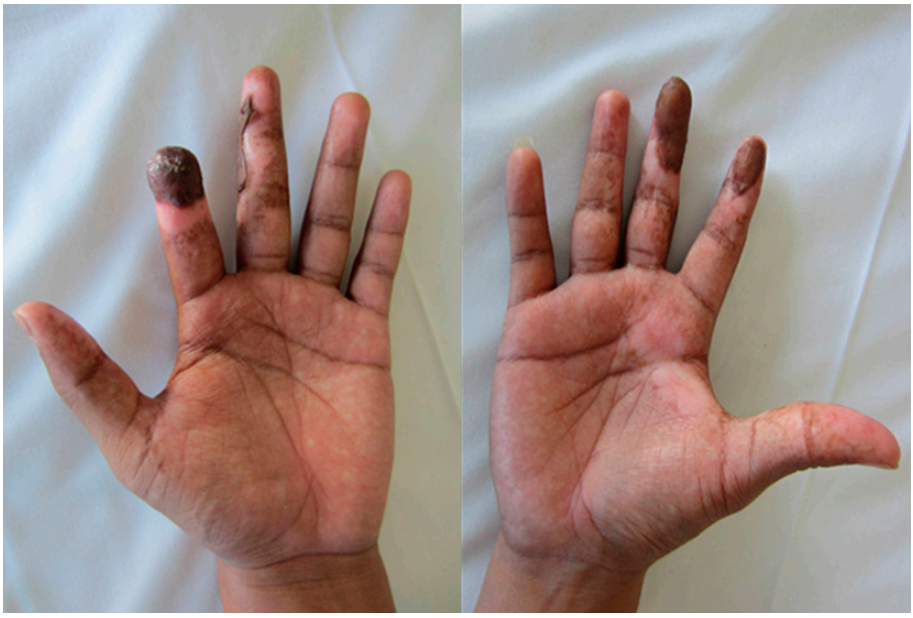

*FIG. 20. Status/view of the hand of Worker 1 (day 124, 14 May 2012). (Courtesy of the HIA Percy–IRSN.)*

### 9.2.3. Conclusions after the medical treatment of Worker 1 in France

The following is a summary of the evolution and treatment of Worker 1 at the HIA Percy:

(a) Radiation induced aplasia was mild; recovery was spontaneous and did not require administration of growth factors.
(b) Pain was drastically reduced with local MSC injections.
(c) Combined allogenic MSC injections and full thickness skin autograft resulted in complete healing of the wound, with excellent functional recovery of the hands.
(d) Local and multiple MSC injections drastically reduced the number of days of hospitalization; MSC injections associated with full thickness skin autograft limited amputation to the distal phalanx of left index finger.
(e) After the patient was released from the HIA Percy, it was recommended that the Peruvian medical counterpart take up the responsibility of patient treatment follow-up, keeping the French counterpart periodically updated. It was also recommended that the hand rehabilitation programme be continued as long as necessary, probably for at least a few years.

Worker 1 was evaluated on 7 June 2012, 8 August 2012 and 19 November 2012. He was asymptomatic, although the graft of the second finger of his left hand seemed to be retractile. Left hand X rays on 8 August 2012 and 19 November 2012 were normal. From the initial follow-up blood counts carried out in Peru after the return of the patient from France, it seemed that the bone marrow of Worker 1 had fully recovered from the initial damage induced by radiation exposure.

## 9.3. TREATMENT OF WORKER 1 IN CHILE

### 9.3.1. Developments from December 2012

The medical condition of Worker 1 appeared to deteriorate from the end of November 2012. Around 1 December 2012 (day 325), two small ulcers appeared on the left hand index finger. Soon thereafter, additional skin lesions appeared, characterized by erythema and slight oedema in the first and second phalanges in several fingers. This condition was evaluated in INEN and handled with dicloxacillin and topical application of Biafine.

The pain had also increased around the surgical area of the left hand. During the subsequent months, while the Peruvian doctors discussed the condition of the patient with French and IAEA medical experts, the treatment being given to Worker 1 did not result in significant improvement. Instead, some of the symptoms, such as pain, lesion size, blisters and oedema, became more acute. After a teleconference in mid-May 2013, a third formal request for assistance under the Assistance Convention was received by the IAEA's IEC from IPEN. After contacting several Member States that could potentially provide specialized medical treatment, a positive response was received from Chile and an assistance action plan was designed by the IEC. Under this plan, Chile was to provide the medical treatment as needed, provide the Government of Peru with recommendations for any further action by the Peruvian (medical) authorities and prepare assistance reports (in English) detailing the treatment and results of related medical tests. In addition, the plan envisaged that France would provide recommendations for medical treatment as needed and coordinate with the Chilean medical authorities to provide the Government of Peru with recommendations for any further action by the Peruvian (medical) authorities.

### 9.3.2. Scope and structure of the assistance action plan

The objectives of the assistance action plan designed by the IAEA's IEC were to:

(a) Undertake a medical evaluation of the patient's present condition;
(b) Provide medical treatment including a complete medical evaluation of the patient, reconstructive surgery and cell therapy (MSC injection) as required;
(c) Provide a multidisciplinary approach in treatment and strategy, including reconstructive or orthopaedic surgery, radiopathology consultation, cell therapy and pain management;
(d) Provide any other medical treatment as determined necessary by the medical doctors treating the patient;
(e) Establish an arrangement for follow-up reporting on the medical treatment administered to the patient.

The medical treatment of Worker 1 was carried out in Chile, supported by the Mutual de Seguridad Hospital, in cooperation with the Stem Cells Laboratory of Del Desarrollo University and with the Chilean Nuclear Energy Commission. The Government of France provided the services of a team of medical experts from the IRSN and the HIA Percy. The medical expert from the IAEA's IEC headed the international assistance mission team.

### 9.3.3. Surgical procedures accompanied by first set of mesenchymal stem cell injections

The international assistance mission team, composed of experts from France and the IAEA's IEC, arrived in Chile on 27 June 2013. The team visited hospitals and facilities to assess and confirm that Worker 1 could be treated in Chile. The experts also held discussions with a wide range of multidisciplinary professionals. In accordance with the decisions made by the experts, Worker 1 was hospitalized on 17 July 2013 at the Mutual de Seguridad Hospital in Santiago. A French medical expert from the HIA Percy also arrived in Chile to oversee the procedures. An initial medical evaluation confirmed the severity of the lesions, the necrotic ulcers in several fingers and the bone exposure in the left index finger in the distal part of the amputation area. A pre-surgical evaluation of the patient was performed, including laboratory tests, clinical imaging and medical examinations to confirm the extension and the severity of the lesions and also the bone radionecrosis suspected in the fingers. Blood samples were obtained from the patient (by the Chilean Nuclear Energy Commission) for cytogenetic biological dosimetry and for platelet sample collection in order to prepare a platelet lysate, which was to be used in the subsequent stage to cultivate the MSCs.

On 19 July 2014, under general anaesthesia, the first bone marrow collection procedure from the patient was performed, after which he returned to Peru. The

two collected bone marrow samples were cultivated under special conditions in a sealed system for a period of two weeks (MSC Culture Laboratory).

On 4 August 2014, the patient was hospitalized in Santiago to continue with the next stage of the treatment. Medical experts from France and the IAEA's IEC also arrived in Chile to oversee the procedures. After a detailed examination of the patient's condition, a series of procedures was initiated after 3 d:

(a) A second bone marrow collection, to be processed at the MSC Culture Laboratory.
(b) Surgery on both hands that comprised amputation of the second phalanx on the index finger of the left hand and the second phalanges on the index and fourth fingers of the right hand. Bone fragments from the patient were labelled and stored separately for dosimetry studies in France. The clinical status of the patient indicated the recurrence of the LRI, lesions and bone exposure (Figs 21 and 22).
(c) A first set of MSC injections was administered through several injections in both hands immediately after surgery, when the patient was still under general anaesthesia, and consisted of 40 million MSCs for each hand.

On the following days, the pain significantly decreased to the extent that even the opioid drugs were not administered and occasional non-steroidal anti-inflammatory drugs were considered sufficient. There was progressive healing of the wounds, and there were no signs of any infection.

### 9.3.4. Subsequent procedures of mesenchymal stem cell injections

After a second set of MSC injections on both hands on 16 August 2013, Worker 1 went back to Peru with good healing progress of his wounds.

On 30 August 2013, Worker 1 returned to Chile and received the third set of MSC injections. The wounds had completely healed, and the patient did not experience any pain.

On 6 September 2013, the patient received the last (fourth) set of MSC injections on both hands. The medical experts from France and the IAEA's IEC were also present in Chile during this period to oversee the procedures. The medical check at that time showed that Worker 1 was in good condition, with no pain reported in his hands. The wounds had healed, and his clinical status was considered satisfactory (Fig. 23). It was recommended that a medical follow-up be carried out every three months during the first year (up to August 2014) and that, subsequently, an annual medical follow-up be performed for at least the next ten years (up to 2024).

*FIG. 21. View of the left hand of Worker 1 (day 572, 5 August 2013) showing severe recurrence of the local radiation injury, severe lesion of the index finger with bone exposure and bone radionecrosis of the second phalanx, retraction of skin and tissues, and hyper/hypopigmentation skin changes.*

*FIG. 22. View of the right hand of Worker 1 (day 572, 5 August 2013) showing severe recurrence of the local radiation injury, radionecrosis and bone exposure in the distal phalanx of the index finger, retraction of soft tissues, ulcerative lesion with central necrosis of soft tissues in the inner side and anchylosis of the distal interphalangeal joint in the fourth finger, third finger loss of nail, and hyper/hypopigmentation skin changes.*

*FIG. 23. View of the hands of Worker 1 (day 604, 6 September 2013) showing surgical wounds having healed. The worker also reported an absence of pain.*

Additional information related to the treatment of Worker 1 in Chile is provided in Appendix VI, which gives the sequence of events from December 2012 to September 2013, detailing the medical diagnoses, treatment and procedures at various stages, along with related pictures.

## 10. CONCLUSIONS AND LESSONS IDENTIFIED

This section presents the important observations and conclusions, as well as the major lessons identified, from the study of this accident. Many are not unique to this radiological accident but are worth reiterating in this report. Examples of good practice are also included among the observations. The observations and conclusions have been categorized, and for each category, the identified lessons are presented.

## 10.1. OPERATING ORGANIZATIONS: RADIOGRAPHIC INSTITUTIONS

### 10.1.1. Safety procedures

#### *10.1.1.1. Observations*

The observations related to safety procedures were as follows:

(a) The radiography operations were carried out without an RPO present at the site to supervise the implementation of safety precautions, including the proper use of personal dosimeters and the effective use of radiation protection devices. The presence of an RPO would have prevented the accident or reduced its severity.
(b) The set-up of the radiography camera equipment, including the connection of the source pigtail to the drive cable, was carried out by untrained individuals (co-workers) and not by the authorized person who was responsible for the work. This delegation of responsibility was not permitted and was a violation of established safety procedure.
(c) During radiography operations, one of the safety measures that has to be in place for the protection of workers is the use of personal audible and alarm detectors, so that any abnormal situation can be promptly recognized. The workers did not wear alarm dosimeters as required under the safety regulations. This prevented the workers from detecting that the source was not in the safe position.
(d) The monitoring of radiation background levels during operations when the source is pushed out of the camera and then retracted is an essential part of radiography operations and is the only way to ensure that the source has returned safely into its container. In this regard, the area radiation monitor is one of the most important pieces of safety equipment as it allows delineation of the controlled area and serves to indicate immediately any failure of control of the radioactive source. Worker 1, Co-worker 1 and Co-worker 2 did not pay attention to the monitor and were consequently unaware of being exposed during the entire operation.

The above observations indicate that, despite the availability of radiation protection instruments for detecting and measuring radiation, these instruments were not used for their intended purpose. It appears that none of the personnel concerned were fully aware of the risks involved in the operation of the equipment and that all of the personnel concerned overlooked the essential procedures of radiation protection that should have been followed. In this regard, it appears

that, despite having received training, the licensee did not adhere to the safety regulations and procedures.

*10.1.1.2. Lessons identified*

The following lessons were identified from the above observations:

(a) It is essential that all safety procedures and requirements be enforced. In particular, the requirement for the RPO to be present during the whole operation to ensure that all precautions are in place should not be violated under any circumstances.
(b) Effective mechanisms to promote the safety culture and adhere to the prescribed safety procedures are needed, with the objective of ensuring that all personnel are aware of their own responsibilities.
(c) Better mechanisms are needed to review and verify the effectiveness of training programmes, make changes as required in the training content and reconsider the frequency of refresher training so that licensees do not violate safety regulations or procedures under any circumstances.

### 10.1.2. Collimator use

*10.1.2.1. Observation*

The use of a collimator contributed significantly to reducing the consequences of the accident.

*10.1.2.2. Lesson identified*

Collimators should be used whenever possible, as they reduce the radiation levels and subsequent accidental doses, if any.

### 10.1.3. Inconsistencies in preliminary information

*10.1.3.1. Observation*

There were inconsistencies in the preliminary information obtained from the workers. These inconsistencies could be attributed to the fact that they were occupational workers and assumed that queries about what exactly occurred were more a fault finding exercise than a mechanism for assessing and evaluating their exposure to radiation.

*10.1.3.2. Lesson identified*

Organizations need to better address this issue through their training and awareness programmes. Organizations also need to adopt policies that promote the sharing of all the information during the analysis of accidents. One such policy should address the need to emphasize that a good safety culture does not apportion blame when accidents occur. Personnel are expected to learn from mistakes, foster a questioning attitude and seek continuous improvement in the safety of work processes.

### 10.1.4. Coverage of medical expenses

*10.1.4.1. Observation*

Problems were faced when the most severely exposed worker had to be transferred abroad for very specialized treatment; there was no medical coverage for the patient under health insurance, nor was there any legal way to cover his medical expenses.

*10.1.4.2. Lesson identified*

It is essential that licensees be encouraged to arrange for suitable medical insurance coverage for their employees with regard to accidents at the workplace, as this will allow for quicker medical attention including, when required, specialized treatment outside the country.

## 10.2. NATIONAL AUTHORITIES

### 10.2.1. Connection of radioactive source

*10.2.1.1. Observation*

What caused the radioactive source to become disconnected from the drive cable was not clear. One possible explanation is that the source was not connected properly because the task was undertaken by an untrained person. Another reason could have been a mechanical failure of the connector cable.

*10.2.1.2. Lesson identified*

Since there are many cameras in use like the one involved in this accident, experience with similar radiographic cameras should be documented to check if this is a generic problem with this model or a one-off failure.

### 10.2.2. Availability of expertise on biological dosimetry

*10.2.2.1. Observation*

Although expertise on biological dosimetry was available within the country, the preparation of cultures from the bio-samples could not be carried out locally.

*10.2.2.2. Lesson identified*

It is important that such national facilities be maintained in a manner that is fully operational and available to carry out the assessment of bio-samples when required after an accident.

### 10.2.3. Communication with the IAEA

*10.2.3.1. Observations*

The observations related to communication with the IAEA were as follows:

(a) IPEN used the Unified System for Information Exchange in Incidents and Emergencies to send the information on the accident to the IAEA's IEC. IPEN also promptly responded to the IAEA's offer of assistance by making a formal request for advice on dose assessment and medical management. These actions contributed to an effective and fast response to the accident and to the provision of appropriate medical treatment for the workers.
(b) IPEN was transparent in making all information available to the international assistance mission team and also in sharing information for the preparation of this report.

*10.2.3.2. Lesson identified*

Prompt and proactive actions by the competent authority, by way of informing the IAEA's IEC and making decisions on accepting the IEC's offer of assistance, can help with an effective response to a radiation related accident.

## 10.3. INTERNATIONAL COOPERATION

### 10.3.1. Regional biological dosimetry assistance network

#### *10.3.1.1. Observation*

The regional biological dosimetry assistance network, the Latin American Biodosimetry Network, was created to support the response to radiological accidents in the region. This network had been tested in an exercise conducted in 2009–2010. However, during this accident the network was not activated, and the biological samples had to be dispatched to France for testing and analysis.

#### *10.3.1.2. Lesson identified*

Dose assessment by biological dosimetry might not be available at the time of an accident. Regional support should be in place in this case, and arrangements should be implemented to send the samples to other countries if required.

### 10.3.2. Financial resources for international treatment

#### *10.3.2.1. Observation*

There was a time gap between making the decision to send Worker 1 abroad for medical treatment and the subsequent action. The reason for the delay was the need to arrange the necessary financial resources for this purpose.

#### *10.3.2.2. Lesson identified*

A prompt funding mechanism needs to be established to cover expenses related to the medical treatment of workers overexposed in industrial radiography accidents. This mechanism should include the cost of the treatment abroad if the country has not developed the requisite medical capacities.

### 10.3.3. Transport of biological samples

#### *10.3.3.1. Observation*

Problems were faced in the transport of biological samples from Peru to France for dose estimations. These problems arose because the airlines demanded certification that the samples would not be hazardous. Such a situation can delay

the crucial tasks of dose reconstruction and assessment, especially in the case of an LRI, to determine the strategy for medical treatment.

*10.3.3.2. Lesson identified*

It is desirable that procedures be in place to coordinate the quick transport of bio-samples, particularly by air, to avoid procedural bottlenecks at the airlines or at border control points.

### 10.3.4. Cooperation between Member States

*10.3.4.1. Observation*

The response and support from France for the first international assistance mission to give assistance by way of advice on dose assessment and medical management was very prompt and professional. So was the later offer of medical treatment in France for the most seriously exposed worker, Worker 1. Similarly, the offer from the USA to facilitate funding of this medical treatment was prompt and generous. When Worker 1 had to undergo further treatment, the provision of medical experts from France and the offer of treatment by Chile at no cost were significant in treating this patient.

*10.3.4.2. Lesson identified*

Member States should be encouraged to respond in a spirit of mutual help, thereby making available resources and specialized support to radiation injured persons in a timely and effective manner. These examples illustrate how international cooperation can lead to an effective response to these kinds of accident.

### 10.3.5. IAEA response

*10.3.5.1. Observation*

The response of the IAEA's IEC to the accident at various stages was prompt and effective. After the notification, the IEC promptly offered its services to Peru. Once the formal request was received, the IEC immediately facilitated the first international assistance mission to Peru, with minimal delay. The IEC monitored the progress of the radiation exposed workers in Peru. When it recognized that very specialized medical treatment elsewhere was essential, it coordinated the second international assistance mission using RANET resources and facilitated

the funding arrangements, so that medical treatment could be quickly provided. The IEC stayed in contact with the Peruvian medical coordinator to receive information regarding the medical follow-up of Worker 1. This efficient response was repeated when the third international assistance mission was organized to enable the patient to be treated in Chile. All these actions were possible because of the effective response and assistance systems and procedures in place at the IAEA's IEC.

*10.3.5.2. Lesson identified*

The handling of this emergency should be used as an example to encourage Member States to factor international arrangements in to their plans and to avail themselves of the IAEA's expertise in enhancing their emergency preparedness and response capabilities. These actions would improve their effectiveness in offering and receiving assistance while responding to any radiation emergency.

## 10.4. MEDICAL COMMUNITY

### 10.4.1. Delay in identifying radiological accident

*10.4.1.1. Observation*

Significant time (6 d) was taken to recognize the radiological nature of the accident, despite the availability of substantial evidence and clinical manifestations. Consequently, as has happened in many other radiological accidents, valuable time was lost before the workers were given appropriate medical evaluation and treatment.

*10.4.1.2. Lesson identified*

Effective training of the medical community in the diagnosis and initial management of persons involved in radiation emergencies should be addressed by the relevant authorities. Early diagnosis will give rise to better treatment, thereby improving the prognosis of affected patients.

### 10.4.2. Medical management strategy

*10.4.2.1. Observation*

The medical management strategy adopted at the HIA Percy–IRSN, involving surgery and MSC injections, was successful. The experience was replicated in Chile in the treatment of recurrences.

*10.4.2.2. Lesson identified*

Since 2005, the combining of dosimetric guided surgery and MSC injections has demonstrated a significant improvement in the treatment and prognosis of LRI patients. The experience replicated in Chile with the assessment of an international assistance mission (applied for the first time in Latin America) demonstrated that the exchange of knowledge and medical experience is possible during accidents, in the framework of international cooperation, with successful results.

### 10.4.3. Recurrence of symptoms

*10.4.3.1. Observation*

Despite the optimistic prognosis after treatment at the HIA Percy, there was a recurrence of symptoms in Worker 1 about one year after the event. Extensive treatment was required to stabilize the patient.

*10.4.3.2. Lesson identified*

It is essential that the medical status of severely affected persons be followed up on for a significant period to check for recurrence and to take steps for early treatment, which can reduce the need for surgical amputation arising from severe ARS.

## Appendix I

## INTERNATIONAL CONVENTIONS ACCEDED BY PERU, PERUVIAN NATIONAL REGULATIONS, RADIOLOGICAL SAFETY STANDARDS OF IPEN

### I.1. INTERNATIONAL CONVENTIONS TO WHICH PERU IS A SIGNATORY

Peru is a signatory to the following international conventions:

(a) Convention on Early Notification of a Nuclear Accident. Signed on 26 September 1986; in force since 17 August 1995.
(b) Convention on Assistance in the Case of a Nuclear Accident or Radiological Emergency. Signed on 26 September 1986; in force since 17 August 1995.
(c) Convention on the Physical Protection of Nuclear Material. In force since 10 February 1995.

### I.2. PERUVIAN NATIONAL REGULATIONS

Peruvian national regulations related to radiation sources include:

(a) Law 28028: Law to regulate the use of ionizing radiation sources.
(b) Law 27757: Law on prohibition of importation of second-hand goods, machinery and equipment using radiation sources.

### I.3. PERUVIAN NATIONAL DECREES PERTAINING TO RADIOLOGICAL SAFETY

Peruvian national decrees pertaining to radiological safety include:

(a) Supreme Decree 009-97-EM: Radiation safety regulation.
(b) Supreme Decree 039-2008-EM: Regulation of Law 28028.
(c) Supreme Decree 001-2004-EM: Regulation of Law 27757.
(d) Supreme Decree 014-2002-EM: Regulation on physical protection of installations and nuclear material.

## I.4. SAFETY STANDARDS ISSUED BY IPEN

IPEN has issued the following relevant safety standards [17]:

(a) IR.013.98: Radiation safety requirements for using self-shielded gamma irradiators.
(b) IR.012.98: Radiation safety requirements for using panoramic gamma irradiators.
(c) IR.001.01: Radiation safety requirements on teletherapy.
(d) IR.001.2009: Radiation safety requirements on industrial radiography.
(e) PR.002.2011: Technical and administrative requirements for personnel dosimetry services.
(f) IR.002.2012: Radiation protection and safety requirements on nuclear medicine; IR.003.2012: Radiation protection requirements on X ray medical diagnostics.
(g) SF.001.2011: Security requirements for radioactive sources.

## Appendix II

## CHRONOLOGY OF ACTIVITIES OF IAEA'S INTERNATIONAL ASSISTANCE MISSION (22–26 JANUARY 2012)

Table 12 lists the main activities and actions that occurred during the IAEA's international assistance mission from 22 to 26 January 2012.

TABLE 12. CHRONOLOGY OF ACTIVITIES OF IAEA'S INTERNATIONAL ASSISTANCE MISSION (22–26 JANUARY 2012)

| Date | Activity |
|---|---|
| 22 Jan. 2012 | Arrival in Lima. |
| | Meeting with IPEN officials. |
| 23 Jan. 2012 | Visit to the INEN hospital in Lima to evaluate the three patients. |
| | Contact with the IRSN in France to carry out biological dose assessments, evaluation of dose and heterogeneity of the exposure of all five workers involved in the accident so as to decide on the course of medical management and prognosis. Of the five persons involved in the accident, only three were expected to have been overexposed to radiation. However, the team advised that biological samples of all five workers be sent for analysis. |
| | Contact with the IRSN for dose assessment based on samples of the fingernails, toenails and teeth of the most severely exposed patient (Worker 1) to evaluate the dose received on his hands and the heterogeneity of the exposure, and to decide on the course of medical management and prognosis. |
| | Preparation of biological samples for dose assessments (blood samples of all five workers; nails and teeth biopsy of Worker 1). |
| | Facilitation of the preparation of letters and certificates to be issued by IPEN and the IAEA in relation to the biological samples to be sent to France (IRSN). |
| | Discussions with the Biological Dosimetry Laboratory (IPEN). |
| | Briefing of President of IPEN on the preliminary assessment of the situation, general elements of the mission and suggested courses of action under different scenarios. |
| | Presentation by IPEN of its preliminary data on dose reconstruction. |
| | End of the first phase of the mission. |

TABLE 12. CHRONOLOGY OF ACTIVITIES OF IAEA'S INTERNATIONAL ASSISTANCE MISSION (22–26 JANUARY 2012) (cont.)

| Date | Activity |
|---|---|
| 24 Jan. 2012 | Reassessment of Worker 1. |
| | Discussion with officials from IPEN and INEN regarding dose reconstruction for the hand of Worker 1. |
| | Preparation of biological samples (biopsy of two teeth) for dose assessment of Worker 1. |
| | Request for reassessment of the InLight optically stimulated luminescence dosimeter of Worker 1. |
| | Second medical debriefing with officials from IPEN and INEN. |
| | Preparation of mission report. |
| 25 Jan. 2012 | Request made for additional complementary information to clarify key relevant facts of the accident. The chronological sequence of all events leading to the accident was reviewed, along with the available data, to reassess earlier estimates of the doses received. |
| | Team visit to Worker 1 to validate the chronological sequence of events leading to the accident. |
| | Interviews with the RPO and Worker 2 to validate the reconstruction of various events leading to the accident up to the time when Worker 1 first exhibited vomiting. |
| | Third medical debriefing with officials from IPEN and INEN. |
| | Finalization of mission report, along with conclusions and recommendations about the medical issues, emphasizing the need to transfer the patient (Worker 1) if the lesions on his hand or the parameters of his blood counts deteriorated. |
| 26 Jan. 2012 | Exit meeting with IPEN officials and delivery of the first preliminary report. |
| | End of mission's activities and departure from Lima. |

## Appendix III

## DETAILED REPORT ON LOCAL RADIATION INJURY EXHIBITED BY THE THREE AFFECTED PERSONS

III.1. WORKER 1

### II.1.1. Prodromal phase

An erythema appeared on the distal phalanx of Worker 1's left hand index finger on day 4. This location corresponded to the skin area directly in contact with the hole of the collimator containing the iridium source (see Figs 2, 24).

### III.1.2. Latent phase

The erythema evolved progressively to a blister between day 5 and day 13 (Fig. 25). A magnetic resonance imaging scan performed on day 13 on the left hand showed that, at that time, the inflammation was restricted to the distal and intermediate phalanges of the index finger (Fig. 26).

*FIG. 24. Reconstruction showing the position of the index finger of the left hand of Worker 1 on the orifice of the collimator. It was estimated that the distance of the skin from the source was 0.5 cm. (Courtesy of IPEN.)*

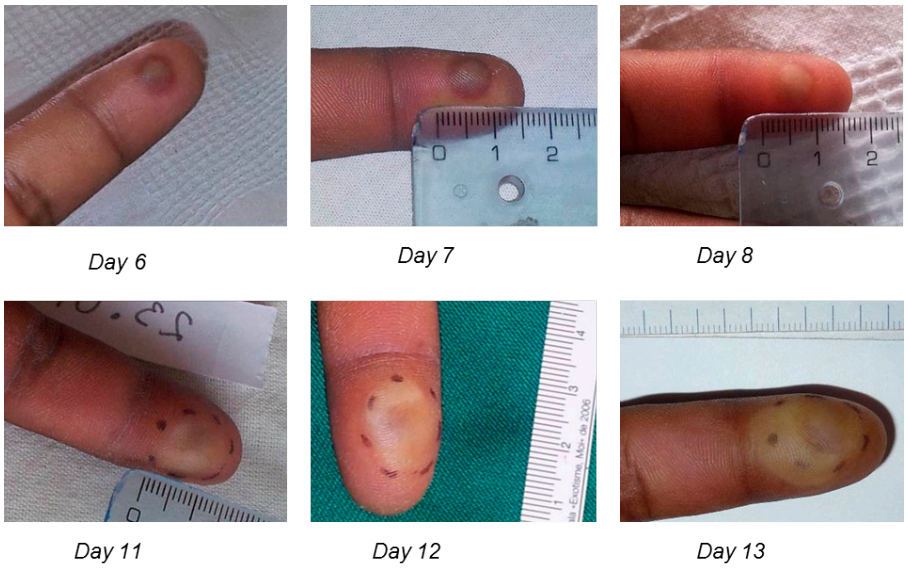


*FIG. 25. Evolution of the local radiation injury during the latent phase — Worker 1. (Courtesy of IPEN.)*


*FIG. 26. Magnetic resonance imaging scan of the left hand of Worker 1, day 13. (Courtesy of IPEN.)*

On day 13, the blister was elliptical, with diameters of 2.2 cm and 1.7 cm. Worker 1 experienced slight pain (an intensity of 2 on a scale of 10) on day 1, which increased by day 11 (an intensity of 5 out of 10) and further increased by days 11 and 12 (an intensity of 7 out of 10). The pain was located on the distal and intermediate phalanges of the index finger on days 12 and 13. On day 16, the blister covered the distal phalanx and half of the intermediate phalanx.

Worker 1 also experienced slight pain (an intensity of 4 out of 10) at a new location on day 12, in the area between the distal and intermediate phalanges of the index finger of his right hand, and this persisted on the next day. On day 13, he experienced a painful (an intensity of 4 out of 10) oedematous; erythema appeared on the right hand thumb, at the space between the distal and intermediate phalanges. These clinical manifestations and their locations were compatible with the scenario described by Worker 1, who stated that he had held the collimator with the thumb and the annular of his right hand.

There were very visible manifestations of LRI on day 19 (see Fig. 27). The manifestations were consistent with the EPR dose evaluation on the nails of the hands of Worker 1. The preliminary dose reconstruction and EPR measurement on the fingernails of Worker 1 had indicated exposures to the extremities of both hands in the range of 20 Gy to more than 50 Gy.

### III.1.3. Conclusion (on day 19)

It was concluded that Worker 1 had a severe LRI on both hands. Given the EPR dosimetry evaluation, the prognosis was very guarded. The extremities of both hands were considered to have been irradiated with doses in the range of 20 Gy to more than 50 Gy. There was a high risk of localized radionecrosis of the hands and fingers.

## III.2. CO-WORKER 1

### III.2.1. Prodromal phase

An erythema appeared on day 19 at the thenar area of Co-worker 1's right hand. The annular finger and thumb were oedematous. A necrotic focal point appeared on the distal phalanx of the thumb (Fig. 28). These clinical signs clearly showed that the hands of Co-worker 1 had been significantly overexposed to radiation.

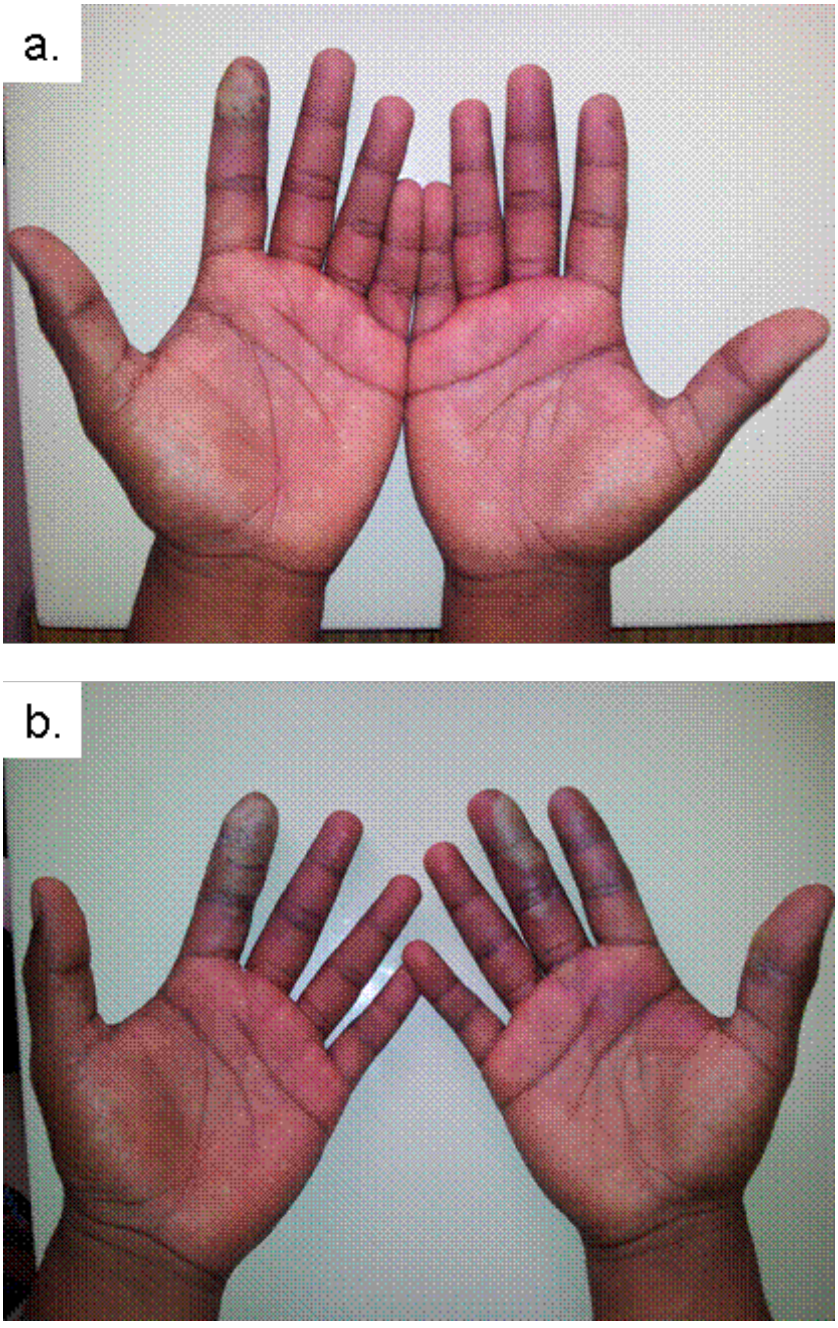


*FIG. 27. Development of the local radiation injury on Worker 1 on (a) day 14 and (b) day 19. (Courtesy of IPEN.)*

*FIG. 28. Development of the local radiation injury on the right hand of Co-worker 1, day 19. (Courtesy of IPEN.)*

### III.2.2. Conclusion (on day 19)

Pain, erythema and oedema manifested on the right hand of Co-worker 1. It was concluded that he had developed an LRI on his right hand. There was a high risk of localized radionecrosis. The EPR dosimetry of the fingernails was considered important in confirming the preliminary dose evaluations to both hands, based on which it was possible to arrive at the prognosis that the patient would develop an LRI.

III.3. CO-WORKER 2

### III.3.1. Prodromal phase

An erythema appeared on day 19 on the thenar region of Co-worker 2's right hand. The annular finger and thumb were oedematous. A necrotic focal point appeared on the distal phalanx of the thumb (Fig. 29). These clinical signs clearly showed that the hands of Co-worker 2 had been significantly overexposed to radiation.

*FIG. 29. Development of the local radiation injuries on both hands of Co-worker 2, day 19. (Courtesy of IPEN.)*

### III.3.2. Conclusion (on day 19)

Pain, erythema and oedema were manifested on the right hand of Co-worker 2. It was concluded that he had developed LRIs on both hands. There was a high risk of localized radionecrosis. The EPR dosimetry of the fingernails was considered important in confirming the preliminary dose evaluations to both hands, and it was then possible to arrive at a reasonable prognosis for the patient's LRI.

## Appendix IV

## DETAILED REPORT ON HAEMATOLOGICAL MANIFESTATIONS BY THE THREE EXPOSED PERSONS

Exposure of the whole or part of the body to radiation can result in damage to different haematopoietic cell lineages of bone marrow with consequent lymphopoiesis, granulopoiesis, thrombopoiesis and erythropoiesis (ARS, haematological type). Although granulocytopenia can lead to risk of infection, thrombocytopenia can result in bleeding and consequent anaemia. Therefore, daily blood counts of persons who have been overexposed to radiation are extremely important for diagnosis and prognosis and as a parameter to guide medical interventions. This appendix details how the data on the blood counts of the three workers who were overexposed to radiation were used to classify those workers on the METREPOL scale with regard to their haematological aspects. This classification was made on day 14, at the end of the first international assistance mission.

In Figs 30–38, the *x*-axes indicate the number of days from day 0, which is taken as the day of the accident (11 January 2012).

### IV.1. WORKER 1

The data on counts for lymphocytes, granulocytes and platelets for Worker 1 are given Figs 30–32, along with the respective observations and conclusions.

Lymphopenia commenced soon after Worker 1's overexposure, and the lymphocyte count had already dropped significantly when first detected on day 6. The count dropped further for a day, then stabilized and started increasing thereafter. As the patient had experienced lymphopenia, he was graded on 25 January 2012 (day 14) as H3 on the METREPOL scale (corresponding to a count in the range of $<0.5 \times 10^9$/L to $1 \times 10^9$/L).

With regard to granulocyte count, it was observed that neutropenia commenced in the days after the overexposure. However, the granulocyte counts were very unstable (Fig. 31). This instability was attributed to the periodic administration of dexamethasone to alleviate the pain caused by the local injuries.

With regard to platelet count, it was observed that it decreased slowly from day 8 and remained above the lower limit ($150 \times 10^9$/L) until day 13, indicating the development of thrombocytopenia.

It was concluded that Worker 1 had experienced an ARS of haematopoietic type, which on day 14 was graded at H3 on the METREPOL scale. The fact that

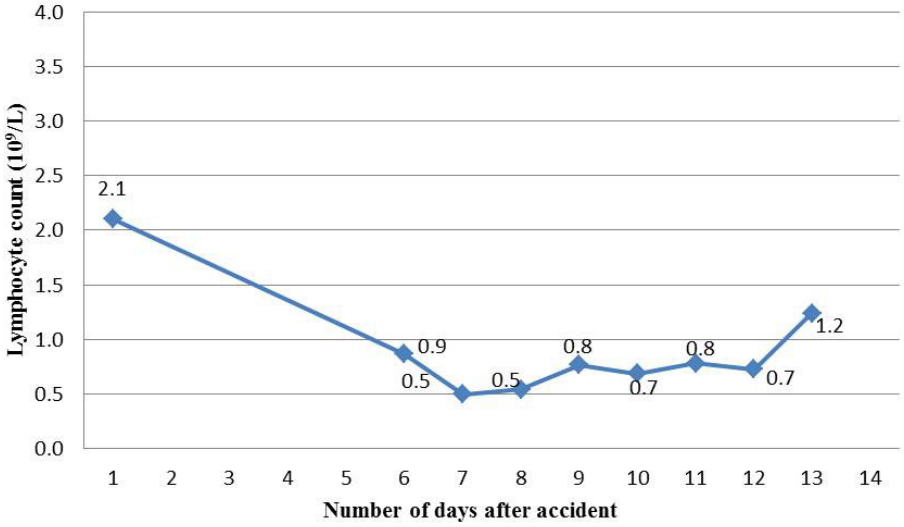


*FIG. 30. Lymphocyte count ($10^9$/L) for Worker 1.*

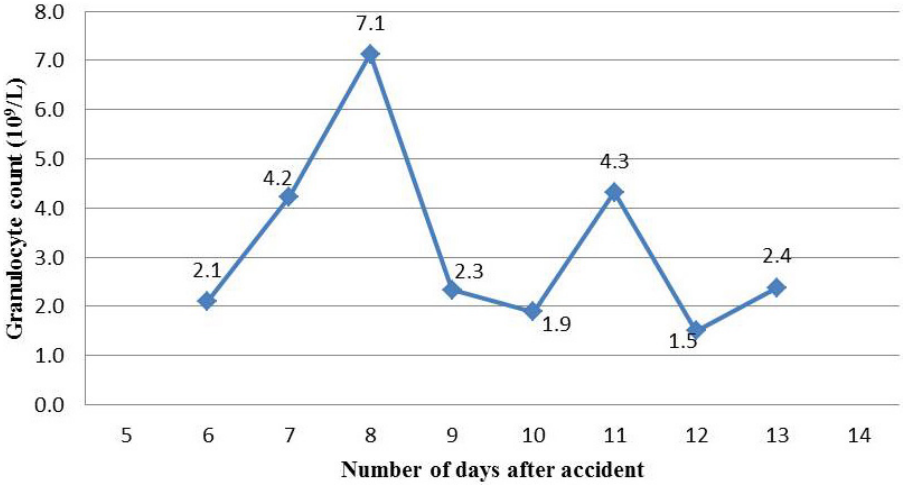


*FIG. 31. Granulocyte count ($10^9$/L) for Worker 1.*

this person had received doses estimated at 4 Gy to the upper part of his body suggested that he had a high risk of aplasia within the following 10 d.

The above clinical manifestations of Worker 1 were compatible with subsequent information, such as:

(a) The physical dose reconstruction, which estimated a total body exposure of 1–2 Gy;

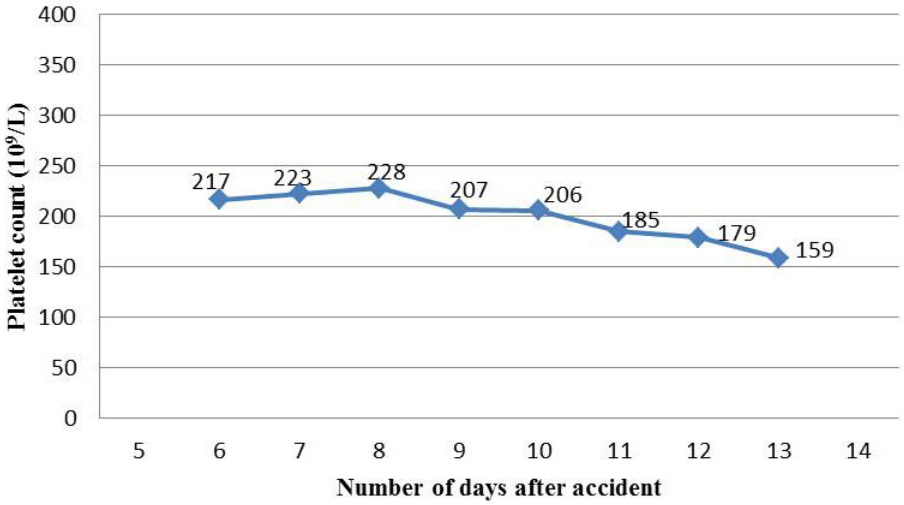


*FIG. 32. Platelet count ($10^9$/L) for Worker 1.*

(b) The biological dosimetry, which estimated a dose of 1.86 Gy combined with high heterogeneity (the upper part of the body having received doses that ranged from 2.5 to 3.5 Gy);
(c) The EPR dosimetry to the teeth, which estimated doses of 3 and 4 Gy;
(d) The EPR dosimetry of the fingernails and toenails, which also confirmed the significant heterogeneity in the overexposure of the person to radiation.

## IV.2. CO-WORKER 1

The data on counts for lymphocytes, granulocytes and platelets for Co-worker 1 are given in Figs 33–35, along with the respective observations and conclusions.

Lymphopenia commenced soon after Co-worker 1's overexposure. His lymphocyte count dropped to $1.1 \times 10^9$/L on day 9. Subsequently, there appeared to be an improvement, and by day 13 he was judged to have mild lymphopenia. On the basis of these observations, he was graded on day 14 at H2 on the METREPOL scale (corresponding to a count in the range of $<1 \times 10^9$/L to $1.5 \times 10^9$/L).

Co-worker 1's granulocyte count was considered normal after day 9. His platelet counts were also considered normal after day 9.

It was concluded that Co-worker 1 had developed a mild haematopoietic syndrome, which on day 14 was graded at H2 on the METREPOL scale.

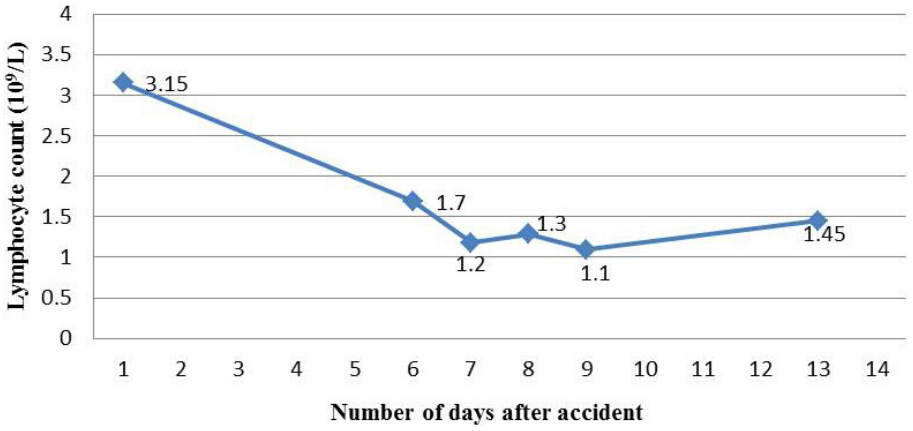


*FIG. 33. Lymphocyte count ($10^9$/L) for Co-worker 1.*

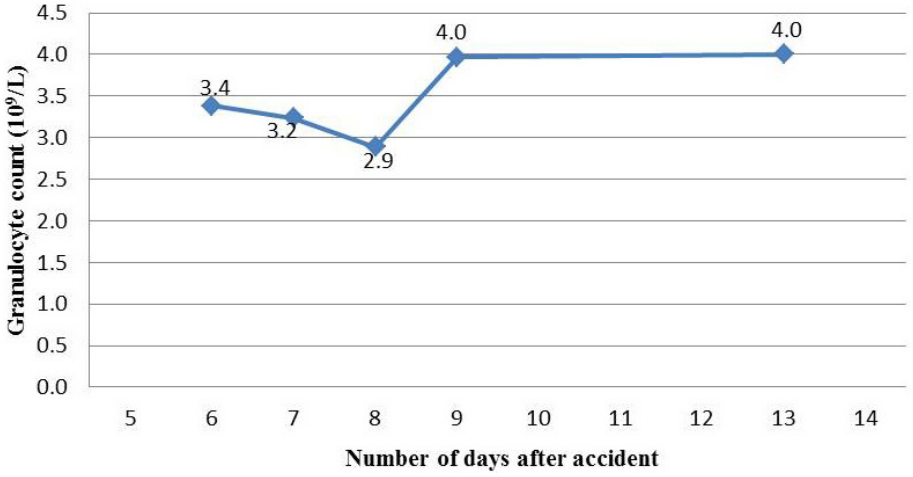


*FIG. 34. Granulocyte count ($10^9$/L) for Co-worker 1.*

Given that the dose received by him was estimated at 0.45 Gy, the possibility of any severe aplasia was excluded. However, as a precautionary measure, a follow-up of the blood count, twice a week for one month, was recommended.

The above clinical manifestations of Co-worker 1 were compatible with subsequent information from biological dosimetry, which estimated a dose of 0.45 Gy. Furthermore, after taking into consideration the uncertainties in the exposure history of this person, these manifestations were also judged to be consistent with the dose reconstruction that estimated an exposure of 0.3 Gy.

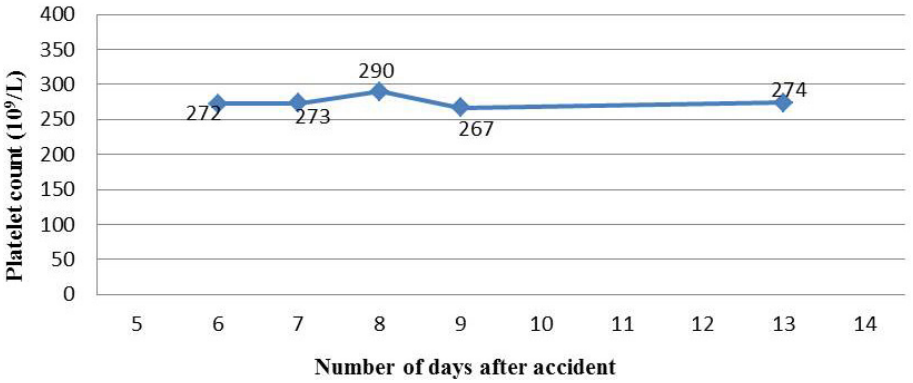


*FIG. 35. Platelet count ($10^9$/L) for Co-worker 1.*

## IV.3. CO-WORKER 2

The data on counts for lymphocytes, granulocytes and platelets for Co-worker 2 are shown in Figs 36–38, along with the respective observations and conclusions.

Lymphopenia commenced soon after Co-worker 2 was exposed. His lymphocyte count dropped to 1.24 × $10^9$/L on day 11. A mild lymphopenia was present on day 13. On the basis of these observations, he was graded on day 14 at H2 on the METREPOL scale (corresponding to a count in the range of <1 ×$10^9$/L to 1.5 × $10^9$/L).

Co-worker 2's granulocyte count was observed to be normal as of day 13. His platelet counts were also considered normal as of day 13.

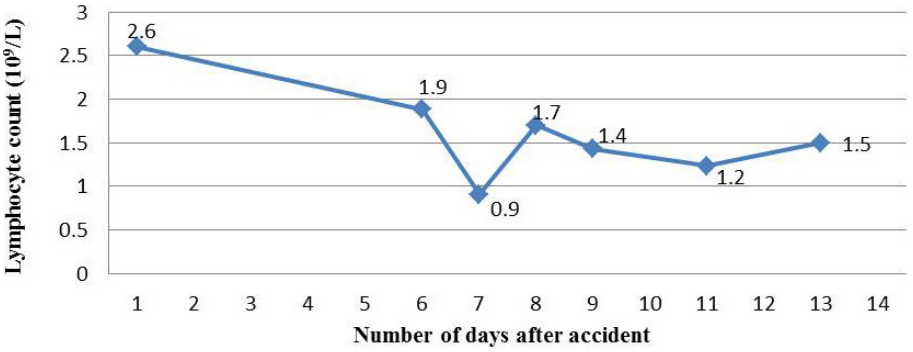


*FIG. 36. Lymphocyte count ($10^9$/L) for Co-worker 2.*

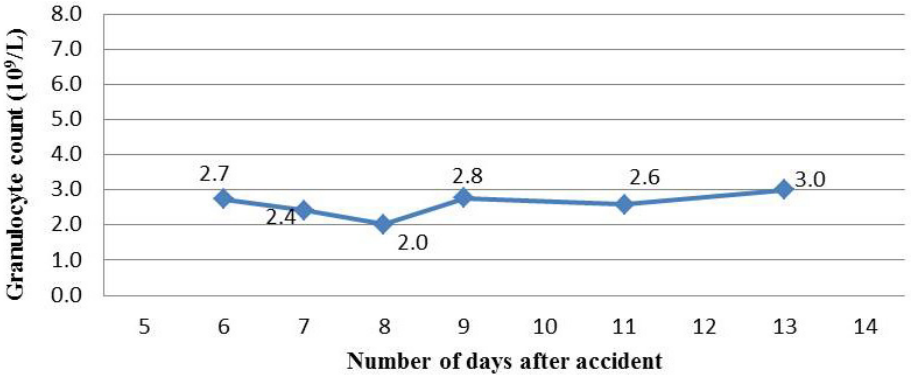


*FIG. 37. Granulocyte count ($10^9$/L) for Co-worker 2.*

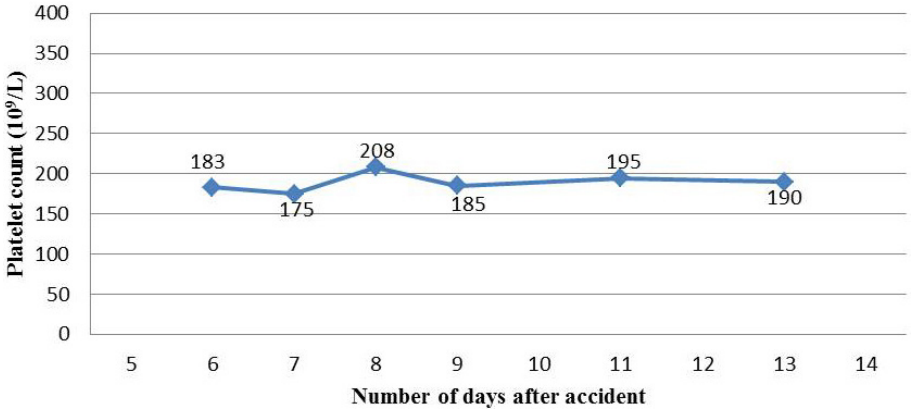


*FIG. 38. Platelet count ($10^9$/L) for Co-worker 2.*

It was concluded that Co-worker 2 had developed mild haematopoietic syndrome, which on day 14 was graded at H2 on the METREPOL scale. Given that the dose received by him was estimated at 0.75 Gy, the possibility of any severe aplasia was excluded. However, as a precautionary measure, a follow-up of the blood count twice a week for one month was recommended.

The above clinical manifestations of Co-worker 2 were compatible with subsequent information from biological dosimetry, which estimated a whole body dose of 0.75 Gy. Furthermore, after taking into consideration the uncertainties in the exposure history of this worker, these manifestations were also judged to be consistent with the dose reconstruction that estimated an exposure of 0.15 Gy.

## Appendix V

## BIOLOGICAL DOSIMETRY RESULTS OF THE FIVE BLOOD SAMPLES SENT TO FRANCE

The biological samples from Peru were received in France on 25 January 2012. The biological dosimetry was carried out at the IRSN. Detailed information on the results for each person who was overexposed to radiation is given below.

### V.1. WORKER 1

The analysis of dicentric chromosomes was completed on 28 January 2012. In total, 635 metaphases with 46 centromeres were randomly chosen and examined. The following counts were observed:

— Ninety-four cells with one dicentric chromosome with its associated fragments;
— Twenty cells with two dicentric chromosomes with their associated fragments;
— Two cells with three dicentric chromosomes with their associated fragments;
— One cell with four dicentric chromosomes with their associated fragments;
— Seven cells with one dicentric chromosome without its associated fragments;
— Seven cells with one ring chromosome with its associated fragments;
— Forty-three cells with one fragment surplus;
— Four cells with two fragments surplus.

The frequency of chromosomal aberrations of dicentric and ring chromosomes observed in the blood sample from Worker 1 was 0.2488, with a 95% confidence level (in the range 0.2115–0.2908) for the 635 cells that were analysed. On the basis of the mathematical interpolation of the dose response curve from the laboratory and the measurements performed on the blood sample provided, it was estimated that Worker 1 had received a whole body dose between 1.56 and 2.20 Gy, with a mean dose of 1.86 Gy. In addition, an overdispersion of chromosome aberrations was observed among cells compared to Poisson's distribution (Papworth *u*-test = 3.5). This finding could indicate a partial body exposure. Following this hypothesis and using the contaminated Poisson method for dose reconstitution, it was estimated that 75% of the body of Worker 1 could

have received a dose between 1.97 and 3.05 Gy, with a mean dose of 2.50 Gy. Under the Qdr method, the estimated partial dose was between 2.94 and 3.86 Gy, with a mean dose of 3.44 Gy. (The contaminated Poisson and Qdr methods for the statistical analysis of chromosome aberration data are based on similar principles and are used to derive dose estimates for the irradiated part of the body under partial body exposure situations.)

### V.2. CO-WORKER 1

The dicentric analysis was completed on 28 January 2012. In total, 512 metaphases with 46 centromeres were randomly chosen and examined. The following counts were observed:

— Thirteen cells with one dicentric chromosome with its associated fragment;
— One cell with one dicentric chromosome without its associated fragment;
— Ten cells with one fragment surplus.

The frequency of dicentric and ring aberrations in chromosomes observed in the blood sample from Co-worker 1 was 0.0273, with a 95% confidence level (in the range 0.0149–0.0459) for the 512 cells that were analysed. On the basis of the mathematical interpolation of the dose response curve from the laboratory and the measurements performed on the blood sample provided, it was estimated that Co-worker 1 had received a whole body dose between 0.23 and 0.75 Gy, with a mean dose of 0.45 Gy.

### V.3. CO-WORKER 2

The dicentric analysis was completed on 28 January 2012. In total, 531 metaphases with 46 centromeres were randomly chosen and examined. The following counts were observed:

— Twenty-six cells with one dicentric chromosome with its associated fragment;
— Two cells with one dicentric chromosome without its associated fragment;
— Two cells with one ring chromosome with its associated fragment;
— Eight cells with one fragment surplus.

The frequency of dicentric and ring aberrations in chromosomes observed in the blood sample from Co-worker 2 was 0.0565, with a 95% confidence level

(in the range 0.0381–0.0807) for the 531 cells that were analysed. On the basis of the mathematical interpolation of the dose response curve from the laboratory and the measurements performed on the blood sample provided, it was estimated that Co-worker 2 had received a whole body dose between 0.5 and 1.06 Gy, with a mean dose of 0.75 Gy.

## V.4. RADIATION PROTECTION OFFICER

The dicentric analysis was completed on 30 January 2012. In total, 506 metaphases with 46 centromeres were randomly chosen and examined. The following counts were observed:

— One cell with one dicentric chromosome without its associated fragment;
— Two cells with one fragment surplus.

The frequency of dicentric and ring aberrations in chromosomes observed in the blood sample from the RPO was 0.002, with a 95% confidence level (in the range 0.0000–0.0111) for the 506 cells that were analysed. On the basis of the mathematical interpolation of the dose response curve from the laboratory and the measurements performed on the blood sample provided, it was estimated that the dose, if any, received by the RPO was below the technique's limits of sensitivity[1], which is consistent with the first estimate as indicated in Table 5.

## V.5. WORKER 2

The dicentric analysis was completed on 31 January 2012. In total, 510 metaphases with 46 centromeres were randomly chosen and examined. Two cells with one fragment surplus were observed.

The frequency of dicentric and ring aberrations in chromosomes observed in the blood sample from Worker 2 was 0.0000, with a 95% confidence level (in the range 0.0000–0.0073) for the 510 cells that were analysed. On the basis of the mathematical interpolation of the dose response curve from the laboratory and measurements performed on the blood sample provided, it was estimated

[1] The mean frequency of dicentric and ring aberrations observed in the chromosomes of unexposed individuals is 0.0011, with a confidence level of 95% (in the range 0.0000–0.0073) for the 510 cells that are counted. This mean frequency was based on the observation of 19 194 cells obtained from a group of 42 non-exposed individuals.

that the dose, if any, received by Worker 2 was below the technique's limits of sensitivity (see footnote 1), which is consistent with the first estimate as indicated in Table 5.

## Appendix VI

## SEQUENCE OF EVENTS FROM DECEMBER 2012 TO SEPTEMBER 2013: WORKER 1

### VI.1. EVENTS OF DECEMBER 2012

In December, skin lesions appeared, characterized by erythema and slight oedema in the first and second phalanges of several of the patient's fingers. An increase in pain was experienced by the patient around the surgical area in the left hand. The patient developed ulcerative dermal lesions and high levels of pain in the fingers of both hands. There was exposure of the bone of about 1 cm in the distal edge of the second phalanx in the left index finger (surgical area of the amputation). A burning sensation was reported in the index and third fingers of the right hand.

### VI.2. EVENTS OF JANUARY 2013

#### VI.2.1. 17 January 2013

On 17 January, a medical evaluation of the patient was conducted in Lima, Peru.

#### VI.2.2. 28 January 2013

Figures 39–42 show the condition of the patient's hands on 28 January 2013. Figure 41 shows the hyper- and hypopigmented skin zones in the index and middle fingers of both hands. Figure 42 shows the loss of the fingernail in the middle finger and desquamative lesions in the second, third and fourth fingers of the right hand. Ulcerative and necrotic processes can be observed on the second and fourth fingers.

#### VI.2.3. 29 January 2013

On 29 January 2013, Peruvian medical doctors discussed the developments with the medical experts in France and at the IAEA's IEC. The initially suggested treatment included oral administration of cloxacillin, corticotherapy and non-steroidal anti-inflammatories. In addition, image and laboratory exams were suggested. The pain was reported to have subsided significantly


*FIG. 39. Worker 1: Hands of the patient on day 383 after the accident — recurrence of local radiation injuries. (Courtesy of A. Lachos, INEN.)*


*FIG. 40. Clinical manifestations on the left hand. Erythema and oedema around the surgical area, skin graft retraction, and bone exposure in the distal edge of the second phalanx of the left index finger can be observed. (Courtesy of A. Lachos, INEN.)*


*FIG. 41. Hyper- and hypopigmentation in the fingers on both hands. (Courtesy of A. Lachos, INEN.)*


*FIG. 42. Worker 1: Signs of necrosis in the distal area of the right index finger (second finger) and in the interphalangeal area of the fourth finger. Note the absence of a nail in the third finger. (Courtesy of A. Lachos, INEN.)*

for some days. The available test results included (a) a haemogram indicating leucocytosis in the range of 11 × $10^9$/L to 12 × $10^9$/L, (b) X rays of the hands indicating osteopenia in the medium phalanx of the left index finger, (c) bone scans indicating non-hyperactivity areas and (d) semen analysis indicating 50% abnormal mobility.

Figure 43 shows an X ray of the left hand suggesting two lytic bone defects in the distal phalanx of the left index finger in the zone of amputation and sclerotic changes of adjacent bone.

## VI.3. EVENTS OF FEBRUARY 2013

During February 2013, there was an aggravation of symptoms and an increase in the size of the lesions. After consultations between medical experts from France and the IAEA's IEC, it was suggested that new surgery and injection of MSCs be carried out.

*FIG. 43. X ray from the left hand of the patient. Note the absence of the third phalanx and resorption of the bone in the distal area of the second phalanx in the second finger. (Courtesy of A. Lachos, INEN.)*

## VI.4. EVENTS OF MARCH 2013

### VI.4.1. 5 March 2013

On 5 March 2013, Peruvian authorities transferred the patient to the country's Social Security Hospital. The patient had pain in his hands and fingers, and blisters and oedema in the index, third and fourth fingers of his right hand. The medical treatment consisted of non-steroidal anti-inflammatories, dexamethasone and dicloxacillin.

### VI.4.2. 20 March 2013

Treatment administered on 20 March 2013 included topical treatment and oral anti-inflammatories. Surgery was suggested.

VI.5. EVENTS OF APRIL 2013

### VI.5.1. 4 April 2013

Figure 44, taken on 4 April 2013, shows blisters and severe lesions in the second, third and fourth fingers of the patient's right hand.

### VI.5.2. 8 April 2013

As of 8 April 2013, clindamycin and dexamethasone 4 mg (1/d) were included in the treatment. Acetaminophen was administered to give relief from stabbing pain in the inner side of the right arm and from pain in the right hand and left index finger. A medical examination revealed that the patient had oedema on the third finger of his right hand and dry ulcers on the index and fourth fingers.


*FIG. 44. Evolution of the lesions in the right hand on day 449 after the accident. (Courtesy of G. Mendoza, IPEN.)*

### VI.5.3. 24 April 2013

Worker 1 was admitted to the Hospital Nacional Guillermo Almenara Irigoyen in Lima on 24 April 2013. The same therapy was continued. The pain was reported to have slightly diminished. However, the ulcers and lesions were increasing daily. A stump surgery was planned.

### VI.5.4. 3 May 2013

Pathologic laboratory tests of 3 May 2013 gave the following results:

— Creatinine: 0.98 mg/dL.
— Glucose: 124 mg/dL.
— Fibrinogen: $4.1 \times 10^9$/L.
— Activated partial thromboplastin time: 33 s (normal value: 27–41 s).
— Haemoglobin: 13.4 g/dL.
— Leucocytes: $12.1 \times 10^9$/L.
— Eosinophil: 3.3%.
— Lymphocytes: 12%.
— Basophils: 0.2%.
— Monocytes: 7%.
— Neutrophils: 77.6%.
— Platelets: $286 \times 10^9$/L.

### VI.5.5. 15 May 2013

Figures 45 and 46 show the development as of 15 May 2013. Figure 47 shows signs of ulcers and necrosis in the second and fourth fingers of the right hand. Figure 48 is of the left hand and shows the bone exposure of the second phalanx in the index finger in the amputated zone, retraction of the skin and signs of necrosis. Ulcers can be seen in the anterior of the thumb, along with pigmentation changes in the skin.

### VI.5.6. 17 May 2013

On 17 May 2013, a magnetic resonance imaging scan was conducted in Lima. The results were that no bone or soft tissue abnormalities were observed on the right hand, although the index finger showed osseous resorption and signs of osteonecrosis. A teleconference was arranged in which medical experts and other officials from Peru, France and the IAEA's IEC participated, including officials from IPEN and the IRSN.

The objective was a clinical analysis to agree on a quick therapeutic approach in view of the severe manifestations in the patient. Surgical procedures and MSC injections were proposed on the basis of these discussions.


*FIG. 45. Right thumb showing skin atrophy, ulcers and pigmentation changes in the skin, 490 d after the accident. (Courtesy of J.-J. Lataillade, HIA Percy.)*


*FIG. 46. Necrotic lesions in the second finger on the right hand, 490 d after the accident. (Courtesy of J.-J. Lataillade, HIA Percy.)*


*FIG. 47. Evolution of the recurrent lesions 490 d after the accident. (Courtesy of J.-J. Lataillade, HIA Percy.)*


*FIG. 48. The left hand shows the bone exposure in the second finger and ulcer in the thumb, 490 d after the accident. (Courtesy of J.-J. Lataillade, HIA Percy.)*

### VI.5.7. 18 May 2013

On 18 May 2013, the IAEA's IEC received the third request for assistance from IPEN under the auspices of the Assistance Convention for follow-up and medical assistance with the treatment of Worker 1.

## VI.6. EVENTS OF JUNE 2013

### VI.6.1. 20 June 2013

On 20 June 2013, the IAEA's IEC received a positive response from Chile, which offered to treat Worker 1. On the basis of this response, an assistance action plan was developed to provide medical assistance to Peru under the above convention. The plan had the following objectives:

(a) Undertake a medical evaluation of the patient's present condition.
(b) Provide medical treatment, comprising a complete medical evaluation of the patient, reconstructive surgery and cell therapy (MSC injection) as required.
(c) Adopt a multidisciplinary approach in the treatment strategy, including reconstructive or orthopaedic surgery, radiopathology consultation, cell therapy and pain management.
(d) Provide any other medical treatment as determined necessary by the medical doctors treating the patient.
(e) Establish an arrangement for follow-up reporting on the medical treatment administered to the patient.

The medical treatment of Worker 1 was to be carried out in Chile, supported by the Mutual de Seguridad Hospital in cooperation with the Stem Cells Laboratory of Del Desarrollo University and with the Chilean Nuclear Energy Commission. The Government of France was to provide the services of a team of medical experts from the IRSN and the HIA Percy with regard to the proposed medical treatment. The IAEA's IEC was also part of the international assistance mission.

### VI.6.2. 27–28 June 2013

On 27 and 28 June 2013, in accordance with the assistance action plan, an international assistance mission team comprising medical experts from the IRSN, the HIA Percy and the IAEA's IEC arrived in Santiago. The team was

joined by medical experts from the Mutual de Seguridad Hospital, the Hospital de Urgencia Asistencia Pública, the Chilean Nuclear Energy Commission and Del Desarrollo University. The team held several meetings to review the medical condition of the patient and to suggest a suitable course of treatment in Chile that would address the recurrence of radiation injury symptoms in the patient. The medical treatment recommended by the team, in consultation with the Chilean institutions, comprised two bone marrow collections, a platelet collection, a surgical procedure and injections of MSCs in four stages, depending on the progress in the medical condition of the patient.

## VI.7. EVENTS OF JULY 2013

### VI.7.1. 17 July 2013

The patient arrived in Chile and was hospitalized in the Mutual de Seguridad Hospital, Santiago, on 17 July 2013. An initial medical evaluation confirmed the severity of the lesions, the necrotic ulcers in several fingers and the bone exposure in the left index finger in the distal part of the amputation area. There were very painful lesions with no signs of infection. A pre-surgical evaluation, which included a blood culture, tests for bacteria and fungi, a laboratory test, exams and clinical images, was performed to confirm the extent of the severity of the lesions and also the degree of bone radionecrosis suspected in the fingers. Blood samples were obtained from the patient for cytogenetic biological dosimetry (by the Chilean Nuclear Energy Commission) and for platelet sample collection in order to prepare a platelet lysate, which was to be used to cultivate the MSCs.

### VI.7.2. 19 July 2013

On 19 July 2013, the first bone marrow collection procedure on the patient was performed under general anaesthesia to obtain two samples of 40 mL each to be cultivated under special conditions for a period of two weeks in the MSC Culture Laboratory. Thereafter, the patient returned to Peru.

## VI.8. EVENTS OF AUGUST 2013

### VI.8.1. 4 August 2013

The patient returned to Chile on 4 August 2013 and was hospitalized in the Mutual de Seguridad Hospital to undergo the next stage of treatment.

### VI.8.2. 5 August 2013

The team of medical experts from Chile, France and the IAEA's IEC reassembled in Chile on 5 August 2013 and reviewed the clinical status of the patient to arrive at a diagnosis.

With regard to the right hand, the diagnosis showed that there was severe recurrence of LRIs in the index and fourth fingers, ulcerative lesions with central necrosis of soft tissues in the inner side, and anchylosis of the distal interphalangeal joint in the fourth finger, with secondary loss of function. Radionecrosis was suspected in the first and second phalanges in both these fingers. There was bone exposure in the distal phalanx of the index finger and skin and tissue retraction in the distal parts of the index finger.

Figures 49–51 show the status of the right hand as of 5 August 2013. They show (a) bone exposure in the distal part of the index finger, (b) an ulcerative lesion with central necrosis of soft tissues and anchylosis of the distal interphalangeal joint in the fourth finger, (c) loss of the third fingernail and (d) hyper- and hypopigmentation changes.

For the left hand (Fig. 52), the diagnosis was severe recurrence of the LRI on the index finger. There was bone exposure of the second phalanx, which was suspected to have developed radionecrosis. Also observed were skin retraction and an ulcerative lesion in the index finger surrounding the surgical area of amputation, as well as an ulcerative lesion on the left thumb. In addition, hyper- and hypopigmentation of the skin were apparent.

*FIG. 49. Right hand 572 d after the accident: Bone exposure in the second finger and hyperpigmentation changes in the rest of the hand.*

*FIG. 50. Right hand, 572 d after the accident: Anchylosis of the distal interphalangeal joint in the fourth finger, loss of the nail and pigmentation changes in the third finger, and bone exposure in the second finger.*

*FIG. 51. Right hand, 572 d after the accident: Pigmentation changes can be also observed in the thumb.*

*FIG. 52. Left hand, 572 d after the accident: Bone exposure in the second finger, ulcer in the thumb and pigmentation changes in the skin of the fingers.*

### VI.8.3. 7 August 2013

On the basis of the patient's clinical status, three medical teams comprising members from the international group of medical experts performed a sequence of procedures on 7 August 2013.

The first team carried out a second bone marrow collection from the pelvis of the patient under general anaesthesia. This collection procedure was performed under conditions similar to those adopted for the previous such procedure and consisted of two samples of 40 mL for processing at the MSC Culture Laboratory (see Figs 53 and 54).

The second team carried out the surgical procedures. These included the amputation of the second phalanx on the left hand index finger and the amputation of the second phalanges on the second and fourth fingers of the right hand. Figures 55 and 56 show both hands after surgical procedures.

The bone fragments obtained during these procedures were labelled and stored separately to be sent to France for electron spin resonance dosimetry studies.

The third team administered the first set of MSC injections to both hands. These injections were completed immediately after surgery and under general anaesthesia; a total of 40 million MSCs were injected into each hand. Figures 57–60 illustrate this procedure.

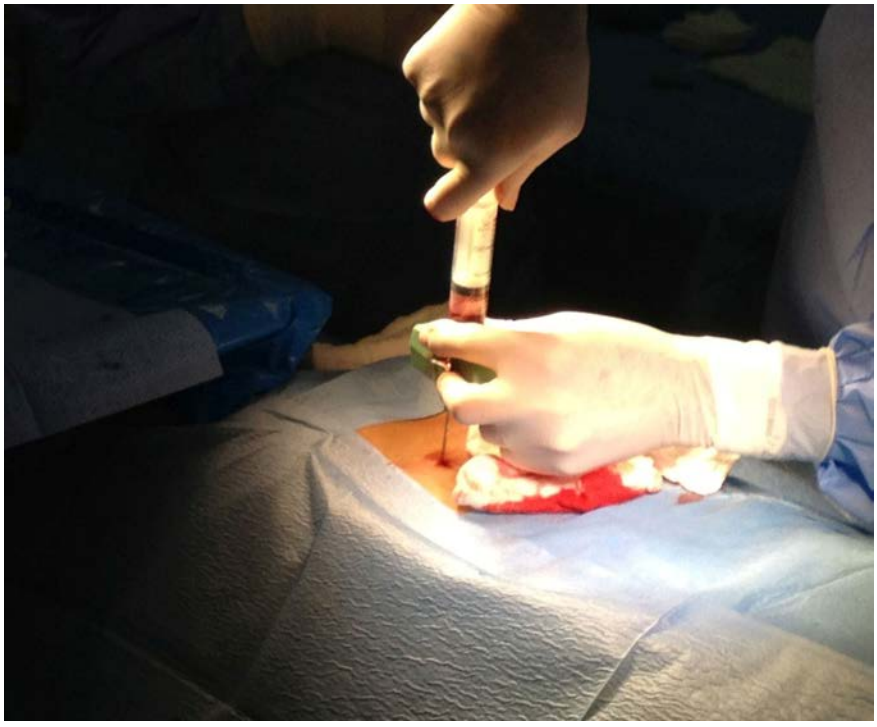

*FIG. 53. Collection of bone marrow on 7 August 2013, 574 d after the accident.*

*FIG. 54. Storage of bone marrow for proceeding with the second mesenchymal stem cell culture.*

*FIG. 55. Left hand after surgical procedure, 574 d after the accident.*

*FIG. 56. Right hand after surgical procedure, 574 d after the accident.*

*FIG. 57. Syringe containing approximately 40 million mesenchymal stem cells before being injected.*

*FIG. 58. Injection of mesenchymal stem cells in the thenar area of the right hand, 574 d after the accident.*

*FIG. 59. Injection of mesenchymal stem cells in the web close to the thenar area of the right hand, 574 d after the accident.*

*FIG. 60. Administration of mesenchymal stem cell injection in the intramuscular region between the second and third fingers of the right hand, 574 d after the accident.*

### VI.8.4. 8–15 August 2013

Between 8 and 15 August 2013, the patient experienced a significant reduction in pain, to the extent that even the opioid drugs were not administered, and only occasional non-steroidal anti-inflammatories were required. The wounds started to heal progressively. There were no indications of infection after the surgery.

### VI.8.5. 16 August 2013

The second set of MSC injections was administered to both hands on 16 August 2013. After a medical check, which indicated that the wounds were healing rapidly, the patient returned to Peru.

### VI.8.6. 30 August 2013

The patient returned to Chile on 30 August 2013, and the third set of MSC injections was administered to both hands. He was experiencing no pain, and the wounds were completely healed.

## VI.9. EVENTS OF SEPTEMBER 2013

On 6 September 2013, the medical experts from France and the IAEA's IEC arrived in Chile to review the medical status of the patient. The fourth and final set of MSC injections was administered to both hands. Figures 61–63 show the hands of the patient as of 6 September 2013.

*FIG. 61. Healing of the surgical wounds on the right hand, 604 d after the accident.*

At the last medical examination in Chile, the surgical wounds were fully healed; the patient did not refer to any pain and presented a good general condition. His progress was considered satisfactory. A medical follow-up was recommended once every three months during the first year, and once a year thereafter for at least ten years. The patient returned to Peru after the last set of MSC injections.

*FIG. 62. Healing of the surgical wounds on the left hand, 604 d after the accident.*

*FIG. 63. Healing on both hands, 604 d after the accident.*

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# ABBREVIATIONS

| | |
|---|---|
| ARS | acute radiation syndrome |
| EPR | electron paramagnetic resonance |
| HIA Percy | Hôpitale d'instruction des armées Percy |
| IEC | Incident and Emergency Centre |
| INEN | National Institute of Neoplastic Diseases (Instituto Nacional de Enfermedades Neoplásicas) |
| IPEN | Peruvian Institute of Nuclear Energy (Instituto Peruano de Energía Nuclear) |
| IRSN | Institute for Radiological Protection and Nuclear Safety (Institut de radioprotection et de sûreté nucléaire) |
| LRI | local radiation injury |
| MCNPX | Monte Carlo *N*-Particle Extended |
| METREPOL | Medical Treatment Protocols for Radiation Accident Victims |
| MSC | mesenchymal stem cell |
| NDT | non-destructive testing |
| RANET | Response and Assistance Network |
| RPO | radiation protection officer |

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