The Radiological Accident in Nueva Aldea

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

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FOREWORD

The use of radioactive material offers a wide range of benefits to medicine, research and industry throughout the world. Precautions are, however, necessary to limit the exposure of people to the radiation that is emitted. Where the amount of radioactive material is substantial, as in the case of radiotherapy or industrial radiography sources, great care is necessary to prevent accidents, which could have severe consequences. Nevertheless, in spite of the precautions taken, serious accidents with involvement of radiation sources continue to occur, although infrequently. As part of its programme on emergency preparedness and response, the IAEA conducts follow-up reviews of such serious accidents, to give an account of their circumstances and consequences, from which organizations with responsibilities for radiation protection, safety of sources and emergency preparedness and response may learn.

A serious radiological accident occurred in Chile, on 14 December 2005, when at a cellulose plant under construction a radioactive source containing ^{192}Ir fell out of gamma radiography equipment unnoticed, and was later found and handled by three scaffolding workers. Under the Convention on Assistance in the Case of a Nuclear Accident or Radiological Emergency, the Chilean authorities requested assistance from the IAEA in terms of advice on the dose assessment and medical management of those involved in the accident.

The IAEA wishes to thank the experts from Argentina, Brazil and France who went to Santiago as members of the IAEA Assistance Mission and, in particular, France and its Institut de radioprotection et de sûreté nucléaire and the Burn Treatment Centre of the Hôpital d'instruction des armées Percy, in Paris, for treatment of the most exposed victim.

The IAEA is grateful to the Government of Chile for the opportunity to report on this accident in order to disseminate the valuable lessons learned. In particular, the IAEA wishes to express its gratitude to the Chilean Nuclear Energy Commission and Mutual de Seguridad de la Cámara Chilena de la Construcción (C.Ch.C.) for their assistance in the preparation of this report.

The IAEA officers responsible for the preparation of this publication were E. Buglova and R. Martinčič of the IAEA's Incident and Emergency Centre.

CONTENTS

1. INTRODUCTION

1.1. BACKGROUND

Gamma radiography reveals defects in welding between two sections of pipeline or some other flaw in a casting or metal component, using the properties of gamma radiation to penetrate components without damaging them. The necessary equipment is highly portable and ideally suited to the sometimes remote and often difficult conditions at construction sites. Iridium-192 is ideal for gamma radiography, but other radionuclides can also be used depending on the characteristics (thickness) of the object material. In Chile alone there are more than 130 gamma radiography sources in use.

The accident occurred on 14 December 2005 at a cellulose plant under construction in Nueva Aldea, Concepción, Chile. After completing radiography one evening on the platform at one of the towers under construction, a radiographer dismantled the radiography equipment, not noticing that the source had fallen out on to the tower platform. The following day a scaffolding worker found it, picked it up and closely examined it, trying to discover what this object was. He showed the source to two other workers but no one knew what this was. He decided to take it to his supervisor. While examining the source in his supervisor's office an electronic alarm dosimeter in a neighbouring office was activated. The worker was instructed to put the object into a 'container'. He threw the source into a metal pipe lying in the yard near the office facility. From there, it was then recovered and put back into the gammagraphy equipment container. Three workers who handled the source were examined at the site medical facility from where they were hospitalized in the Mutual de Seguridad de la Cámara Chilena de la Construcción (C.Ch.C.) hospital in Concepción, and the following day transferred to a hospital in Santiago. The Chilean authorities promptly requested assistance from the IAEA under the Convention on Assistance in the Case of a Nuclear Accident or Radiological Emergency (the 'Assistance Convention') [1].

1.2. OBJECTIVES

For a number of years the IAEA has provided support and assistance under the Assistance Convention, and developed the follow-up reports. Numerous accident reports have been published, and the findings and conclusions of these reports have provided a basis for learning lessons on safety improvements.

The Chilean authorities requested assistance in the accident emergency phase, and subsequently invited the IAEA to evaluate the emergency management system in the country and make recommendations for improvements.

The objective of this report is to compile and disseminate information about the causes of the accident and the subsequent emergency response, including the medical response and the dose assessment aspects. With the dissemination of the lessons to be learned, Member States may be able to identify similar or precursor situations and take the actions necessary to prevent similar accidents from occurring.

The information contained in this report is intended for the use of competent authorities, regulatory bodies, emergency response planners and a broad range of specialists, including medical specialists, physicists and persons responsible for radiation protection. This report also contains information relevant to licensees and operating organizations using radioactive sources.

1.3. SCOPE

This report provides an account of the events reported to have occurred leading up to the accident and those following the accident, and the response actions reportedly taken thereafter. It describes in detail the methods used in the dose assessments and their results, and how the dose assessments complemented the medical assessments. It also describes the medical management of those involved in the accident, including details of the diagnosis and treatment of the most exposed person.

The report ends with the findings, conclusions and lessons to be applied in order to help avoid such accidents in the future and to minimize the consequences of any that do occur.

1.4. STRUCTURE

Background information about the radiation protection infrastructure in Chile and details of the device and its source are provided in Section 2. An account of the events leading up to the accident, the discovery of the accident and of the source is described in Section 3. The emergency response to the accident by local and national authorities, as well as the IAEA's response in providing assistance, is presented in Section 4. Radiological considerations including dose assessment and detailed biodosimetry data are provided in Section 5. The medical management of the individuals exposed as a result of the accident (excluding worker A) is described in Section 6. Initial medical management of the most exposed worker, worker A, which was performed in Chile, is presented in Section 7, while the medical management of that worker performed in France is described in Sections 8 and 10. Sections 9 and 11 present the details of medical follow-up of worker A in Chile during different periods of time. The findings and conclusions are presented in Section 12 and the lessons to be drawn in Section 13. The Appendix contains lists of applicable Chilean regulations, IAEA Safety Standards, radiological norms and safety norms.

2. BACKGROUND INFORMATION

2.1. REGULATORY INFRASTRUCTURE

The Chilean legal framework consists of the international regulations and the national regulations.[1] In the area of the radiation protection, radiation practices are in general classified into three categories according to the risk they pose, Category I being the one with the highest risk. The Chilean Nuclear Energy Commission (CCHEN) is the body responsible for regulation, authorization, control and inspection of the facilities and practices in Category I, while the facilities and practices in Categories II and III fall under the authority of the Regional Ministerial Secretariat (SEREMI) of the Ministry of Health (MINSAL). The nuclear facilities, such as nuclear power plants, enrichment plants, reprocessing plants and permanent waste repositories, are under the authority of the Ministry of Mining. The Chilean regulatory structure is shown in Fig. 1.

Safety evaluation and licensing of nuclear and radiological practices are prescribed by the CCHEN safety norms [2]. Only after verification that the facilities and practices, personnel and operations that require authorization comply with the safety requirements established for the practice has been performed successfully can the authorization for the practice be granted.

The inspections of the facilities and practices in Category I are based on the following two criteria:

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[1] As a general policy, the Chilean Government considers the international conventions at a supra-law level and includes them in the national regulations where applicable. See the list of applicable regulations in the Appendix.

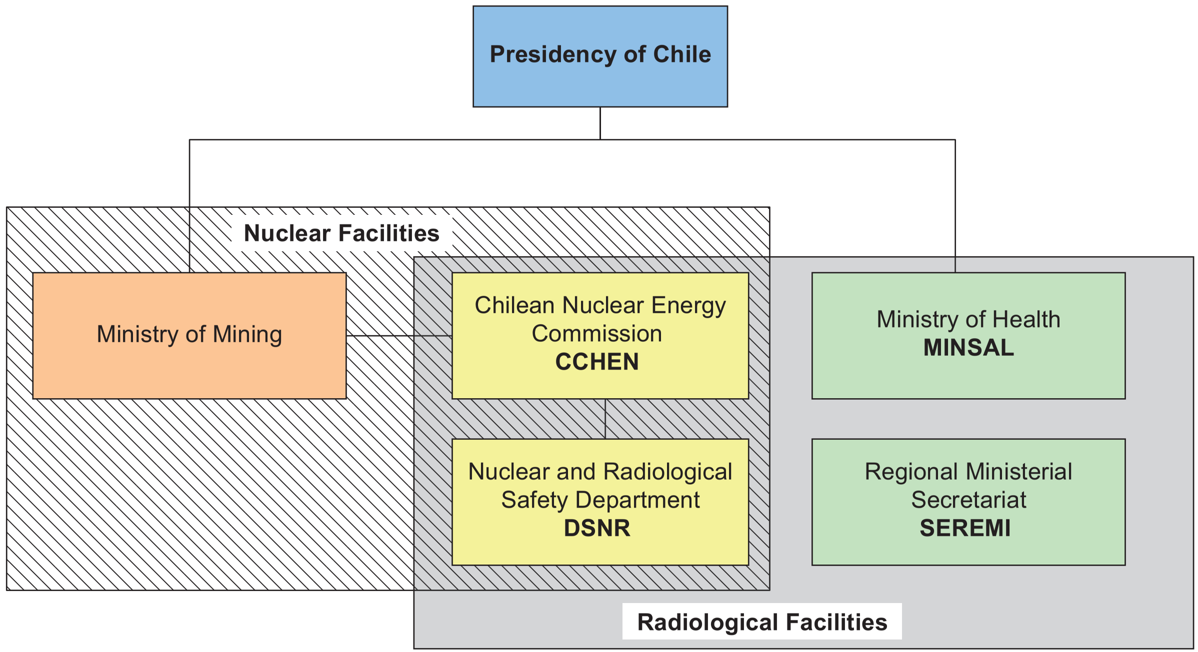

FIG. 1. The regulatory structure for nuclear and radiological facilities in Chile.

(1) In accordance with the recommendations of the IAEA, the facilities and practices shall be inspected at least once a year;
(2) The inspections shall be carried out by a team of two inspectors to avoid any bias.

The aim of the inspections is to verify that:

(a) The safety condition of the equipment included in the authorization process has not become degraded: visual examination of the equipment (looking for dents, abrasions, operational problems; lack of problematic signals) and of the remote control operating apparatus.
(b) The licensee organization has the safety systems and equipment required, including: radiation detectors, personal dosimeters, area warning signs and emergency response elements.
(c) The operators of the licensee organization have a valid operator authorization.
(d) The operational radiation protection and emergency procedures are valid and available, including the correct use of the radiation detectors and dosimeters.

The facilities and practices controlled by the CCHEN at the time of the accident (December 2005) are listed in Table 1[2].

The number of companies and authorized operators in Chile in December 2005 is shown in Table 2.

The authorized operators shall:

(a) Have a high school diploma or higher educational qualification;
(b) Have a valid certificate of a radiation protection course attended that is approved by the CCHEN;
(c) Have passed their eighteenth birthday;
(d) Be in an appropriate psychophysical health condition.

To renew authorization of an operator, the regulations require that personal doses over the last three years be evaluated.

By law[3], all workers in Chile shall be insured against accidents at work and occupational illness by public or private insurance companies that take care of health and monetary compensation[4].

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[2] Facilities owned by the CCHEN are included.

[3] Chilean Law No. 18.744 (1968).

[4] Mutual de Seguridad (C.Ch.C.) provides insurance for most construction workers in Chile.

TABLE 1. FACILITIES CONTROLLED BY THE CCHEN *(in December 2005)*

Type of facility	Number	Type of facility	Number
Conditioning plant for radioactive waste	1	Industrial accelerator	2
Deep roentgen therapy units	1	Industrial X rays	27
Brachytherapy, Cs-137	14	Interstitial brachytherapy, Ir-192	3
Shielded rooms in industry/ medicine	12	Irradiator, class IV (irradiation plant)	1
Shielded rooms in medical use	44	Laboratory for non-sealed sources (nuclear medicine clinic)	33
Equipment for remote brachytherapy	2	Linear accelerator (one energy), teletherapy	14
Fractioning cell	2	Linear accelerator (more than one energy), teletherapy	17
Gamma radiography with Co-60	4	Production and fractioning laboratory	2
Gamma radiography with Cs-137	4	Self-shielded irradiator	4
Gamma radiography with Ir-192	118	Storage facility, medical use	15
Gamma radiography with Se-75	9	Storage facility, industrial use	108
Nursing room	41	Teletherapy equipment, Co-60 source	11
Nuclear humidity gauge (CCHEN)	1	Treatment plant for liquid radioactive effluents	1
Total: 491	253		238

TABLE 2. THE NUMBER OF COMPANIES AND AUTHORIZED OPERATORS ACTIVE IN CHILE

	Industrial	Medical	Services[a]	CCHEN	Total
Companies[b,c]	140	88	7	1	236
Operators	374	233	25	85	717

[a] Import, export, installation, maintenance, calibration, etc.
[b] Facilities owned by CCHEN are included.
[c] Some of the companies, both industrial and medical, have affiliates in regions that are not considered in this table.

2.2. THE DEVICE AND SOURCE INVOLVED IN THE ACCIDENT

The device involved in the accident was a gamma radiography unit manufactured by the Amersham company (USA) as model 660, series 5657. The equipment was owned by one private company but lent to another private company. The radioactive source was ^{192}Ir, model T-5, series MK0807[5]. At the time of the accident, the activity of the source was 3.33 TBq (90 Ci).

The standard gamma radiography unit is made of three parts (Figs 2–5):

(1) The gamma radiography equipment container (projector) that contains the source and devices to connect the remote control and the guide tube;
(2) The remote control, which allows the exposure of the source and the retraction to its safe position inside the projector (it is composed of a crank, conductor cable, protection tubes and an embedding to the projector); the conductor cable has a male piece that fits into a female connector of the radioactive source;
(3) The guide tube, which allows guiding of the source from the projector to the exposure point. This tube has an exposure tip, the one that is placed in a collimator to limit the exposure of unwanted areas.

[5] The source is a cylinder measuring 2.5 cm in length and 6.5 mm in diameter located in the pigtail with a total length of about 18 cm (pigtail plus the source plus the connection system).

FIG. 2. Amersham Sentinel gamma radiography equipment, model 660, series 5657.

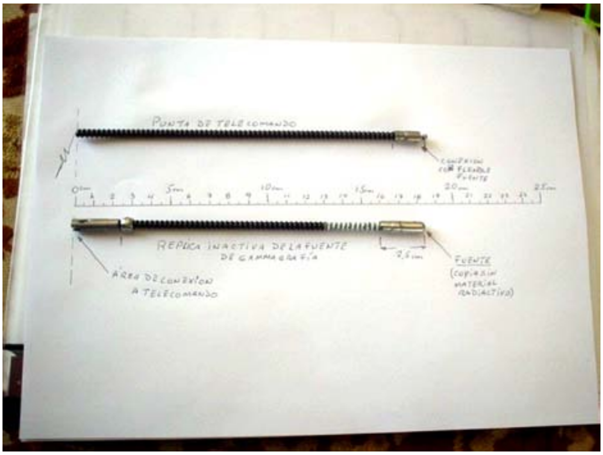

FIG. 3. A dummy ^{192}Ir source (below) and part of the source connector (above).

According to the Chilean regulations, authorization for operations requires:

(a) The Operational Radiological Procedure Manual, defining procedures for routine operations and emergencies approved by the CCHEN;
(b) A calibrated ionizing radiation detector, which must be used whenever the unit is in operation;

FIG. 4. A connector to the source and the projection exposure container (projector).

FIG. 5. A gamma radiography unit: the complete connection, including the guide tube.

(c) The designation of the area where the radiography is taking place as a controlled area, where access is prohibited to everyone except the authorized radiographer and radiography assistants.

3. THE ACCIDENT

3.1. DESCRIPTION OF THE ACCIDENT

The accident occurred on 14 December 2005 at a cellulose plant under construction in Nueva Aldea, Concepción, Chile.

The sequence of events was reconstructed on the basis of:

(a) Interviews with three workers (A, B and C), four radiographers and radiography assistants (D, E, F and H) and their manager (I);
(b) Discussions with the CCHEN staff.

On 14 December 2005 between 20:00 and 21:15 local time (in the following all times stated are local times), radiographer D and two radiography assistants, E and F, were performing radiography on the platform of tower 3 (about 22 m above the ground, see Fig. 6). After completing the fourth exposure, radiography assistant F collected the films and radiography assistant

FIG. 6. Tower 3: the arrow shows the platform where radiographers were working on 14 December 2005 between 20:00 and 21:15.

E dismantled the radiography equipment (taking 2–3 min)[6]. Radiographer D had a thermoluminescent dosimeter (TLD) and an alarm dosimeter, but the alarm dosimeter was turned off[7]. When radiography assistant E was disconnecting the source guide tube, the source fell out of the tube on to the tower platform unnoticed (Fig. 7).

Radiographer D took the films for processing and returned back at about 22:00 to continue radiography at another location. Six or seven exposures were taken on each pipe. About midnight some films were processed. Unfortunately, only the last three films from tower 3 were processed and these were properly exposed; that gave the radiography workers the impression that everything was in order.

The following day (15 December 2005), scaffolding worker A found the source (but did not recognize it as being such) and picked it up with his bare

FIG. 7. A dummy source on the tower platform.

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[6] It took the three radiography workers about 15 min to descend from the platform to the ground to go to another location.

[7] Radiography assistant E was also wearing his TLD, but according to his account he lost it the following day.

hands (about 11.20 according to his account[8]). He held it in his hands for 10–15 min, shifting it from his left to his right hand and turning it upside down. Then he put it into his left back trousers pocket for about 10 min[9] when he started to feel hot. Therefore, he took it out of his back pocket and put it into the left outside pocket of his jacket for a short period (about 1 min) until scaffolding worker B arrived at the platform (about 11:30).

Worker A took the source out of his pocket with his right hand and showed it to worker B, who was at that moment standing close to him. Worker B took the source with his left hand and handled it with both his hands[10] (while wearing leather gloves[11]) for about 5–10 min. Worker A took the source back and examined it carefully, holding it close to his eyes for about 1–2 min in total[12]. Now worker A started to feel warmth in his left hand and burning in his right cheek. He gave the source to worker B and went down to wash his face[13].

A few minutes later, worker B also descended with the source in his hand and close to his face because the ladder was steep and narrow. He joined worker A at the bottom of tower 3. He held the source for about 15 min in total (according to his account).

At the bottom of tower 3 they met scaffolding worker C (their supervisor) and showed him the source. Worker C held the source with his right hand (while wearing leather gloves) for about 5 min[14]. Then worker B left.

Worker C, holding the source and accompanied by worker A, went to the company's office to report to their director[15] the finding (taking 3–5 min). In front of the office building, worker C gave the source back to worker A and

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[8] He noticed the time because he looked at his mobile phone clock when picking up the source.

[9] He bent the flexible cable of the source so that it would fit into his pocket.

[10] Shifting the source from one hand to another.

[11] Although this information is irrelevant from the point of view of protection and shielding, it is important due to the fact that the leather gloves kept the source at some distance from the skin, hence lowering the dose to the skin.

[12] He said: "I looked at it close to the eye many times trying to read the code number."

[13] At this point, worker B noticed that the right cheek of worker A was swollen (but not red). He also commented that worker A was complaining of paraesthesia in his cheek.

[14] He is not sure if he held the source only in his right hand. He also noticed that the right cheek of worker A was swollen.

[15] The director of the scaffolding assembly company; workers A, B, C and G were his employees.

left. Just before entering the office, worker A met scaffolding worker G, who accompanied him to the office.

While the director and workers A and G were in the director's office, a person from a Finnish company entered to check what was going on, as his electronic alarm dosimeter had gone off while he was in a neighbouring office. Worker A was instructed to put the source in a 'container'. The Finn left the office, followed by worker G (the source was in the office for about 5–10 min). He advised worker A to throw the source into a metal pipe that was lying on the ground near the office facility (Fig. 8). Worker A threw the source into the pipe at about 12:00 (according to his account).

3.2. RECOVERY OF THE SOURCE

Two to four persons (workers A and G and possibly two other unidentified workers) were standing near the pipe (about 5 m from the pipe) when radiographer H passed by. They asked him if he recognized the object in the pipe. Radiographer H looked into the pipe, saw the small object, and took it out with his right hand to examine it. He immediately recognized that this was the source and threw it back into the pipe. He instructed the group to stay away and make sure that no one approached the pipe. He went to the office to report to his manager (manager I, the manager of the radiography company).

FIG. 8. The pipe that worker A threw the source into.

Meanwhile, the person from the Finnish company had called manager I[16] by mobile phone and informed him about “high level radiation” (time of the call: 11:47). Manager I picked up a survey meter and went to the site. On the way, he met radiographer H who told him that the source was in the pipe. They measured the dose rate and the survey meter went off the scale at a distance of 2 m from the pipe (upper level: 1 mSv/h)[17].

Manager I and radiographer H cordoned off the area 80–100 m around the pipe and planned the recovery. The manager instructed the radiographer to bring a spare gamma radiography equipment container and place it close to the pipe. They wanted to recover the source from the pipe by lifting the pipe, but the pipe was too heavy. Then the radiographer succeeded in removing the source from the pipe using a wooden stick. The manager himself connected the source connector to the source driver connector and pushed the source into the gamma radiography equipment container.[18] According to their account, the whole operation lasted no more than 2 min. The recovery operation ended about 12:00.

Worker A was instructed to go to the site medical facility. He informed the medical staff that workers B and C had also handled the source, and they were also called in. Later that day (15 December 2005), all three workers were hospitalized in C.Ch.C. hospital in Concepción and then, on 16 December, transferred to the Mutual de Seguridad C.Ch.C. hospital in Santiago.

4. THE RESPONSE

4.1. RESPONSE AT THE NATIONAL LEVEL

The following Chilean national authorities and institutions were involved in the emergency response: the CCHEN, the Ministry of Health, the 8th Region SEREMI, the Ministry of Foreign Affairs and the Mutual de Seguridad C.Ch.C. The management and coordination of the response communications

[16] Manager I was at that moment at a meeting.

[17] At this time, a few people were working close to one wall at a distance of about 15 m from the source; some other people were in the opposite direction, in front of the office building at a distance of about 20 m from the source.

[18] The whole operation was performed using neither gloves nor any dosimeter.

were performed on the basis of the CCHEN's crisis communication manual. Furthermore, a Crisis Committee was established for the coordination of information gathering and its exchange at the local, national and international levels. In addition, the Crisis Committee kept the Directive Council of the CCHEN and the National Emergency Office of the Interior Ministry (ONEMI) informed about all relevant activities.

The Nuclear and Radiological Safety Department (DSNR) of the CCHEN was in charge of gathering all facts about the accident, investigating the causes of the accident and evaluating the safety and occupational radiation protection regime at all involved parties. It was also responsible for preparing technical reports related to dose assessment, affected areas, equipment involved, detailed accident analyses and safety culture issues. The Department of Radiological and Environmental Protection performed cytogenetic analyses for a large number of potentially exposed workers, and consulted with the medical treatment team. The legal aspects of the accident and the actions taken in the emergency response were analysed by the CCHEN's legal affairs department. The CCHEN's international affairs section facilitated the international aspects of the response to the accident by:

(a) Invoking the Assistance Convention;
(b) Informing neighbouring countries (Argentina and Brazil);
(c) Requesting their specialized assistance.

The CCHEN's Executive Director along with its Public Awareness and Extension Section appointed a single spokesperson[19] for communicating with the media. Information about the accident was also sent to the Ministry of Foreign Affairs, which coordinated communications with official entities abroad.

A number of written statements, prepared by the CCHEN and the Mutual de Seguridad C.Ch.C., were sent to the press and, at the same time, to the scaffolding assembly company and the cellulose plant for display at work sites. In addition, letters were later sent to the general managers of all companies involved in the accident, containing the recommendations of the IAEA Assistance Mission. The 8th Region SEREMI coordinated and facilitated the work of the CCHEN's experts, including the discussions and interviews with the workers, as well as training activities.

The Mutual de Seguridad C.Ch.C. coordinated the transfer of the three workers to the Mutual de Seguridad C.Ch.C. hospital in Santiago and later,

[19] Assisted by the technical experts of the CCHEN.

with the Ministry of Health and the CCHEN, coordinated the transport of the most severely injured individual to the highly specialized Burn Treatment Centre of the Hôpital d'instruction des armées Percy near Paris, France. The Mutual de Seguridad C.Ch.C. also coordinated discussions on the treatment expenses and maintained constant communication with the medical experts in France. From the very beginning of the accident, the hospital appointed medical professionals who were in charge of the coordination of medical activities, and who were in constant communication with the CCHEN's radiation medicine expert.

The CCHEN received initial information about the accident at about 13:00 on Thursday 15 December via a telephone call from the Headquarters of the Mutual de Seguridad C.Ch.C. in Santiago, initiating the actions concerning the safety and security of the source and the initial medical management of the victims. The chronology of the actions taken in this early phase of the response is presented in Table 3.

TABLE 3. RESPONSE CHRONOLOGY IN THE EARLY PHASE OF THE RESPONSE

Date	Action
Thursday 15 December	Workers A, B and C are instructed to go to the medical facility at the site Workers A, B and C are transferred to the Mutual de Seguridad C.Ch.C. hospital in Concepción CCHEN is informed about the accident and gives initial instructions. A handbook on Medical Management of Victims of Radiation Accidents (written in Spanish and developed under a regional IAEA ARCAL Technical Cooperation project) was sent electronically to the local hospital
Friday 16 December	A team of CCHEN inspectors is sent to Concepción Inspectors verify the safety and security of the source and of the other equipment Workers A, B and C are transferred to the Mutual de Seguridad C.Ch.C. hospital in Santiago[a] CCHEN staff take blood samples of workers A, B and C for biodosimetry. 130 blood samples for the complete blood count (CBC) are taken by the SEREMI staff from workers identified as being within 10 m range of the source[b]
Saturday 17 December	Inspectors have a meeting with the management of the Nueva Aldea project Inspectors interview personnel from all the institutions involved Inspectors interview the radiography workers and their manager CCHEN decides to contact Argentinian experts on biodosimetry CCHEN sends an advisory message to the IAEA under the Convention on Early Notification of a Nuclear Accident

TABLE 3. RESPONSE CHRONOLOGY IN THE EARLY PHASE OF THE RESPONSE (cont.)

Date	Action
Sunday 18 December	CCHEN requests the IAEA's assistance under the Assistance Convention
Monday 19 December	The IAEA Assistance Mission arrives in Santiago CCHEN establishes a multidisciplinary national work team composed of the CCHEN staff and representatives of the Ministry of Health, the Mutual de Seguridad C.Ch.C. hospital and the Public Health Institute The multidisciplinary national working team meets with the IAEA Assistance Mission team at the CCHEN headquarters (initial meeting)
Tuesday 20 December	The multidisciplinary national work team meets with the IAEA Assistance Mission team at the CCHEN headquarters (second meeting)
Wednesday 21 December	The multidisciplinary national work team meets with the IAEA Assistance Mission team at the CCHEN headquarters (third and final meeting) A second CCHEN team of inspectors is sent to Concepción
21–23 December	Inspectors meet with the Risk Prevention Expert of the Nueva Aldea project to request coordination with all participating companies (in the project); and a complete list of the personnel of the scaffolding assembly company who were near the site when the source was found A safety check of the gamma radiography equipment was performed (a safety check of the remote control cable connection to the source and an inspection of the blocking system) The Mutual de Seguridad C.Ch.C. and the CCHEN inspectors explain the situation and the consequences to the three most exposed persons to the workers of the scaffolding assembly company (day shift and night shift workers) The CCHEN inspectors convene a meeting with a senator and the management of the Nueva Aldea project to explain the situation CCHEN appoints a Radiation Summary Prosecutor in order to investigate the details of the accident and to determine any possible responsibilities The scaffolding assembly company seals the source storage deposit with special locks in order to avoid the use or manipulation of the equipment before the necessary investigation takes place

[a] There was TV coverage of the transfer of the patients to the Mutual de Seguridad C.Ch.C. hospital in Santiago.

[b] In the following days, blood samples from an additional 103 workers were taken (making 233 in total), because more employees were identified as having been potentially within 10 m of the source and because of public pressure at the local level.

The gamma radiography storage facility is shown in Figs 9 and 10. Figure 11 shows the test carried out of the connection between the cable and the source. The connection complied with the requirements of the manufacturer as stipulated by the CCHEN.

FIG. 9. The gamma radiography storage facility.

FIG. 10. Security details at the facility.

FIG. 11. Verification of the connection between the conductor cable and the source.

In response to the accident, the CCHEN:

(a) Performed biodosimetry tests for the 34 workers potentially exposed to doses higher than 100 mSv.
(b) Performed a review of the requirements and conditions for the authorizations of practices and facilities.
(c) Convened meetings with all risk and safety officers in the cellulose industry, distributed posters of gamma radiography equipment and radioactive sources, and recommended training in industrial gamma radiography and radiation protection.
(d) Inspected all Amersham 660 units and their accessories, verifying their condition. Where necessary, the equipment was repaired using original spare parts from the manufacturer.
(e) Inspected the emergency tools (tongs, cutting elements, shields and shield containers) required for industrial gamma radiography in all companies, verifying in situ that these tools are available before gamma radiography is performed.
(f) Increased the number of inspections of gamma radiography companies. Inspections are not announced in advance in order to verify the actually used operational procedures and equipment (gamma radiography unit, personal dosimeters, audible alarms, radiation detectors, set of emergency tools, signalling, remote control, guide tube and collimator), and to inspect the authorization for the operation, the storage facilities, transport, the training of assistants and the existing radiation protection programme.
(g) Sent a letter to all the companies dealing with gamma radiography with information about the accident, background information, lessons learned and the position of the competent authorities.
(h) Elaborated an inspection checklist for industrial gamma radiography and used it for all the companies in this area.
(i) Conducted workshops on industrial gamma radiography for operators.[20]
(j) Conducted a training course on preparedness for the medical response to radiological emergencies.

The Mutual de Seguridad C.Ch.C. headquarters defined two groups of workers and a plan of activities for each group:

[20] This type of workshop became a regular part of CCHEN's activities.

(1) Workers who were in contact with the source and showed radiation induced injuries[21];
(2) Workers who were not in direct contact with the source.

For the first group, the following plan of medical follow-up was prepared:

(a) Monthly check-ups for a period of one year (evolution of the healed skin lesions to be followed);
(b) Complete check-ups every six months, including blood tests for a period of two years, followed by annual check-ups over the next five years. An additional follow-up programme was prepared for the most exposed person, worker A.

The second group of workers was subdivided into three subgroups:

(1) Those who were outside the 10 m zone around the source;
(2) Those who were within the 10 m zone and for whom a conservative physical dose assessment showed that their doses were below 100 mSv;
(3) Those who were within the 10 m zone and for whom a conservative physical dose assessment showed that their doses could be equal to or higher than 100 mSv.

No medical follow-ups were planned for the first and second subgroups. For the third subgroup, biodosimetry tests were performed, and the following activities were planned: check-ups every six months (including CBC tests) in the first year, followed by annual check-ups for the next two years.

4.2. INVOLVEMENT OF THE IAEA

On Sunday 18 December 2005, the IAEA's Incident and Emergency Centre (IEC) received a request for assistance from the CCHEN under the auspices of the Assistance Convention. On the same day, an IAEA Assistance Mission was sent to Santiago, arriving there on Monday 19 December. The team was composed of six international experts[22]. The objectives of the IAEA

[21] Workers A, B and C, and radiography assistant E.

[22] Two experts were from the IAEA, one from France, one from Brazil and two from Argentina.

Assistance Mission, which was conducted in the period 19–21 December 2005, were to assist the Chilean authorities in:

(a) Ensuring that the radiation source involved in the accident was now in a safe and secure condition;
(b) Evaluating the doses incurred by the affected patients by, inter alia, analysing the history of exposure and the medical status of the patients;
(c) Evaluating the treatment given to the affected workers, making medical prognoses and advising on necessary further treatment;
(d) Identifying issues on which the IAEA could offer to provide and/or coordinate assistance to minimize the consequences of the accident.

After initial discussions with the Chilean authorities, the IAEA Assistance Mission:

(a) Interviewed and performed physical examinations of workers A, B and C;
(b) Studied the medical records of workers A, B and C;
(c) Discussed current and planned treatments with the medical personnel of the Mutual de Seguridad C.Ch.C. hospital in Santiago;
(d) Interviewed radiography workers D, E, F, H, and their manager I;
(e) Studied the occupational doses and shift records of workers on the night and morning shifts of 14/15 December 2005;
(f) Reconstructed the sequence of events;
(g) Made preliminary dose estimates for workers A, B and C;
(h) Assessed the possible dose rate fields in all the areas where the source was located/handled (until source recovery);
(i) Made an initial dose assessment for persons working in areas of the plant where the source was located/handled;
(j) Prepared a preliminary report and initial recommendations.

On Monday afternoon of 19 December 2005, the team of experts interviewed all three workers (A, B and C) at the Mutual de Seguridad C.Ch.C. hospital in Santiago (Fig. 12). Using a ‘thermo-camera’, photographs were taken of the hands, face and chest of worker A, and of the hands of workers B and C. On the basis of these interviews and of a physical examination of worker A, the initial clinical manifestations of the exposure were reconstructed. Workers B and C had no manifestations of local or whole body exposure at the time of these interviews.

FIG. 12. Members of the team interviewing worker A.

On Tuesday 20 December 2005, the team of experts interviewed the radiography workers D, E, F and H and their manager I at the CCHEN Department of Radiomedicine, at the Nuclear Centre La Reina. Radiographer D, who led the radiography work on 14 December in the evening, explained in detail the work performed that night (after the shift change at 20:00[23]). Manager I, using a dummy source, showed the experts how to connect the source connector to the driver connector (it took him less than 10 s).

The conclusions and recommendations of the IAEA Assistance Mission were discussed and agreed upon during a debriefing meeting at the CCHEN premises on 21 December 2005.

5. RADIOLOGICAL CONSIDERATIONS

5.1. INITIAL DOSE ASSESSMENT

Dose estimations were performed on the basis of clinical manifestations of overexposure, physical dose reconstruction, biodosimetry tests and modelling based on Monte Carlo simulations.

[23] In the discussion that followed, the radiographers complained that they were working under time pressure due to their workload.

The initial clinical manifestations of overexposure of worker A are given in Table 4 and the exposure histories reconstructed on the basis of interviews with workers A, B and C are presented in Table 5.

The dose estimates were made by the Chilean, Argentinian, French and IAEA experts.

TABLE 4. INITIAL CLINICAL MANIFESTATIONS OF OVEREXPOSURE OF WORKER A

Clinical manifestation	Time of onset after T_0 (11:20)	Estimated exposure duration of corresponding body part
Left hand fingers		10–15 min
Warmness	10–15 min	
Right cheek		1–2 min
Burning	20–25 min	
Swelling	30 min	
Right eye		1–2 min
Burning	2 h[a]	
Left buttock		10 min
Warmness	20–25 min	
Primary erythema	5 h	
Whole body		45–60 min[b]
Nausea	2 h[c]	
Vomiting	2 h[d]	
Tiredness	1 h[e]	
Anorexia	1 d[a]	
Abdominal cramps	1 d[a]	
Insomnia	First night only	
Diarrhoea	No	
Headache	No	
Fever	No	

[a] Persisted until the examination date (19 Dec.).
[b] Exposure at different distances with different dose rates.
[c] Continued for 30 min.
[d] Three episodes within 5 min.
[e] Continued for 1 d.

TABLE 5. EXPOSURE HISTORY[a] UNTIL THE PIPE CONTAINING THE SOURCE WAS CORDONED OFF

Estimated duration (min)	Earliest/latest times (T_0 = 11:20)	Location	Exposed person	Type of exposure	
				Local	Whole body
10–15	11:42/11:48	Tower platform	A	Hands	Yes
10				Left buttock	Yes
1				Chest (left side)	Yes
1–2				Cheeks, eyes, brain	Yes
5–10	11:47/11:58	Tower platform	A	No	At 1 m
			B	Hands (in gloves)	Yes
5	11:52/12:03	Tower stairs	B	Hands (in gloves)	Yes
5	11:57/12:08	Bottom of tower	A	No	At 1 m
			B	No	At 1 m
			C	Hands (in gloves)	Yes
3–5	12:00/12:13	On the way to the office	A	No	At 1 m
			C	Hands (in gloves)	Yes
1	12:01/12:14	On the way to the office	A	Hands	Yes
5–10	12:06/12:24	In the office	A	Hands	Yes
			G	No	At 1 m
			Director	No	At 1 m
1	12:07/12:25	On the way from the office to the ground	A	Hands	Yes
5	12: 12/12:30	Near the pipe	A	No	At 5 m
			G	No	At 5 m
			No ID[b]	No	At 5 m
1		Source recovery	H	No	Yes
			I	Hands	Yes
At this point, radiographer H instructed everyone to move away from the pipe.					

[a] Worker A said that he threw the source into the pipe about 12:00, which is consistent with the timing (12:07) if shorter exposure periods are taken into account. However, this is not consistent with the information given by radiographer H and manager I who stated that the source recovery operations had already been completed by about 12:00. The telephone company confirmed the time of the phone call from the Finnish worker to manager I as being 11:47, which supports their statement.

[b] No ID: identity not known.

5.1.1. The results of the Chilean experts

The initial assessment of the whole body doses (effective dose) was made by personnel of the SEREMI 8th Region[24] under instructions from the DSNR[25], in order to group workers for medical surveillance. The assessment was made on the basis of the activity of the source at the time of the event, the estimated distances from the source for groups of workers and their estimated exposure times (using exposure versus distance graphs prepared by the DSNR staff, Figs 13–15).

The calculations were made using the following initial assumptions:

(a) An activity of the ^{192}Ir source at the time of the event of 3.33 TBq (90 Ci);
(b) No shielding between the source and the workers;
(c) A distance from the source of up to 100 m;
(d) An exposure time of 11 h for the night shift of 14–15 December and 3 h for the day shift of 15 December.

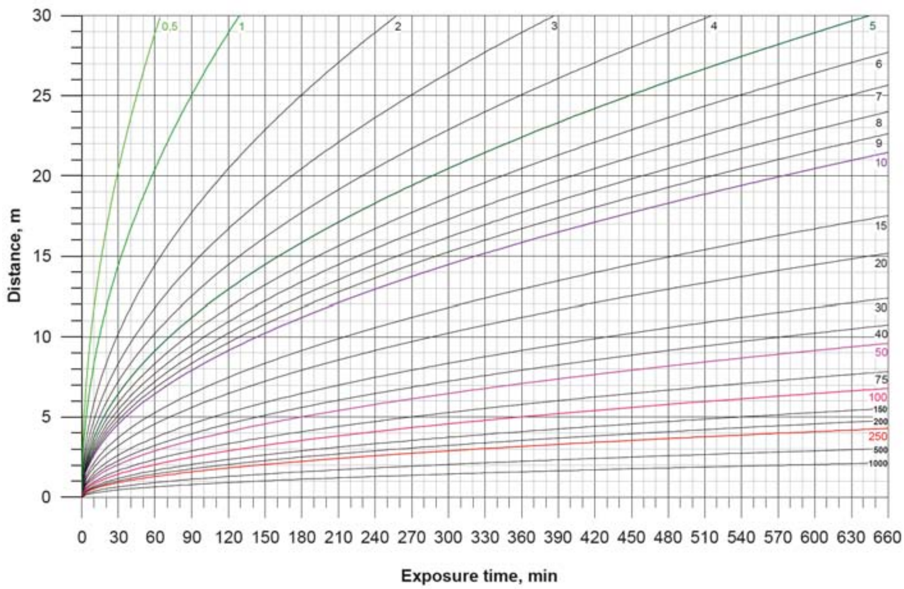

FIG. 13. Effective dose (mSv) as a function of distance and exposure time.

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[24] In charge of the response at the local level.

[25] SEREMI 8th region personnel had no knowledge or experience of radiation protection.

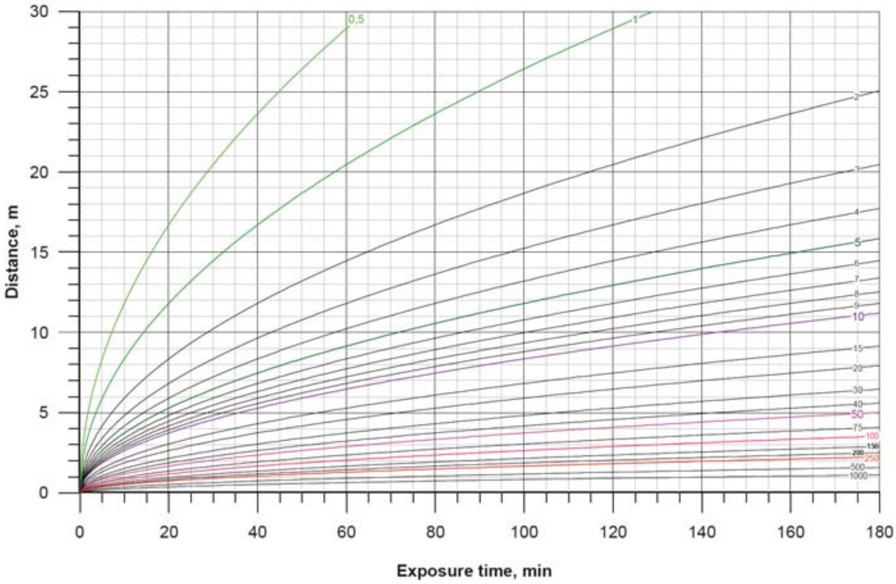

FIG. 14. Effective dose (mSv) as a function of distance and exposure time.

Exposure rates at different distances were calculated using the MicroShield version 5 code of Grove Software, Inc.

The results showed (Figs 13 and 14) that beyond a distance of 30 m the doses were negligible from the radiation protection point of view. In order to obtain additional information for decision making, an additional chart for the exposure times of up to 20 min within 10 m from the source was produced (Fig. 15).

On the basis of these estimations, the following conclusions were drawn:

(a) Doses significant for deterministic effects: No deterministic effects could be expected among the workers who did not handle the source.
(b) Doses significant for stochastic effects: Beyond 5 m from the source, regardless of the exposure time, no worker received more than 250 mSv, and no significant increase in development of stochastic effects could be reasonably expected.
(c) Doses reconstructed by biodosimetry methods: No workers who were beyond 7 m from the source, regardless of the exposure times, received doses exceeding 100 mSv, which is the minimum detectable dose by biodosimetric methods; in cases where it was suspected that the doses

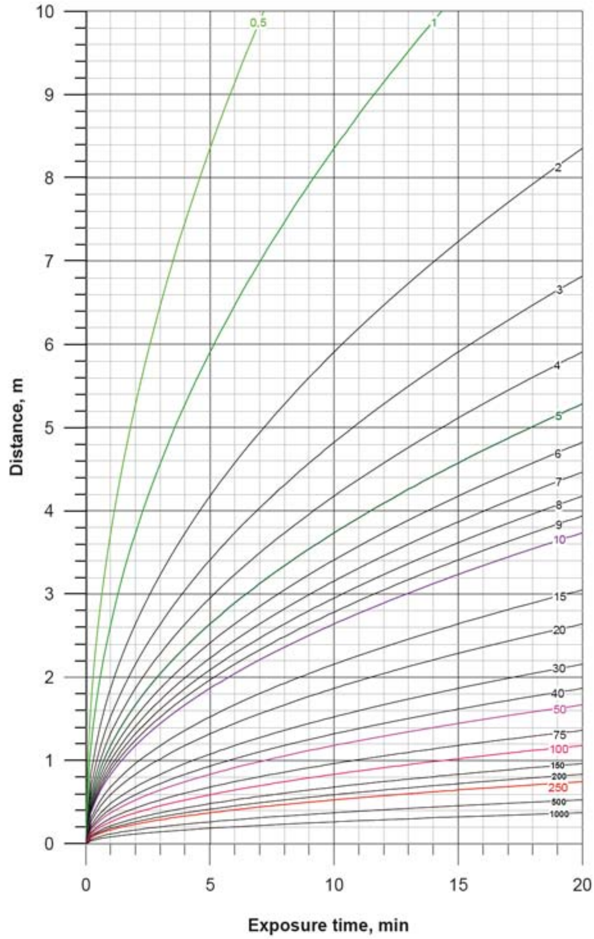

FIG. 15. Effective dose (mSv), as a function of distance and exposure time.

exceeded 100 mSv, individual dose assessments using biodosimetry methods were made.

(d) Doses exceeding annual dose limits: Occupational workers who were beyond 10 m from the source, regardless of the exposure time, could not have received doses exceeding 50 mSv (the annual limit for the effective dose in Chile); for members of the public, the equivalent distance corresponded to a little more than 30 m.

On 14 January 2006 the SEREMI 8th region carried out the first interview surveys and made initial estimates of individual doses for 190 workers. Interviewing the workers, it was recognized that some workers had been interviewed twice; others were exaggerating how close to the source they were or for how long they were in the vicinity of the source. For example, some workers on the night shift claimed that they stayed for about 7 h at 2 m from the source (which was clearly not possible since they were no longer working at tower 3[26]), and some workers on the day shift claimed that they had stayed for 4 h in contact with the source. This was clearly not possible, since the source was recovered 3 h after the day shift started and none of these workers showed any signs of deterministic effects, which clearly would be the case if they were correct. More realistic dose assessments showed that 23 workers on the night shift could have been exposed to some degree. Those workers on the day shift who were working for 3 h[27] within 16 m of the source could have possibly received doses that exceed the dose limit for the public. Nevertheless, the DSNR performed individual dose assessments for every worker who requested this[28] on the basis of re-surveyed data compiled by personnel of the Chilean Ministry of Health. Final dose assessments were made for 251 persons (Table 6).

TABLE 6. RESULTS OF PHYSICAL DOSE ASSESSMENTS FOR WORKERS ON NIGHT AND DAY SHIFTS

Effective dose range (mSv)	Number of workers			
	Scaffolding assembly company	Radiography company	Others	Total
$0 < E \leq 5$	61	0	9	70
$5 < E \leq 50$	106	0	24	130
$50 < E < 100$	9	1	5	15
$E \geq 100$	25	3	8	36
Total	201	4	46	251

[26] Where the source was lying until the following morning.

[27] The time from the beginning of the day shift until the source was recovered.

[28] Requests were gathered by the SEREMI 8th Region and the Mutual de Seguridad C.Ch.C. hospital.

5.1.2. The results of the international experts

The French and IAEA experts made their dose estimations on the basis of clinical symptoms (for workers A, B and C) and physical dose reconstructions using a Monte Carlo simulation. The Argentinian experts performed biodosimetry assessments.

5.1.2.1. The results for worker A

The initial dose estimates for worker A were performed during the mission by the Institut de radioprotection et de sûreté nucléaire (IRSN, France) and the IAEA.

The IRSN calculated the local dose distribution in the left buttock (the most irradiated part of worker A's body). The preliminary results showed that worker A received 1600 Gy (with 40–50% uncertainty depending on the scenario) at the surface, with a steep decrease in dose with depth (Fig. 16). Using a Monte Carlo simulation method, the IAEA estimated the dose at a depth of 3 mm from the surface of the skin as being 940 Gy (with 40% uncertainty). Both calculations were carried out under the assumption that the source was 10 min in worker A's rear left pocket.

The IAEA calculated the whole body dose under the following four assumptions for how long the source was at various locations:

(1) 10 min in his rear left pocket;
(2) 1 min in his front left pocket;
(3) 20 min in his hands;
(4) 3 min at a distance of 10 cm from his eyes.

The calculation resulted in a whole body dose of 1.2 Gy. In addition, worker A was also near the source (e.g. at 1 m) for about 20 min in total. This was estimated to add to his whole body dose another 0.1–0.3 Gy.

Blood samples were taken from worker A prior to the arrival of the IAEA Assistance Mission team in Santiago. The Argentinian member of the team analysed the samples and, on the basis of chromosome aberrations, estimated the dose for worker A to be about 1.3 Gy.

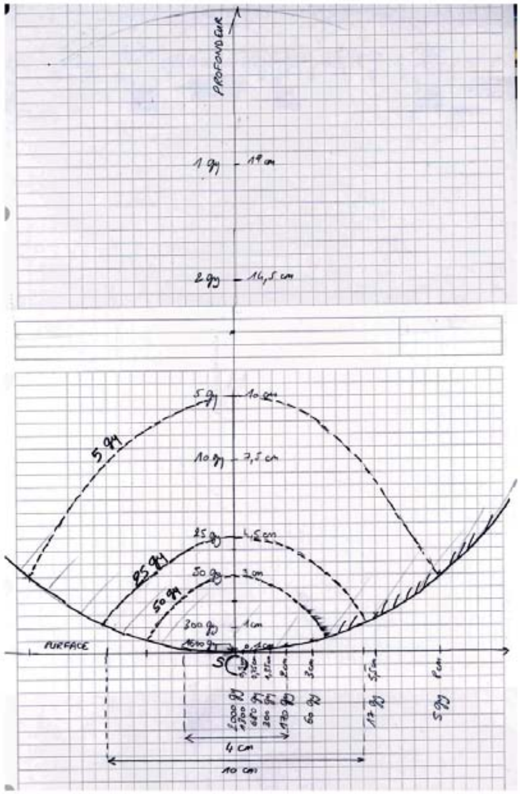

FIG. 16. Initial assessment of the dose distribution in the left buttock of worker A (courtesy: IRSN, France).

On the basis of the clinical manifestations[29] of the exposure, the team estimated the whole body dose for worker A to be between 1 and 2 Gy.

A summary of these estimates is presented in Table 7.

5.1.2.2. The results for workers B and C

The whole body doses for workers B and C were estimated on the basis of the following assumptions: the source was held in their hands for 10 min (worker B) and for 5 min (worker C). In addition, worker B was near the

[29] See Table 4.

TABLE 7. SUMMARY OF THE RESULTS OF PRELIMINARY DOSE ESTIMATES FOR WORKER A

Basis of estimate	Whole body dose (Gy)	Local dose to left buttock[a] (Gy)
Clinical manifestation	1–2	—
Chromosome aberrations	1.3	—
Physical dose reconstruction	1.3–1.5	940–1600

[a] Dose at the surface with a steep decrease with depth.

source (at 1 m) for at least 5 min. The results of these estimates for both workers are presented in Table 8.[30]

5.1.2.3. The results for radiography workers D, E, F, H and manager I

Since the dose estimates depend heavily on the possible scenarios, no reliable dose estimates could be made. Therefore, blood samples for biodosimetry were taken from all four radiography workers. The results based on the chromosome aberrations are shown in Table 10.

In addition, the CCHEN provided the TLD results for radiographers D and H and manager I. These results are presented in Table 9.

TABLE 8. ESTIMATES OF THE WHOLE BODY DOSES FOR WORKERS B AND C

Basis of estimate	Whole body dose (Gy)	
	Worker B	Worker C
Clinical manifestation	No prodromal manifestations	No prodromal manifestations
Physical dose reconstruction	<0.5	<0.25

[30] Blood samples from both workers were also taken for the analysis of chromosome aberrations; see the results presented in Table 10.

TABLE 9. THE TLD RESULTS FOR THE LAST THREE MONTH PERIOD PROVIDED BY THE CCHEN ON 19 DECEMBER 2005

Person	TLD code	TLD results (mSv)
Radiographer D	No. 963	35.76
Radiographer H	No. 1124	7.13
Manager I	No. 102	0.67

5.1.2.4. The results for other possibly exposed persons

The persons who may have been within 10 m of tower 3 were workers on the night shift (from about 21:15 on 14 December 2005 until 08:00 next morning) and the morning shift (15 December 2005 from 08:00 until 11:00). Shift records showed that, in total, 159 persons were working on both shifts (25 on the night shift and 134 on the morning shift). Blood samples for blood count analyses were taken from all 159 persons. Some other persons may also have been exposed while the source was in the office and in the pipe. Dose estimation depends on the scenarios possible; for example, 5 min exposure at a distance of 1 m would give about 25 mSv (Fig. 17).

In addition, IRSN performed an assessment of the fields about tower 3, where the dose would have been lower than 10 mSv (Fig. 18), and an

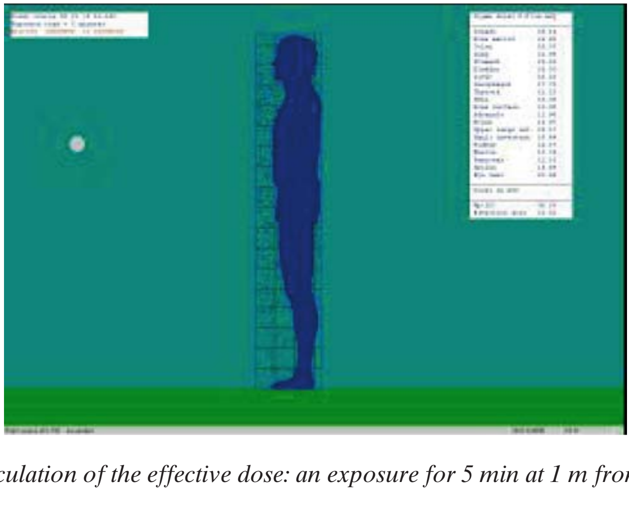

FIG. 17. Calculation of the effective dose: an exposure for 5 min at 1 m from the source.

assessment of the areas at ground level where the dose would have been lower than 10, 5 and 1 mSv, respectively (Fig. 19). These assessments were made for the night shift workers, with the duration of exposure assumed to be 11 h.

5.2. BIODOSIMETRY

5.2.1. Workers A, B and C and radiography workers

5.2.1.1. Initial dose evaluation

The initial dose evaluation scoring of the unstable chromosome aberrations (dicentrics and rings) in the first division metaphases of peripheral blood lymphocytes was performed in the period from 16 December 2005 to 16 January 2006. In this period, the following samples were taken:

(a) Blood samples from workers A, B and C — 24 hours after the exposures, when the circulating and extravascular pools were considered to be fully mixed in the body (sampling date: 16 December 2005);
(b) Blood samples from radiography workers D, E, F, H, and manager I, and a second blood sample from worker A (sampling date: 20 December 2005).

The blood sampling, cultures, harvesting and slide preparations were performed in the biodosimetry laboratory of the CCHEN in collaboration with the Argentinian experts. The technique applied for the lymphocyte culture conformed to the criteria outlined in IAEA Technical Reports Series No. 405 [3].

On 21 December 2005, the biodosimetry result for worker A (1.3 Gy) confirmed previous results obtained by clinical dosimetry and physical dose reconstruction. On the basis of these results, the physicians decided to discontinue injections of haematological growth factors (which were started because prodromal symptoms and initial blood cell counts had suggested a higher whole body dose).

On 23 December 2005, 500 metaphases from worker A and about 100 metaphases from workers B and C and radiography assistant E were evaluated.

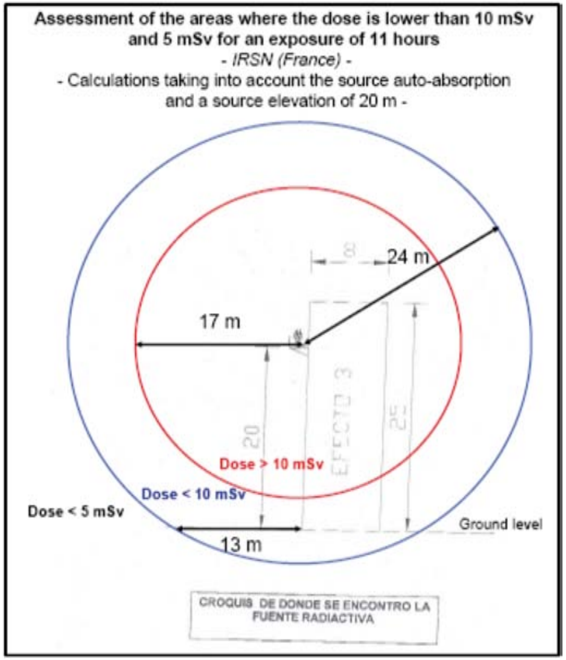

FIG. 18. Assessment of the areas around tower 3 where the dose would have been lower than 10 mSv for 11 h of exposure (courtesy: IRSN, France).

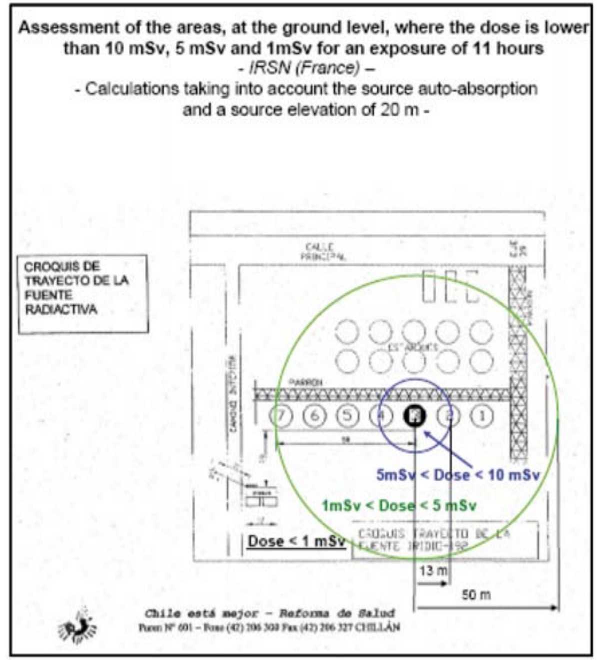

FIG. 19. Assessment of the areas at ground level where the dose would have been lower than 10, 5 and 1 mSv for 11 h of exposure (courtesy: IRSN, France).

5.2.1.2. Final dose evaluation

The Chilean and Argentinian biodosimetry laboratories, in collaboration, performed the scoring of the slides taken. The final results obtained were based on the interpretation from a standard dose–response curve for ^{192}Ir.[31]

A chromosome aberration analysis for worker A revealed that the distribution of dicentrics did not follow a Poisson distribution, indicating that the worker had been exposed to partial body irradiation, which was in agreement with the severe localized lesion observed.

Two methods were applied to assess the mean dose for the irradiated fraction of the body: Qdr, simplified form[32], Sasaki and Miyata model [4] and the Dolphin model [5].

The results obtained using these two methods were consistent (Tables 10–12).

TABLE 10. RESULTS OF THE ESTIMATED DOSES FOR WORKERS A, B AND C, RADIOGRAPHY WORKERS D, E, F AND H, AND MANAGER I

Worker	Scored metaphases	Dicentrics and rings	Dicentric frequency	Mean dose (Gy) and 95% CI*	Irradiated body fraction
Worker A	1106	77	0.0696	0.83 (0.53–1.07)	Whole body
				1.92 (1.57–2.22)	40%
Worker B	500	6 + 2	0.0120	0.24 (0–0.42)	Whole body
Worker C	500	4	0.008	0.17 (0–0.33)	Whole body
Radiographer D	500	4	0.0080	0.17 (0–0.33)	Whole body
Radiography assistant E	618	1	0.0016	<0.10	Whole body
Radiography assistant F	530	6	0.0113	0.23 (0–0.40)	Whole body
Radiographer H	500	3	0.0060	0.13 (0–0.27)	Whole body
Manager I	343	1	0.0029	<0.10 (0–0.18)	Whole body

* CI: confidence interval.

[31] (12.8 R/min), ($\alpha \pm$ ES) Gy^{-1}= 0.0318 ± 0.0180; ($\beta \pm$ ES) Gy^{-2} = 0.0609 ± 0.0072 [6].

[32] Qdr simplified form considers the yield of dicentrics only from those cells that contain unstable aberrations and it assumes that these cells were present at the time of the accident. Qdr is the expected yield of dicentrics among the damaged cells.

TABLE 11. CYTOGENETIC RESULTS FOR WORKER A: THE FREQUENCY OF DICENTRICS IN BLOOD LYMPHOCYTES

Sampling date	Scored metaphases	Dicentrics	Dicentric frequency	Dicentric distribution							u test
				0	1	2	3	4	5	6	
2005-12-16	507	39	0.077	470	35	2	0	0	0	0	0.45
2005-12-20	599	38	0.063	569	27	1	1	0	0	1	16.47
Total	1106	77	0.070	1039	62	3	1	0	0	1	11.29

TABLE 12. DOSE ESTIMATES FOR WORKER A BASED ON THE FREQUENCY OF DICENTRICS IN BLOOD LYMPHOCYTES

Sampling date	Whole body mean dose (Gy) and 95% CI	Mean dose for irradiated body fraction (Gy) and 95% CI*		Irradiated body fraction	
		Dolphin model	Qdr model	Dolphin model (%)	Qdr model (%)
2005-12-16	0.89 (0.54–1.15)	1.09 (0.80–1.32)	1.08 (0.49–1.49)	79	80
2005-12-20	0.78 (0.46–1.03)	2.59 (2.19–2.95)	2.60 (1.98–3.10)	28	28
Total	0.83 (0.53–1.07)	1.92 (1.57–2.22)	1.92 (1.53–2.25)	40	40

* CI: confidence interval.

The *p* fraction of irradiated cells, which survived and reached metaphase, was $p = 0.58$.

The results of the application of both methods showed that the fraction of the body irradiated was not accurately estimated and an underestimation of the dose to the irradiated body fraction was observed. Mitotic delay and interphase death may lead to a preferential elimination of heavily damaged cells, which could explain such dose underestimation.

5.2.1.3. Biodosimetry performed in France

During the treatment of worker A in France (Section 8), a further blood sample was taken on 2 January 2006. Blood sampling, cultures, harvesting and slide preparations were conducted in the biodosimetry laboratory of the IRSN and the cytogenetic analysis was performed according to the IAEA protocol [3]. The reference curve used was obtained by counting dicentrics and centric rings in blood samples exposed in vitro to homogeneous and acute gamma radiations from a ^{60}Co source with a dose rate of 0.5 Gy/min. The results are presented in Tables 13 and 14.

The distribution of chromosome aberrations in the blood sample from worker A did not fit the Poisson distribution. The overdispersion as calculated using the *u* test revealed an inhomogeneous exposure with a 25% irradiated body fraction.

Translocations were measured on the same blood sample using FISH painting techniques (chromosomes 2, 4 and 12). The results obtained (Table 15)

TABLE 13. CYTOGENETIC RESULTS FOR WORKER A OBTAINED FROM THE BLOOD SAMPLE TAKEN IN FRANCE ON DAY 18 AFTER EXPOSURE

Sampling date	Scored metaphases	Dicentrics and centric rings	Dicentric frequency	Dicentric distribution							*u* test
				0	1	2	3	4	5	6	
2006-01-02	512	28 + 1	0.06	485	25	1	1	0	0	0	3.42

TABLE 14. DOSE ESTIMATE FOR WORKER A FROM THE BLOOD SAMPLE TAKEN ON DAY 18 AFTER EXPOSURE

Sampling date	Whole body mean dose (Gy) and 95% CI*	Dolphin mean dose for irradiated body fraction (Gy) and 95% CI	Dolphin irradiated body fraction (%)
2006-01-02	0.76 (0.56–0.93)	2.86 (1.34–3.78)	25

* CI: confidence interval.

TABLE 15. CYTOGENETIC RESULTS FOR WORKER A OBTAINED FROM THE BLOOD SAMPLE TAKEN IN FRANCE ON DAY 18 AFTER EXPOSURE

Sampling date	Scored cells	Scored stable cells (without dicentrics)	Reciprocal translocation	Incomplete translocation	Total translocation
2006-01-02	1501	1486	13	6	19

are complementary to the dose estimates based on dicentric counts. Translocation has the advantage of being more stable as a function of the delay post-radiation.

The reference curve used was obtained by counting the chromosome 2, 4 and 12 translocation frequencies in blood samples exposed in vitro to homogeneous and acute gamma radiations from a ^{60}Co source with a dose rate of 0.5 Gy/min. Dose evaluations were 1 Gy (95% confidence interval (CI): 0.7–1.3) when taking into account reciprocal translocations and 0.8 Gy (95% CI: 0.6–1.0) when taking into account the total number of translocations.

5.2.2. Other individuals

Blood samples from the two workers and the director of the scaffolding assembly company were taken during February 2006.[33] The results of the analyses performed in the CCHEN biodosimetry laboratory are shown in Table 16.

The shift records showed that, in total, 159 persons working on both shifts (25 on the night shift and 134 on the morning shift) might have been within 10 m of tower 3.[34]

For 34 individuals, the doses obtained as a result of physical dose reconstruction were above 100 mGy. For these individuals, biodosimetry was performed. Blood samples were taken from March to April 2006. Blood sampling, cultures, harvesting and slide preparations were performed by the CCHEN biodosimetry laboratory. The unstable chromosome aberration

TABLE 16. BIODOSIMETRY RESULTS FOR THE TWO WORKERS AND DIRECTOR OF THE SCAFFOLDING ASSEMBLY COMPANY

Individual	Code number	Scored metal phases	Dicentrics and rings	Dicentric frequency	Mean dose (Gy) and 95% CI	Irradiated body fraction
Worker G	01/06	500	1	0.002	<0.1 (0.0–0.13)	Whole body
Worker J	02/06	500	0	0	<0.1	Whole body
Director	03/06	500	1	0.002	<0.1 (0.00–0.13)	Whole body

[33] Blood sampling, cultures, harvesting and slide preparations were performed in the CCHEN biodosimetry laboratory.

[34] Night shift: from about 21:15 on 14 December 2005 until 08:00 on the next morning; morning shift: 15 December 2005 from 08:00 until 11:00.

scoring was done in collaboration with the biodosimetry laboratories of Argentina (Autoridad Regulatoria Nuclear (ARN)), Brazil (Institute for Radiation Protection and Dosimetry) and Mexico (Instituto Nacional de Investigaciones Nucleares).[35] Brazil joined the efforts in the spirit of the Assistance Convention, and Mexico under an informal bilateral agreement. The results (Table 17) were based on an interpretation from the above referenced standard dose–response curve for ^{192}Ir [6].

TABLE 17. BIODOSIMETRY RESULTS OBTAINED BY THE CHILEAN LABORATORY TOGETHER WITH CONTRIBUTIONS FROM ARGENTINA, BRAZIL AND MEXICO

Individual	Code number	Scored metaphases	Dicentrics and rings	Dicentric frequency	Mean dose (Gy) and 95% CI	Irradiated body fraction
Worker 1	04/06	500	0	0	<0.1	Whole body
Worker 2	05/06	500	0	0	<0.1	Whole body
Worker 3	06/06	500	1	0.002	<0.1 (0.00–0.13)	Whole body
Worker 4	07/06	500	4	0.008	0.17 (0.00–0.34)	Whole body
Worker 5	08/06	531	0	0	<0.1	Whole body
Worker 6	09/06	500	0	0	<0.1	Whole body
Worker 7	10/06	500	0	0	<0.1	Whole body
Worker 8	11/06	500	2	0.004	<0.1 (0.00–0.22)	Whole body
Worker 9	12/06	500	2	0.004	<0.1 (0.00–0.22)	Whole body
Worker 10	13/06	500	0	0	<0.1	Whole body
Worker 11	14/06	500	2	0.004	<0.1 (0.00–0.22)	Whole body
Worker 12	15/06	500	0	0	<0.1	Whole body
Worker 13	16/06	500	0	0	<0.1	Whole body
Worker 14	17/06	500	0	0	<0.1	Whole body
Worker 15	18/06	500	0	0	<0.1	Whole body
Worker 16	19/06	500	1	0.002	<0.1	Whole body
Worker 17	20/06	500	0	0	<0.1	Whole body

[35] The Chilean laboratory scored 13 samples on its own, while 13 samples were scored together with the Argentinian laboratory, four samples together with the Brazilian laboratory, and the Mexican laboratory evaluated four samples.

TABLE 17. BIODOSIMETRY RESULTS OBTAINED BY THE CHILEAN LABORATORY TOGETHER WITH CONTRIBUTIONS FROM ARGENTINA, BRAZIL AND MEXICO (cont.)

Individual	Code number	Scored meta-phases	Dicentrics and rings	Dicentric frequency	Mean dose (Gy) and 95% CI	Irradiated body fraction
Worker 18	21/06	504	1	0.002	<0.1 (0.00–013)	Whole body
Worker 19	22/06	500	0	0	<0.1	Whole body
Worker 20	23/06	500	0	0	<0.1	Whole body
Worker 21	24/06	500	0	0	<0.1	Whole body
Worker 22	25/06	500	0	0	<0.1	Whole body
Worker 23	26/06	500	1	0.002	<0.1 (0.00–0.13)	Whole body
Worker 24	27/06	500	0	0	<0.1	Whole body
Worker 25	28/06	543	0	0	<0.1	Whole body
Worker 26	29/06	500	1	0.002	<0.1 (0.00–0.13)	Whole body
Worker 27	30/06	500	0	0	<0.1	Whole body
Worker 28	31/06	500	0	0	<0.1	Whole body
Worker 29	32/06	500	0	0	<0.1	Whole body
Worker 30	33/06	500	0	0	<0.1	Whole body
Worker 31	34/06	500	0	0	<0.1	Whole body
Worker 32	35/06	500	0	0	<0.1	Whole body
Worker 33	36/06	500	0	0	<0.1	Whole body
Worker 34	37/06	500	0	0	<0.1	Whole body

The results of the evaluation have shown that only one worker (worker 4) from the night shift received a whole body dose of over 0.1 Gy (0.17 Gy). The doses of other workers were below 0.1 Gy.

5.2.3. Dose comparisons

Comparisons of the doses obtained using clinical manifestations, physical dose reconstructions and biodosimetry are presented in Tables 18 and 19.

The results of the dose reconstructions performed for worker A with the use of different methods are in good agreement.

Biodosimetry estimates performed by the CCHEN laboratory in collaboration with the ARN laboratory (sampling dates: 16 December 2005

TABLE 18. COMPARISON AMONG CLINICAL, BIOLOGICAL AND PHYSICAL DOSE RECONSTRUCTIONS FOR WORKER A

Basis of estimate	Worker A	
	Whole body dose (Gy) and 95% CI	Local dose to left buttock (Gy)
Clinical manifestation	1–2	—
Biodosimetry		—
First day after exposure	0.89 (0.54–1.15)	
Fifth day after exposure	0.78 (0.46–1.03)	
Eighteenth day after exposure	0.76 (0.56–0.93)	
Physical dose reconstruction	1.3–1.5	940–1600

TABLE 19. COMPARISON AMONG CLINICAL, BIOLOGICAL AND PHYSICAL DOSE RECONSTRUCTIONS FOR WORKERS B AND C

Basis of estimate	Whole body dose (Gy)	
	Worker B	Worker C
Clinical manifestation	Below dose for prodromal manifestation	
Biodosimetry	0.24 (0–0.42)	0.17 (0–0.33)
Physical dose reconstruction	<0.5	<0.25

and 20 December 2005, respectively) are very similar to those of the IRSN laboratory (sampling date: 2 January 2006): 0.78 and 0.76 Gy, respectively. Moreover, dose estimates of the fraction of irradiated lymphocytes were 2.59 Gy (obtained in the ARN) and 2.86 Gy (obtained in the IRSN), with irradiated blood percentages of 25 and 28%, respectively.

The results of the dose reconstructions performed for workers B and C with the use of different methods are in good agreement.

6. RADIOPATHOLOGICAL CONSIDERATIONS

This section provides details of the radiopathology of workers B and C, and radiography assistant E.

6.1. CLINICAL SIGNS OF EXPOSURE AND TREATMENT

6.1.1. Worker B

Worker B was hospitalized at the Mutual de Seguridad C.Ch.C. hospital in Concepción on the same day as worker A (15 December 2005). The following day, he was transferred to the Mutual de Seguridad C.Ch.C. hospital in Santiago. He was discharged from this hospital on 22 December 2005, but afterwards received medical check-ups as an outpatient every second day.

On 2 January 2006, an erythema appeared in his right hand. The lesion evolved to moist epithelitis with phlyctena. On 16 January 2006, he was hospitalized again due to the erythema in his right hand and the need for a consultation with a plastic surgeon. The blister was treated on the following day. About a month after this treatment, the tissue was found to be epitelized and healed.

The chronology of the evolution of the clinical symptoms of exposure and treatment is presented in Table 20.

The results of blood counts for worker B are presented in Table 21.

The evolution of the injury to the right hand of worker B is shown in Figs 20–22.

TABLE 20. EVOLUTION OF CLINICAL SYMPTOMS AND TREATMENT OF WORKER B

Date	Symptoms and treatment
2005	
December 15	No clinical signs of overexposure Observation, blood tests and hydration (at the Mutual de Seguridad C.Ch.C. hospital in Concepción)
December 16	Transfer to the Mutual de Seguridad C.Ch.C hospital in Santiago Blood counts normal, no signs of skin lesions Regular medical check-ups and daily haemograms Interview with the personnel from CCHEN Blood samples taken for biodosimetry tests Psychological support provided
December 22	In good condition: no lesions; neurological and ophthalmological statuses normal; thyroid gland and spermiogram normal Discharged from the hospital in good condition; regular medical check-ups (every second day) as an outpatient (at the hospital in Santiago)
2006	
January 2	Erythema appeared in his right hand
January 11	Lesion evolved to blistering on his right hand
January 16	Hospitalized at the Mutual de Seguridad C.Ch.C. hospital in Santiago due to erythema and blistering on his right hand
January 17	Aspiration of blister and resection of necrotic skin Discharged from the hospital in Santiago
February 3	Conservative treatment as an outpatient at the Mutual de Seguridad C.Ch.C. hospital in Concepción Wound epitelized and healed
February 2006–February 2007	Monthly check-ups of the evolution of the healed skin lesions
February 2006–February 2008	Complete check-ups every six months, including blood tests
February 2008–February 2013	Annual check-ups, including blood tests

TABLE 21. RESULTS OF BLOOD COUNTS FOR WORKER B

Date		Parameter			
		Leucocytes (10^3/μL)	Lymphocytes (10^3/μL)	Neutrophils (10^3/μL)	Platelets (10^3/μL)
Normal range		4.0–11.0	1.0–5.0	2.0–8.0	100.0–400.0
Day 1	2005-12-15	7.9	1.6	5.9	225
Day 2	2005-12-16	5.2	1.1	3.8	241
Day 2	2005-12-16	6.6	1.7	4.8	234
Day 2	2005-12-16	5.4	1.6	3.5	220
Day 3	2005-12-17	5.3	1.8	3.2	231
Day 4	2005-12-18	4.9	1.5	2.9	224
Day 5	2005-12-19	5.6	3.1	2.4	228
Day 6	2005-12-20	5.4	2.0	3.0	223
Day 7	2005-12-21	5.6	1.5	3.4	249
Day 8	2005-12-22	5.3	1.9	3.0	222
Day 34	2006-01-17	4.7	1.5	2.7	168
Day 40	2006-01-23	6.0	1.9	3.7	196
Day 91	2006-03-15	4.9	1.3	3.3	205
Day 125	2006-04-18	5.0	1.6	3.0	187
Day 146	2006-05-09	4.7	1.4	3.0	167

FIG. 20. Worker B: moist epithelitis with phyctena on his right hand (9 January 2006).

FIG. 21. Worker B: status of lesion on his right hand (17 January 2006).

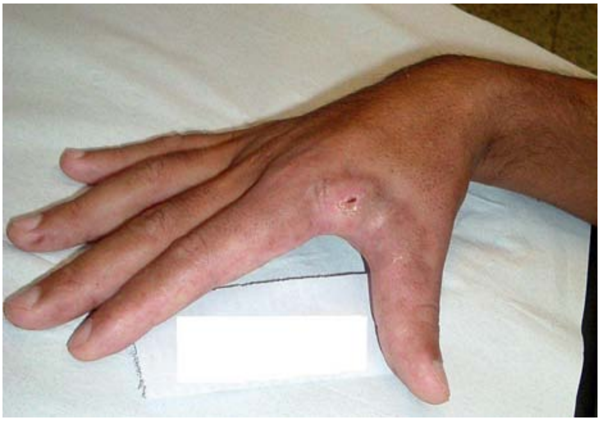

FIG. 22. Worker B: status of lesion on his right hand (3 February 2006).

6.1.2. Worker C

Worker C was hospitalized on the same day as the other two workers (15 December 2005). The evolution of the clinical symptoms of exposure and treatment is shown in Table 22.

TABLE 22. EVOLUTION OF THE CLINICAL SYMPTOMS AND TREATMENT OF WORKER C

Date	Symptoms and treatment
2005	
December 15	No clinical signs of overexposure Observations, blood tests and hydration (at the Mutual de Seguridad C.Ch.C. hospital in Concepción)
December 16	Transfer to the Mutual de Seguridad C.Ch.C. hospital in Santiago Regular medical check-ups and daily haemograms Interview with personnel from CCHEN Blood samples taken for biodosimetry tests Psychological support provided
December 22	In good condition: no lesions; neurological and ophthalmological statuses normal; thyroid gland and spermiogram normal Discharged from the hospital in good condition

TABLE 22. EVOLUTION OF THE CLINICAL SYMPTOMS AND TREATMENT OF WORKER C (cont.)

Date	Symptoms and treatment
2006	
January 11	A burning-type painful sensation of the skin, with pinpoint spots of 3 mm diameter, appeared in the index, thumb and middle fingers of his left hand
January 16	Hospitalized at the Mutual de Seguridad C.Ch.C. hospital in Santiago for observation
January 17	No local treatment required Psychological support provided
January 2006–January 2007	Monthly check-ups of the evolution of the healed skin lesions
January 2006–January 2008	Complete check-ups every six months, including blood tests
January 2008–January 2013	Annual check-ups, including blood tests

The spot on the index finger of the left hand of worker C is shown in Fig. 23.

FIG. 23. Worker C: pinpoint spot on the index finger of his left hand (11 January 2006).

6.1.3. Radiography assistant E

Radiography assistant E developed a lesion on his right foot, which might have appeared as early as 28 December 2005; however, he had not asked for any medical assistance when being interviewed by the CCHEN's incident investigator at the beginning of January 2006. When a burn-type lesion of 1.5 cm extent developed, he was transferred to the Mutual de Seguridad C.Ch.C. hospital in Santiago for treatment.

Table 23 presents the chronology of the evolution of the clinical symptoms of overexposure and treatment of radiography assistant E.

TABLE 23. EVOLUTION OF THE CLINICAL SYMPTOMS AND TREATMENT OF RADIOGRAPHY ASSISTANT E

Date	Symptoms and treatment
2005	
December 20	Blood sample taken for biodosimetry tests
December 28	Lesion on his right foot appears (most likely date; not known exactly)
2006	
January 12	Burn-type lesion of 1.5 cm extent observed on his right foot Transfer to the Mutual de Seguridad C.Ch.C. hospital in Santiago Conservative treatment started
January 30	Lesion almost completely healed Transfer back to the Mutual de Seguridad C.Ch.C. hospital in Concepción for the medical follow-up as an outpatient
February 20	Lesion completely healed An area of hyperalgesia remains
April 3	Headache and leg pain; computed tomography (CT) scan, electromyography and electroencephalography results normal Psychiatric evaluation; psychological support to manage stress
January 2006–January 2007	Monthly check-ups of the evolution of the healed skin lesions
January 2006–January 2008	Complete check-ups every six months, including blood tests
January 2008–January 2013	Annual check-ups, including blood tests

Figure 24 shows the right foot of radiography assistant E with the lesion before treatment, and Fig. 25 shows the lesion after treatment.

FIG. 24. Radiography assistant E: lesion on his right foot (11 January 2006).

FIG. 25. Radiography assistant E: favourable evolution of the lesion (3 February 2006).

7. INITIAL MEDICAL MANAGEMENT OF WORKER A IN CHILE

Worker A was hospitalized at the Mutual de Seguridad C.Ch.C. hospital in Concepción on 15 December 2005 approximately 2 h after being exposed. The caring physician discussed the worker's condition with a staff doctor of the CCHEN and decided to transfer the worker to Santiago for specialized medical evaluation. The following day, he was transferred to the Mutual de Seguridad C.Ch.C. hospital in Santiago.

On 28 December 2005, on recommendations made by the IAEA Assistance Mission team, worker A was transferred under the framework of the Assistance Convention to the highly specialized Burn Treatment Centre of the Hôpital d'instruction des armées Percy near Paris. He returned to Chile on 4 May 2006, where he received further treatment. The chronology of the evolution of the clinical symptoms of overexposure and treatment of worker A is given in Table 24.

TABLE 24. EVOLUTION OF THE CLINICAL SYMPTOMS AND TREATMENT OF WORKER A

Date	Symptoms and treatment
2005	
December 15	Erythema of about 4 cm extent on the left buttock (5 h after the accident); a burning sensation and erythema on his hands; nausea and vomiting First supportive treatment
December 16	Transfer to the Mutual de Seguridad C.Ch.C. hospital in Santiago Buttock erythema now 5 cm in diameter Treatment given: oral and intravenous hydration, vitamin E and pentoxyphiline to prevent fibrosis; preventive isolation Local buttock injury dressed
December 17	Erythema, blister and eschar now 6 cm in diameter; ecography reveals a soft tissue swollen region of 2.2 cm extent; subcutaneous and fat oedema. Antibiotics given: Ciprofloxacin 200 mg every 12 h and clindamycin 600 mg three times a day; analgesic given: Ketoprofen Psychological support provided New dressing for local buttock injury

TABLE 24. EVOLUTION OF THE CLINICAL SYMPTOMS AND TREATMENT OF WORKER A (cont.)

Date	Symptoms and treatment
December 18	Erythema in the buttock increases to 8 cm extent; an oedematous region appears on the borders and in the centre, the lesion is yellow; primary erythema of hands disappears. Administration of granulocyte colony stimulating factor (GCSF) Treatment continued as described above
December 19	Persistent oedema in the left buttock. Appearance of central phlyctena Magnetic resonance imaging (MRI) and ultrasonography shows an extended oedema throughout the whole left buttock Thermography shows increased temperature of hands, face and buttock Treatment continued as described above
December 20	Central ulceration in the left buttock (Fig. 26); paraesthesia and disaesthesia of the left thumb and forefinger; an eye burning sensation and a left subconjunctive haemorrhage; intense pain in the left buttock Administration of GCSF stopped Treatment continued as described above
December 21	Dental hygiene and removal of decayed parts of teeth in order to prevent possible infection sources
December 26	Leukoplaquia appears on the right hand side of the oral mucosa (Fig. 28) Treatment continued as described above
December 27	Lesions appear on the thumb, index and middle fingers of the left hand with progressive erythema, oedema and pain (Fig. 29); signs of dry epithelitis in the left hand; right hemifacial oedema; central necrosis in the left buttock (Fig. 27); extended erythema throughout the entire left buttock New dressings for the fingers affected and for the left buttock injury Treatment continued as described above
December 28	Transfer to the Burn Treatment Centre of the Hôpital d'instruction des armées Percy near Paris, under the Assistance Convention

The results of blood counts for worker A are shown in Table 25. After an initial increase of the numbers of leucocytes and neutrophils on the day of the accident, the number of these cells started to decrease (still being within the normal range). On the basis of this continued tendency of decrease of

TABLE 25. RESULTS OF THE BLOOD COUNTS FOR WORKER A

Date		Parameter			
		Leucocytes (10^3/μL)	Lymphocytes (10^3/μL)	Neutrophils (10^3/μL)	Platelets (10^3/μL)
Normal range		4.0–11.0	1.0–5.0	2.0–8.0	100.0–400.0
Day 0	2005-12-15	16.1	1.0	14.8	295
Day 1	2005-12-16	9.1	2.0	6.7	281
Day 1	2005-12-16	8.9	2.2	6.1	272
Day 2	2005-12-17	6.7	2.4	3.5	263
Day 3	2005-12-18	5.8	1.7	3.2	275
Day 4	2005-12-19	5.2	1.7	2.9	273
Day 5	2005-12-20	5.1	1.3	2.4	263
Day 6	2005-12-21	24.5	1.0	3.0	304
Day 7	2005-12-22	27.4	5.5	3.4	247
Day 8	2005-12-23	14.2	2.0	11.9	242
Day 9	2005-12-24	8.5	1.7	5.9	248
Day 10	2005-12-25	8.1	1.9	5.3	290
Day 11	2005-12-26	7.2	1.4	5.2	219
Day 12	2005-12-27	6.1	2.1	3.7	204
Day 13	2005-12-28	6.9	2.1	3.9	202
Day 141	2006-05-05	5.8	2.0	3.2	261
Day 154	2006-05-18	5.0	2.2	2.5	254
Day 330	2006-11-10	6.6	2.3	3.0	263
Day 369	2006-12-19	5.5	2.5	2.5	214

leucocytes and neutrophils, the staff of the Mutual de Seguridad C.Ch.C. hospital in Santiago decided to apply GCSF on 18 December 2005. However, this administration was not fully justified, taking into account the radiological data: the level of whole body dose and the inhomogeneous character of the exposure. This radiological information was not fully known at the time of GCSF administration. After collecting radiological data, which provided information on the level and type of exposure, the IAEA Assistance Mission experts and the staff of the hospital analysed the haematological and radiological information, and decided to stop the administration of GCSF on 20 December 2005.

Some of the clinical symptoms are also shown in the photographs below (Figs 26–29).

FIG. 26. Worker A: left buttock lesion (20 December 2005).

FIG. 27. Worker A: central necrosis in the left buttock (27 December 2005).

FIG. 28. Worker A: leukoplaquia on the right hand side of the oral mucosa (26 December 2005).

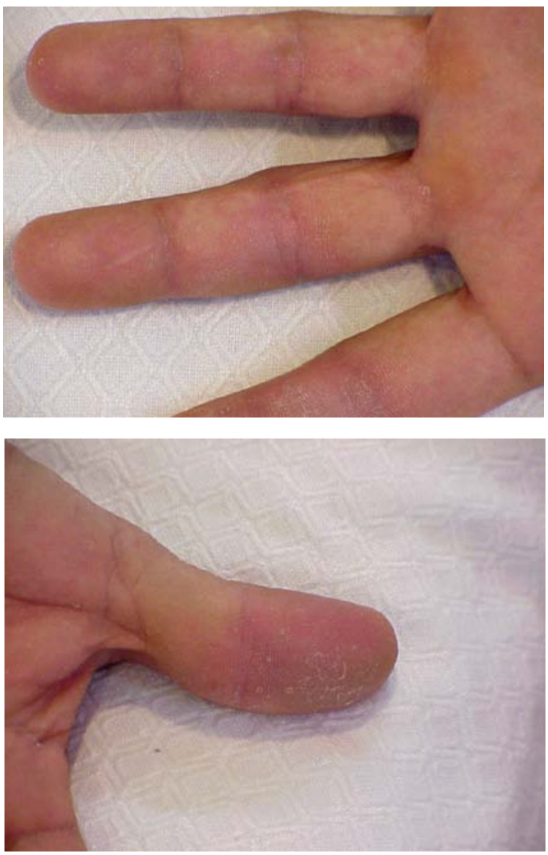

FIG. 29. Worker A: signs of dry epithelitis in the left hand (27 December 2005).

8. MEDICAL MANAGEMENT OF WORKER A IN FRANCE (DECEMBER 2005–MAY 2006)

8.1. MEDICAL MANAGEMENT OF THE BUTTOCK LESION

8.1.1. Dose estimation (calculations using a voxel anthropomorphic phantom)

A dose reconstruction of the radiation lesion using a numerical method and taking into account the anatomical characteristics of worker A was performed. Once the worker had been hospitalized in France, CT and MRI images were made at the Hôpital d'instruction des armées Percy. One hundred and sixty-three slices were selected from mid-abdomen to mid-thigh. Then, using SESAME software, a voxel phantom with external contours and bone structure was generated and defined. An ^{192}Ir source was positioned at 2 mm from the centre of the skin lesion surface of the left buttock. A dosimetric reconstruction using a numerical simulation was performed on the basis of the scenario described by the victim. Finally, the area was selected for which calculation of the isodoses was required, i.e. at the centre of the lesion. The three dimensional (3-D) voxel phantom and the source are shown in Fig. 30.

A map of the dose distribution on the skin surface and underlying tissues of the buttock was obtained using numerical simulations based on a Monte Carlo code and the personalized voxel phantom (Fig. 31). The calculations, performed for a source placed at a distance of 2 mm from the surface of the skin and for an exposure time of 10 min, showed a maximum dose of almost 2000 Gy in the centre of the lesion and a very sharp gradient of the dose as a function of both depth and surface distance. The 20 and the 5 Gy isodoses were, respectively, situated at 5 and 10 cm from the centre of the lesion. Up to the 5 Gy isodose, the isodoses for tissue dose and surface dose are perfectly symmetrical and have the form of a circle.

On the basis of this mapping, an excision measuring 5 cm in depth by 10 cm in diameter was performed on the buttock on 5 January 2006 by the team at the Hôpital d'instruction des armées Percy in Clamart, France.

8.1.2. Innovative therapeutic strategy

The French health authority, l'Agence française de sécurité sanitaire des produits de santé (AFSSaPS), has made ethical and technical approvals of an innovative therapeutic strategy, which combines a classical surgical therapy (excision + skin autograft) and a local mesenchymal stem cell (MSC) therapy for treatment of local radiation injuries (Fig. 32). This strategy was applied to

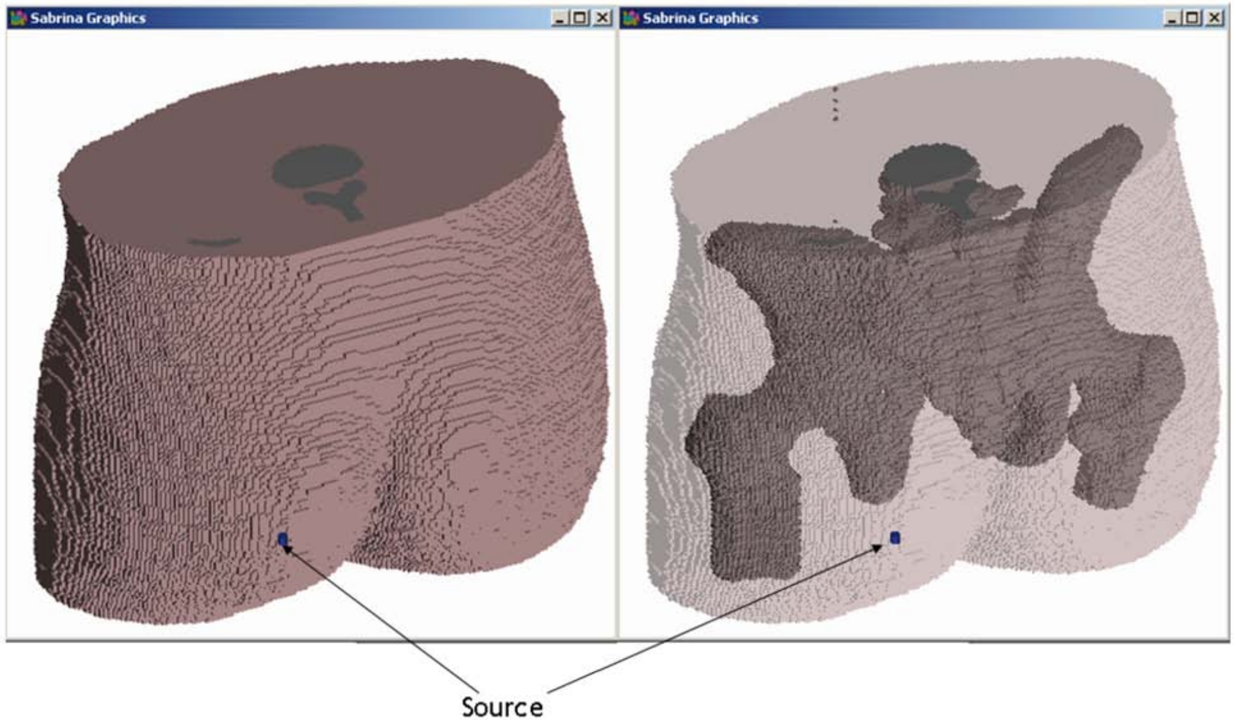

FIG. 30. The 3-D view of the voxel phantom (external envelope and skeleton) and of the source using SABRINA software (courtesy: IRSN, France).

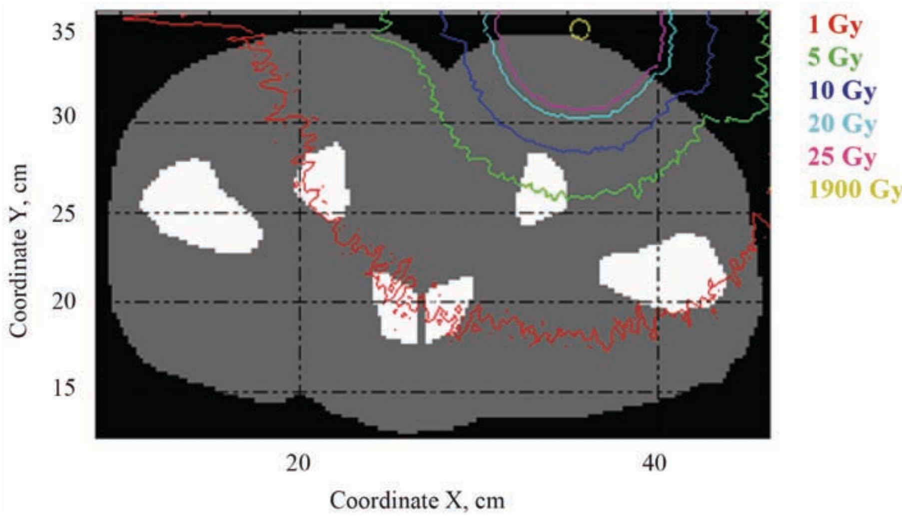

FIG. 31. Dose distribution on the skin surface and in the underlying tissues of the buttock obtained using the personalized voxel phantom (courtesy: IRSN, France).

the medical management of the local radiation injuries of the patient, as it appeared to be the method of choice for his treatment (without the application of such a strategy, the prognosis of the patient's treatment would not be favourable, as was shown by experience of the medical management of the local injuries of exposed individuals in other radiological emergencies). The patient gave his written consent for the application of this therapeutic strategy.

8.1.3. Autologous MSC production

The procedure for production of human grade autologous MSCs has to be validated by the appropriate national health authority. The stem cells unit of the Centre de transfusion sanguine des armées (CTSA) of the Hôpital d'instruction des armées Percy possesses an official agreement with the AFSSaPS.

For MSC production, autologous bone marrow mononuclear cells (BMMNCs) were isolated from unexposed iliac crest aspirations. A novel clinical grade MSC production process using closed culture devices (CellSTACK®) was employed. Cells were expanded in a clinical grade medium containing alpha-MEM (Macopharma, Tourcoing, France), 10 μg/mL ciprofloxacin (Ciflox® 400 mg/200 mL, Bayer Pharma, Puteaux, France) and 8% human platelet lysate (PL) as a source of growth factors [7]. Platelet lysate

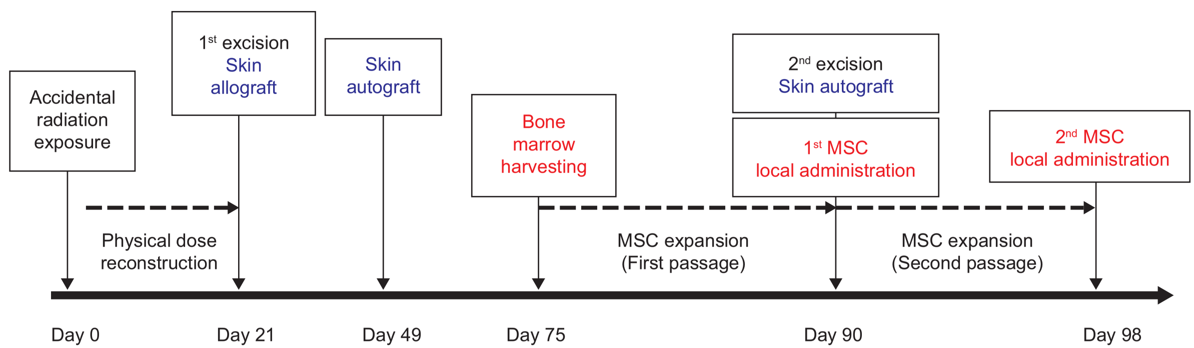

FIG. 32. Schedule of dose assessment, and surgical and cellular therapeutic approaches (courtesy: Hôpital d'instruction des armées Percy, CTSA, IRSN, France).

was obtained from platelet apheresis products, which were biologically qualified according to French legislation. BMMNCs to the number of 254.5 × 10^6 were plated at a density of 200 × 10^3 cells/cm^2 on day 75 after exposure in 1272 cm^2 CellSTACK® devices (Macopharma) containing PL medium and cultured at 37°C in 95% air and 5% CO_2. After three to four days, the non-adherent cells were removed and the cultures were re-fed with fresh medium. On day 14 after the start of the culture, cells reached confluence. One part of the MSCs was harvested after application of trypsin, conditioned in human albumin and freshly administered. The remaining MSCs to the number of 10 × 10^6 were passaged at a density of 8 × 10^3 cells/cm^2 in two 1272 cm^2 CellSTACK® devices and, seven days later, P2 MSCs were harvested for the second local administration.

Quality controls were achieved on each cell product: MSC phenotype characterization (CD45–/CD105+/CD73+/CD90+); colony forming unit-fibroblast (CFU-F) frequency numeration [8]; MSC telomerase activity (using the telomere repeat amplification protocol (TRAP) [8] and contamination control for bacteria, fungi and mycoplasma before administration.

8.1.4. Dosimetry guided surgery

On the basis of dose reconstruction mapping (Fig. 31), a wide resection was performed on day 21 after exposure. All tissues exposed to a dose of over 20 Gy, which were located between the centre of the lesion and the 20 Gy isodose surface, were excised (even if they appeared to be intact on the day of the operation) according to a hemisphere of 10 cm in diameter and then covered with a cryopreserved allograft. Following surgery, no infection or subsequent radiation inflammatory wave was observed for one month. Owing to this apparently normal evolution, a skin autograft was performed on day 49 after exposure. Rapid lysis of the skin graft occurred, with the development of painful infected radiation ulceration.

8.1.5. Histology

All the tissues that were estimated to receive a dose of more than 20 Gy were excised and histologically investigated after the excision.

Histological examination of skin resection (first resection on day 21 after exposure) revealed the characteristic features of skin burns (Fig. 33).

The severity of the observed skin lesion was correlated to the dose distribution as reconstructed by numerical methods. The centre of the lesion was characterized by marked epidermolysis, dermal ulceration and progressive perivascular infiltration of inflammatory cells. Complete destruction of the

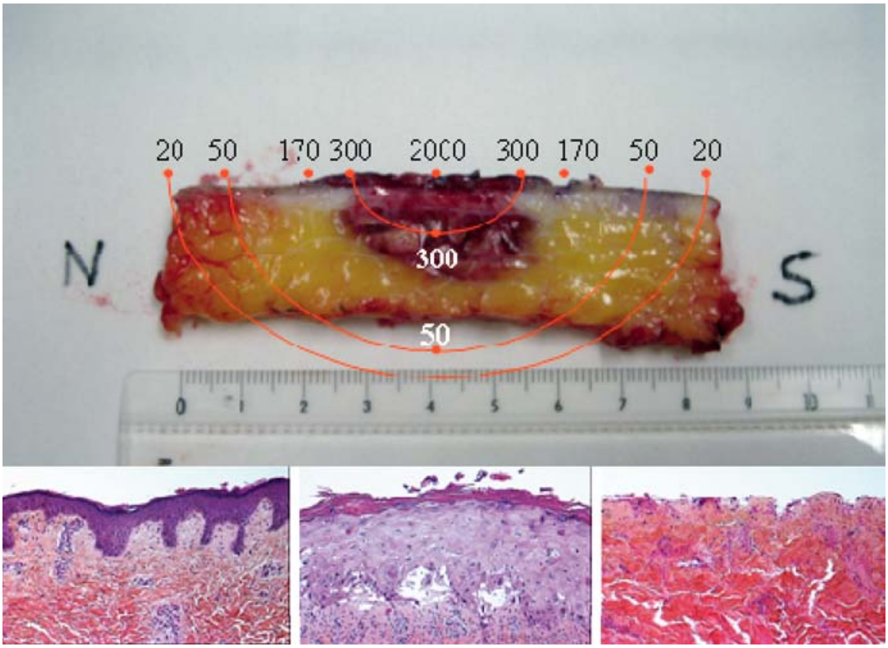

FIG. 33. Histological characteristics of radio-induced tissue damage (tissue taken on day 21 after exposure during the first excision). A transverse section of the skin is shown (on the left: normal skin; in the middle: a skin section of the victim where normal skin merges with the necrotic spot; on the right: a skin section of the victim in the centre of the necrotic spot) (courtesy: IRSN, France).

epidermis, with germinal and keratinocyte interphase cell death associated with a loss of adhesiveness of the epidermis to the basal layer, was observed. A normal appearance histology of the skin was observed at the periphery of the lesion.

Histological examination of muscle resection (second resection on day 90 after exposure) revealed characteristic features of radiation burn recurrence (Fig. 34).

The muscular injury was heterogeneous. Some areas were characterized by fibro-atrophic lesions with compression of the number of muscular fasciculi, evolving sometimes into rhabdomyolysis. The presence of macrophages was a specific sign of intense phagocytic activity. Fibrosis was punctuated by some inflammed mononucleated cells. The vascular damage was remarkable in its polymorphism, its focal characteristics and the absence of systematization.

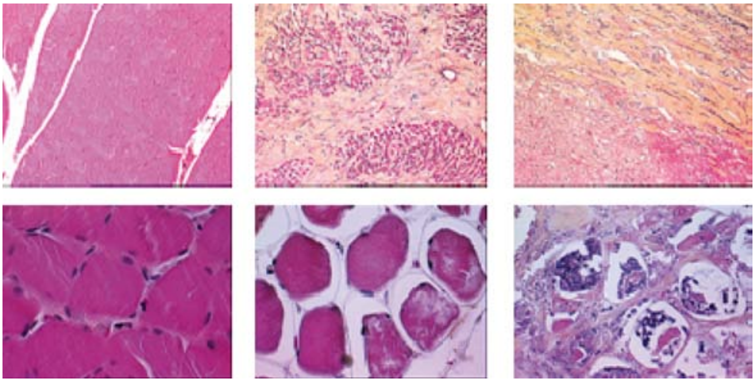

FIG. 34. Histological characteristics of radio-induced tissue damage (tissue removed on day 90 after exposure, during the second excision). A transverse section of the muscle is shown (on the left: normal muscle; in the middle: a muscle section of the victim where normal muscle merges with the fibrotic spot; on the right: a muscle section of the victim in the centre of the fibrotic spot) (courtesy: IRSN, France).

Some fibrinoid necrosis of the vascular wall was associated with perivascular inflammatory cell infiltration.

8.1.6. Autologous MSC injection

The second therapeutic step consisted of the local administrations of 168×10^6 MSCs on day 90 after exposure and 226×10^6 on day 98 after exposure. Mesenchymal stem cells were injected into a circle around the lesion at the cutaneous and muscular levels and into the wound bed of the lesion under the skin graft. The lesion was further dressed with an artificial derma (Integra®). Figure 35 shows the schematic temporal pattern of successive surgical and cellular therapies.

8.1.7. Clinical evolution

Following completion of the innovative strategy (combining surgical excision and two administrations of MSCs), progressive healing of the buttock lesion was observed.

No adverse reactions to the autologous MSC administration were observed. The day following the first MSC injections, pain disappeared and the active clinical evolution of the radiation burn was halted. The healing of the lesion was ascertained by the quality of the engraftment. Unlike the classical

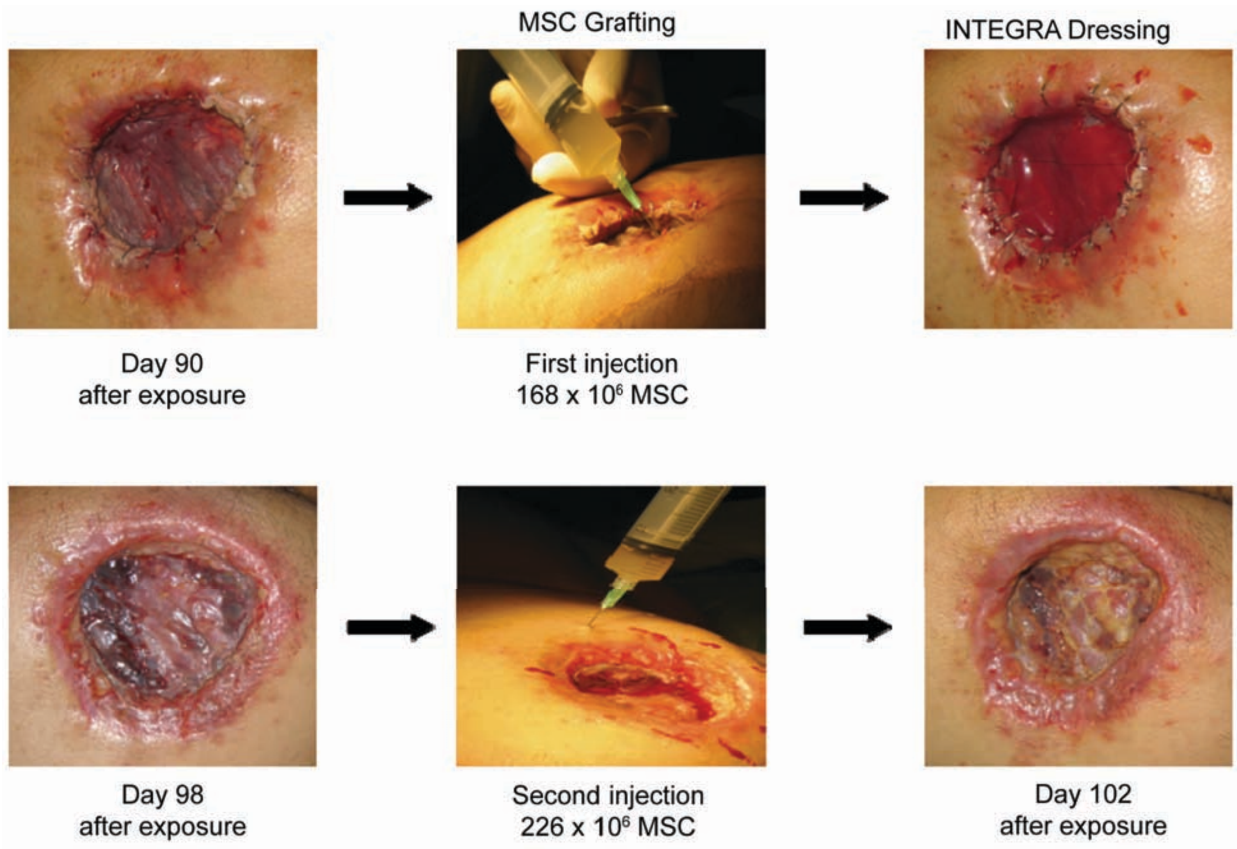

FIG. 35. Autologous MSC injections after dosimetric reconstruction guided surgery (courtesy: Hôpital d'instruction des armées Percy, CTSA, IRSN, France).

evolution of a very severe radiation skin lesion, the size of the wound progressively decreased following a centripetal process (Fig. 36).

Almost complete healing was achieved within three months from the completion of the innovative strategy.

8.1.8. Medical management of the left hand lesions

The first skin lesions appeared on the fingers of the left hand rapidly after the accident (Fig. 37).

On the basis of the unfavourable progression of the hand lesion (as shown in Fig. 37), it was decided to use a combined treatment based on a skin graft and autologous MSC injections (76×10^6 cells injected all around the lesion). The three more severely damaged fingers (thumb, index and middle fingers) of the left hand were treated at that time. The pain in worker A's hand disappeared rapidly after the MSC injection. Complete healing of the radiation burn with excellent functional recovery was achieved within three months.

8.2. MEDICAL MANAGEMENT OF THE ORAL MUCOSITIS

8.2.1. Dose estimation

In order to obtain dosimetric data to support treatment of oral mucositis (Fig. 38), dose reconstruction using electron spin resonance (ESR) of the patient's teeth was performed. Five teeth were removed. As these five teeth were severely damaged, they were extracted by the Chilean medical team for two reasons:

(1) To prevent any infection;
(2) To measure the dose.

They were stored at –80°C, in order to limit the loss of the electron paramagnetic signal (EPR) signal over time.

The five collected teeth were severely damaged and only two teeth (positions 2-4 and 4-5) still had any enamel. The masses of enamel recovered were very low (7 and 9 mg, respectively); the sample masses normally required for this analysis are between 50 and 120 mg. Nevertheless, the EPR signal was measured correctly, considering the relatively high doses received by these samples (Fig. 39).

Doses on the dental enamel were estimated using an additional method, so as to eliminate the influence of variations in the sensitivity of dental enamel

FIG. 36. Clinical evolution of the buttock necrosis after MSC therapy (courtesy: Hôspital d'instruction des armees Percy, CTSA, IRSN, France).

FIG. 37. Clinical evolution of the left hand of worker A (17 January 2006).

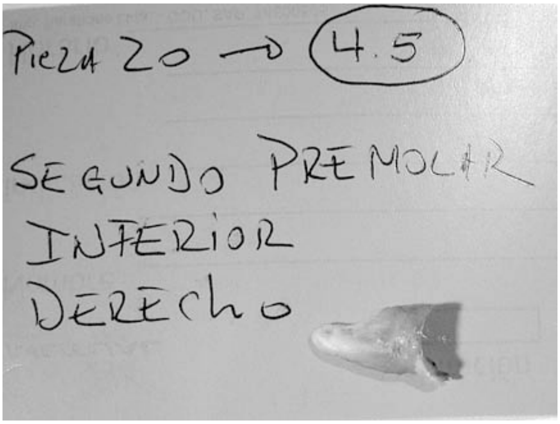

FIG. 38. Tooth 4-5 before removal of the tooth enamel.

in different samples, and the effects of dental caries. This method consists of post-irradiating the sample at known doses and of measuring the signal after each irradiation [9]. The samples were post-irradiated with electronic equilibrium conditions using the DRPH/SDE/LDRI ICO-4000 irradiator (a ^{60}Co source emitting gamma photons of average energy, E_{av} = 1.25 MeV).

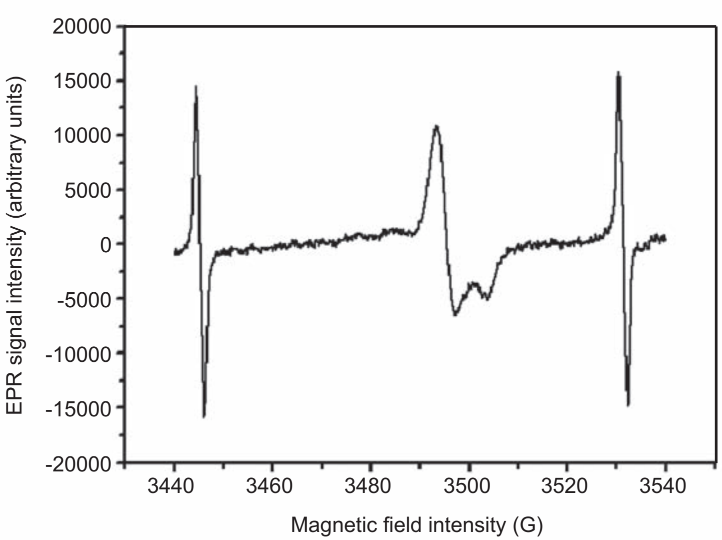

FIG. 39. The EPR spectrum of the dental enamel taken from tooth 2-4 (courtesy: IRSN, France).

A calibration curve specific to the measured sample was thus built up in order to determine the initial dose, by calculating its intersection with the dose axis (Fig. 40).

The doses measured on samples of dental enamel from teeth 2-4 and 4-5 were estimated as 8.5 ± 0.6 and 5.6 ± 0.3 Gy, respectively, in terms of kerma in the tissue.

8.2.2. Treatment

Taking into account the dose received, the oral mucositis experienced by the patient was probably not directly due to radiation exposure. The most probable reason for the oral mucositis was the additional influence of radiation on already infected teeth. The oral mucosa became more sensitive to infection (which already existed in the oral cavity due to diseased teeth) under the influence of radiation.

The patient was successfully treated by intravenous application of 4 mg/d of Kepivance™ (Amgen, Thousand Oaks, California) for three days.

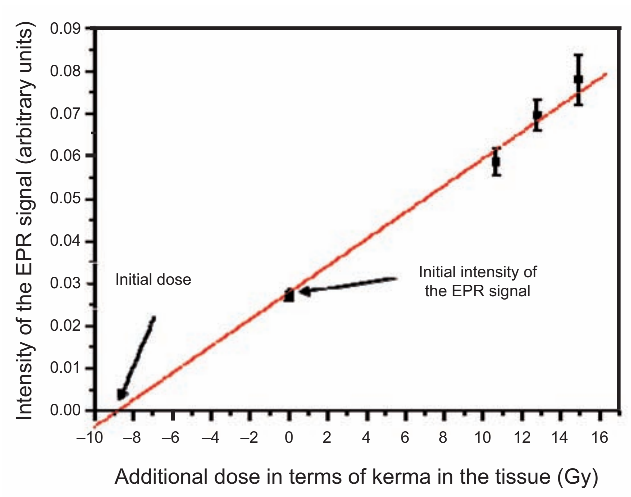

FIG. 40. Determination of the dose received during the accident on the sample of dental enamel of tooth 2-4 using the additional method (courtesy: IRSN, France).

9. FOLLOW-UP OF WORKER A IN CHILE (MAY 2006–OCTOBER 2007)

On 4 May 2006 worker A returned to Chile. The chronology of the follow-up actions is presented in Table 26.

TABLE 26. CHRONOLOGY OF THE FOLLOW-UP ACTIONS FOR WORKER A IN CHILE

Date	Symptoms and treatment
2006	
May 4 (return to Chile)	98% of the buttock lesion is covered, and the remaining ulcer spot still present is without evidence of infection Dressing and bacteriological culture surveys continue
May	No important changes in status of local lesions. Azoospermia diagnosed Positive culture of buttock lesion to *Staphylococcus aureus* is treated with local chlorhexidine
July	Buttock lesion is almost covered
August 30	Buttock lesion is closed
November	No changes in spermiogram; testes diminished in size (demonstrated by a sonogram); ulcerated lesion on the right side of the oral mucosa (in the area of the initial lesion) that was treated with dermal growth factor has a favourable evolution
2007	
January	A skin lesion on the left thumb appears; cultures are negative; a sonogram shows oedema The skin lesion is treated with non-steroidal anti-inflammatory drugs and antibiotics for seven days; the lesion is healed
May	Linear scars on the right thumb and left annular finger appear; other controls remain stable Treatment with Lipikar® and Cicaplast®; good response; stable conditions
June, July, August and September	Lesions appear on the ring and little (fourth and fifth) fingers of the left hand (fingers that were not treated during the first hospitalization in Paris) and osteoradionecrosis of the extremity of the last phalanx of the thumb are revealed Treated with the same medication as in May. Re-epithelization of the lesions appears

The decision was made to hospitalize the patient in the Burn Treatment Centre of the Hôpital d'instruction des armées Percy near Paris for further specialized treatment. The patient was hospitalized at the end of October 2007.

10. MEDICAL MANAGEMENT OF WORKER A IN FRANCE (OCTOBER 2007–JANUARY 2008)

Figures 41 and 42 present the status of worker A's left and right hands when he arrived in France for the second time (October 2007).

FIG. 41. Status of the left hand of worker A (October 2007).

FIG. 42. Status of the right hand of worker A (October 2007).

Osteonecrosis was observed on the extremity of the last phalanx of worker A's left hand thumb. A dose assessment using ESR on the extremity of the last phalanx of his left hand thumb was performed. The ESR results showed that the dose received by the patient's left hand was 28.3 ± 2.9 Gy (dose to the bone). A dose of 30.7 Gy was estimated at the skin surface (taking into account a depth of 3 mm).

A small and superficial necrotic spot was observed on the index finger of worker A's right hand.

For the ring and little (fourth and fifth) fingers of the left hand, a combined treatment based on a skin graft and autologous MSC injections was given. The necrotic part of the extremity of the last phalanx of the thumb was extracted. The results of the treatment were satisfactory. Worker A was released from the hospital in France at the end of January 2008 and returned to Chile.

11. FOLLOW-UP OF WORKER A IN CHILE FROM FEBRUARY 2008

No classical recurrence of radiation burns was observed on any of the five treated fingers during the follow-up of the patient from February 2008 until July 2008. The patient presented some periods of superficial erosions that disappeared after local treatment, but in general the skin was in good condition. The status of the healed buttock injury is presented in Fig. 43 and that of the index finger of the left hand in Fig. 44.

The general programme of follow-up for worker A is the same as those for workers B and C and radiography assistant E; mainly a complete check-up every six months, including blood tests for the first two years, and a yearly check-up including blood tests for the following five years. In addition, worker A received a check once a month for the status of his treated local radiation injuries (his buttock and the fingers of his left hand).

12. FINDINGS AND CONCLUSIONS

The findings and conclusions are based on the report of the IAEA Assistance Mission and on the results of the accident investigation performed by the CCHEN, the Ministry of Health and Mutual de Seguridad C.Ch.C.

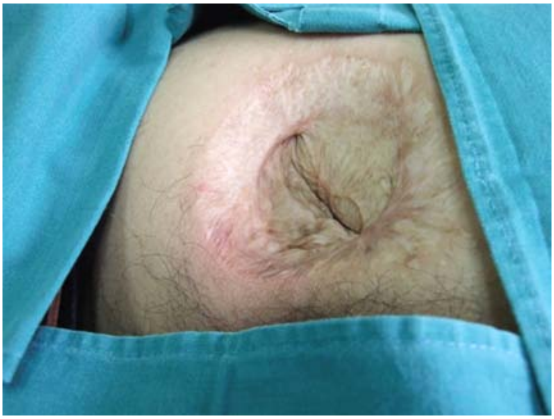

FIG. 43. Status of the healed buttock injury of worker A (1 July 2008, day 929 after exposure).

FIG. 44. Status of the index finger of the left hand of worker A (1 July 2008, day 929 after exposure).

(a) The accident sequence can be broadly divided into three phases: (1) the initial phase, (2) the main exposure phase and (3) the recovery phase:

(1) The initial phase started during the work of the three gamma radiography workers, when the pigtail (the source) detached from

the remote control cable and remained in the guide tube[36] (instead of being retracted to its safe position), and this went unnoticed. The factors contributing to this malfunction were:

(i) The procedures were not strictly followed and their implementation was not supervised.

- The radiography assistant[37] who prepared the gamma radiography equipment for operation was neither trained nor qualified (when attaching the pigtail to the remote control cable, he most probably did not secure the locking key properly).
- This radiography assistant had no alarm dosimeter or survey meter to alert him that the source had come out of the shielding (the pigtail detached from the remote control cable most probably after the first exposure, and remained in the guide tube[38]).
- At the time of the radiography (during the night), the alarm dosimeter of the senior radiography worker[39], the only alarm dosimeter at the scene, was turned off (while dismantling the equipment after the fourth exposure, no one noticed that the pigtail fell out of the guide tube on to the platform).

(ii) The test processing of the exposed films gave the false impression that everything was normal[40].

(iii) The radiography workers were working under time pressure (night shifts).

(2) The main exposure phase began when the scaffolding workers found and handled the source. The factors contributing to the accident were:

(i) The scaffolding workers had no knowledge of the gamma radiography technique.

(ii) The pigtail appeared to them as an interesting object in itself.

(iii) The pigtail bore no warning signs of danger.

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[36] The lesion on the right foot of radiography assistant E strongly supports this conclusion.

[37] Radiography assistant E.

[38] The lesion on the right foot of radiography assistant E strongly supports this conclusion.

[39] Radiographer D.

[40] Being in the guide tube, the source was pushed into its exposure position by the remote control cable, giving correct exposure of films.

(3) The recovery phase started when the pigtail was positively identified. The factors contributing to recovery were:
   (i) The alarm dosimeter in the office that was activated and a correct response to the alarm;
   (ii) The positive identification of the pigtail by a radiographer[41];

(b) Once the radioactive source was under control, the remaining emergency response was related to the management of the exposed persons. The medical management was adequate, with the support of national, regional and local organizations (governmental and private), and with international assistance combining professional experience in, and knowledge of, radiation protection (CCHEN and SEREMI).

(c) The information provided to the public was reasonably well managed, and the crisis generated in the post-emergency period was controlled for the most part.

(d) After the accident, the CCHEN undertook additional regulatory actions and suspended the licences of the company and individuals involved. Furthermore, the CCHEN also introduced additional requirements regarding industrial radiography practices, and conducted training courses for radiography operators, security forces and medical personnel, in order to prevent similar events from occurring in the future.

(e) Apart from the inadequate radiography operation performed by an unlicensed and unskilled radiography assistant, the investigation of the root causes, performed by the CCHEN, revealed incompatibility between the projection exposure container, the drive cable and the sheath (case). This allowed the connection and radiography operation to proceed in spite of the pigtail being incorrectly connected to the driving cable.

In summary, the accident occurred due to non-compliance with regulatory requirements and safety rules. If any of these had been at least considered, for example, use of an alarm dosimeter and a dose rate meter to verify the position of the source after the end of the radiography operation, the most severe consequences of the accident would have been avoided.

[41] Radiographer H.

13. LESSONS TO BE LEARNED

The lessons to be learned (in italics) are presented together with the specific accident findings and conclusions. A number of lessons are not unique to this accident but are worth reiterating in this report (the IAEA has collected lessons learned from other accidents in industrial radiography in Ref. [10]).

13.1. OPERATING ORGANIZATION

The lessons to be learned by the operating organization are as follows:

(a) Although the radiography company had procedures in place and had identified the responsibilities of individuals, they were not strictly followed and their implementation was not supervised. A safety culture was practically absent.
The prime responsibility for the radiation safety lies with the licensee. A safety culture needs to be introduced, fostered and maintained by the management.

(b) The failure to monitor dose rates during the whole radiography operations decisively contributed to the accident consequences.
Safe operation of industrial radiography depends crucially on proper implementation of radiation protection and safety, for example, regular use of alarm dosimeters and dose rate meters.

(c) The radiography workers involved complained that they were overloaded and working under time pressure. The operator assistant who assembled the radiography equipment was not trained, not qualified (unlicensed) and unskilled.
On-site safety in industrial radiography depends vitally on the radiographers' knowledge and skills, and their correct implementation of procedures. Overload and time pressure may hinder safety.

(d) There was no evidence that the gamma radiography company had in place any preventive maintenance programme for the radiography equipment.
Preventive maintenance programmes may reveal technical incompatibilities or problems that can be corrected in time to eliminate possible causes of mishaps.

13.2. NATIONAL AUTHORITIES

The lessons to be learned by national authorities are as follows:

(a) The regulatory authority (the CCHEN) granted the gamma radiography company a licence and performed annual inspections.
Formal licences and inspections by themselves cannot prevent accidents from occurring. The use of specific practical regulations and comprehensive national guidance can provide additional support in the assessment of information submitted with licence applications and in the performance of regulatory inspections. The frequency of inspections should depend on a threat assessment[42] *of the practice. An additional way to prevent or to minimize the occurrence of these types of accidents would be to widely distribute posters with photographs of pigtails and instructions on what actions to take should such an object be found at sites where gamma radiography is to be carried out.*

(b) After the accident, and on the basis of the accident evaluation, the regulatory body reviewed the technical and administrative requirements for the operators, equipment and training, and introduced additional requirements to fill the gaps existing and to improve the system (a new policy, more resources, enhanced procedures and stricter inspections).
A process of continuous review and improvement of the regulatory system by amending the requirements and regulations and by assigning appropriate resources should be instituted.

(c) Due to their having and maintaining basic dosimetry knowledge and capabilities, the Chilean authorities were able to assess the risks and make early knowledge based decisions.
For any radiation emergency, at least basic capabilities for initial dose assessment should exist in a country.

13.3. INTERNATIONAL COOPERATION

The lessons to be learned for international cooperation are as follows:

(a) The Chilean authorities made a timely request for international assistance. A prompt response by the IAEA and the international community reduced the possible consequences.

[42] A threat assessment as defined in Ref. [11].

Coordinated actions among national authorities and international assistance in the early accident phase may significantly reduce the consequences of an accident or even prevent them.

(b) As in the case of this accident, the IAEA can provide assistance, upon request, to Member States in relation to radiation emergencies, within the framework of the Convention on Assistance in the Case of a Nuclear Accident or Radiological Emergency.
The governments of all countries in which radiation sources are used are invited to subscribe to the Convention on Early Notification of a Nuclear Accident and the Convention on Assistance in the Case of a Nuclear Accident or Radiological Emergency.

(c) Preparation of this report has assisted in the recording of a comprehensive account of the radiological and medical management in question, in particular by national authorities.
National authorities are encouraged to share information about radiation emergencies with the IAEA and with other States, in order to help prevent or mitigate the consequences of such accidents in the future.

(d) The IAEA required expert assistance of the highest degree from the French specialists at both the IRSN and the Hôpital d'instruction des armées Percy for the medical management of the most severely irradiated victim.
The IRSN and the Hôpital d'instruction des armées Percy have capabilities and expertise to provide highly specialized treatment of injured persons upon request under the Convention on Assistance in the Case of a Nuclear Accident or Radiological Emergency.

13.4. MEDICAL COMMUNITY

The lessons to be learned by the medical community are as follows:

(a) The medical management of the patients was efficient, taking into account both physical and psychological aspects. The decision to transfer the most severely injured individual to a highly specialized medical treatment centre in France (the Hôpital d'instruction des armées Percy, assisted by the IRSN) significantly contributed to his recovery. All exposed individuals are under medical surveillance with favourable development of their injuries.
Combining the professional experience, knowledge in radiation protection and experience gained in other types of emergencies, and effectively

utilizing international assistance, is vital for success in any emergency response.

(b) The medical management of exposed victims both in Chile and in France included extensive psychological support and counselling. Those involved in the accident were also provided with detailed information and psychological counselling as required.

Social and psychological counselling of the patients contributed to successful recovery by reducing physiological suffering.

(c) One of the unsolved issues in the surgical treatment of radiation burns is the size of the surgical excision needed, based on rapid recognition of the boundaries between healthy and injured tissues. The actual limits of the lesion are unknown in the early stages, and a tissue that may appear at first to be healthy may become necrotic more or less rapidly.

Dosimetry guided surgery is required for effective treatment. Dose reconstruction carried out from a personalized voxelized phantom that has been generated from tomodensitometric images of the victim provides additional specific information on the dose received by the irradiated tissues. Early recognition of the event, with a clear description of the circumstances, contributes to accurate dose reconstruction.

(d) An innovative therapeutic strategy combining classical surgery and local MSC therapy was introduced with success. Mesenchymal stem cells are defined as pluripotent cells able to give rise to tissue regeneration, and can be easily recovered from bone marrow and enriched. Following this strategy, the healing of the lesion proceeded smoothly and without side effects. Complete healing without recurrence was observed for more than two years after the procedure (the period of observation described in this report).

A combined strategy involving classical surgery and MSC therapy is recommended for the medical management of severe radiation burns involving cutaneous and subcutaneous structures. This strategy has to be managed by highly specialized multidisciplinary teams.

Appendix

CHILEAN REGULATIONS, AND SAFETY AND RADIOLOGICAL NORMS

A.1. INTERNATIONAL REGULATIONS (STATUS AND DATE IN PARENTHESES)

Convention on Early Notification of a Nuclear Accident (signed 26 September 1986)

Convention on Assistance in the Case of a Nuclear Accident or Radiological Emergency (signed 26 September 1986)

A.2. IAEA SAFETY STANDARDS

FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS, INTERNATIONAL ATOMIC ENERGY AGENCY, INTERNATIONAL LABOUR ORGANIZATION, OECD NUCLEAR ENERGY AGENCY, PAN AMERICAN HEALTH ORGANIZATION, UNITED NATIONS OFFICE FOR THE COORDINATION OF HUMANITARIAN AFFAIRS, WORLD HEALTH ORGANIZATION, Preparedness and Response for a Nuclear or Radiological Emergency, IAEA Safety Standards Series No. GS-R-2, IAEA, Vienna (2002).

FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS, INTERNATIONAL ATOMIC ENERGY AGENCY, INTERNATIONAL LABOUR OFFICE, PAN AMERICAN HEALTH ORGANIZATION, UNITED NATIONS OFFICE FOR THE COORDINATION OF HUMANITARIAN AFFAIRS, WORLD HEALTH ORGANIZATION, Arrangements for Preparedness for a Nuclear or Radiological Emergency, IAEA Safety Standards Series No. GS-G-2.1, IAEA, Vienna (2007).

FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS, INTERNATIONAL ATOMIC ENERGY AGENCY, INTERNATIONAL LABOUR ORGANIZATION, OECD NUCLEAR ENERGY AGENCY, PAN AMERICAN HEALTH ORGANIZATION, WORLD HEALTH ORGANIZATION, International Basic Safety Standards

for Protection Against Ionizing Radiation and for the Safety of Radiation Sources, Safety Series No. 115, IAEA, Vienna (1996).

INTERNATIONAL ATOMIC ENERGY AGENCY, Occupational Radiation Protection, IAEA Safety Standards Series No. RS-G-1.1, IAEA, Vienna (1999).

INTERNATIONAL ATOMIC ENERGY AGENCY, Assessment of Occupational Exposure Due to Intakes of Radionuclides, IAEA Safety Standards Series No. RS-G-1.2, IAEA, Vienna (1999).

INTERNATIONAL ATOMIC ENERGY AGENCY, Assessment of Occupational Exposure Due to External Sources of Radiation, IAEA Safety Standards Series No. RS-G-1.3, IAEA, Vienna (1999).

INTERNATIONAL ATOMIC ENERGY AGENCY, Building Competence in Radiation Protection and the Safe Use of Radiation Sources, IAEA Safety Standards Series No. RS-G-1.4, IAEA, Vienna (2001).

INTERNATIONAL ATOMIC ENERGY AGENCY, Occupational Radiation Protection in the Mining and Processing of Raw Materials, IAEA Safety Standards Series No. RS-G-1.6, IAEA, Vienna (2004).

INTERNATIONAL ATOMIC ENERGY AGENCY, Application of the Concepts of Exclusion, Exemption and Clearance, IAEA Safety Standards Series No. RS-G-1.7, IAEA, Vienna (2004).

INTERNATIONAL ATOMIC ENERGY AGENCY, Environmental and Source Monitoring for Purposes of Radiation Protection, IAEA Safety Standards Series No. RS-G-1.8, IAEA, Vienna (2005).

INTERNATIONAL ATOMIC ENERGY AGENCY, Categorization of Radioactive Sources, IAEA Safety Standards Series No. RS-G-1.9, IAEA, Vienna (2005).

INTERNATIONAL ATOMIC ENERGY AGENCY, Safety of Radiation Generators and Sealed Radioactive Sources, IAEA Safety Standards Series No. RS-G-1.10, IAEA, Vienna (2006).

INTERNATIONAL ATOMIC ENERGY AGENCY, Radiation Safety in Industrial Radiography, IAEA Safety Standards Series, IAEA, Vienna (in preparation).

A.3. NATIONAL REGULATIONS

Law No. 18.302	Nuclear Safety Law Promulgated in 1984, Article 67 of which established that the radioactive facilities will be under the control of the Chilean Health Services, with the exception of those that are located within a nuclear facility, in which case they will be controlled by the CCHEN; all of the preceding articles are related to nuclear facilities.
Law No. 18.730	Promulgated in 1988, amends Article 67 of Law No. 18.302, transferring the competence on radioactive facilities of the first category to the CCHEN.
Law No. 19.825	Promulgated in 2002, amends several articles of Law No. 18.302, becoming applicable to the dispositions of nuclear facilities to radioactive facilities of the first category, including the authorization of the CCHEN to sanction infractions (Judgment of the General Controllership of the Republic No. 07324, dated 11 February 2005).
Law No. 19.937	Promulgated in 2004, amends Executive Order No. 2.763 of 1979, restructuring the Ministry of Health (MINSAL) and granting competence for radioactive facilities of the second and third categories to the Regional Ministerial Secretariat of the Ministry of Health (SEREMI) in their corresponding jurisdictions.
Supreme Decree 133/84	Regulations on the Authorizations for Radioactive Facilities or Ionizing Radiation Generator Equipment, Staff that Operated Them or that Operates such Equipment and Related Activities
Supreme Decree 3/85	Regulations for the Radiation Protection of Radioactive Facilities This Supreme Decree establishes the minimum radiation protection conditions that must be fulfilled to exploit a radioactive facility and ensure the safe manipulation of radioactive material.

A.4. RADIOLOGICAL NORMS

NRN-G-02	Contents of the Operational Radiological Protection Manual (ORPM) for First Category Radioactive Facilities

A.5. CCHEN SAFETY NORMS

NCS-GG-02	Licensing Procedure of Nuclear or Radioactive Facilities of the Chilean Nuclear Energy Commission

REFERENCES

[1] INTERNATIONAL ATOMIC ENERGY AGENCY, Convention on Early Notification of a Nuclear Accident and Convention on Assistance in the Case of a Nuclear Accident or Radiological Emergency, Legal Series No. 14, IAEA, Vienna (1987).

[2] COMISIÓN CHILENA DE ENERGÍA NUCLEAR, CCHEN Safety Norms, Licensing Procedure of Nuclear or Radioactive Facilities of the Chilean Nuclear Energy Commission, NCS-GG-02, CCHEN, Santiago (2002).

[3] INTERNATIONAL ATOMIC ENERGY AGENCY, Cytogenetic Analysis for Radiation Dose Assessment, Technical Reports Series No. 405, IAEA, Vienna (2001).

[4] SASAKI, M.S., MIYATA, H., Biological dosimetry in atom bomb survivors, Nature **220** (1968) 1189–1193.

[5] DOLPHIN, G.W., "Biological dosimetry with particular reference to chromosome aberration analysis: A review of methods", Handling of Radiation Accidents (Proc. Int. Symp. Vienna, 1969), IAEA, Vienna (1969) 215–224.

[6] LITTLEFIELD, L.G., et al., "Cytogenetic dose estimates from in vivo samples from persons involved in real or suspected radiation exposures", The Medical Basis for Radiation Accident Preparedness, North-Holland, Amsterdam (1980) 375–390.

[7] DOUCER, C., et al., Platelet lysates promote mesenchymal stem cell expansion: A safety substitute for animal serum in cell-based therapy applications, J. Cell. Physiol. **205** 2 (2005) 228–236.

[8] LANGE, C., et al., Accelerated and safe expansion of human mesenchymal stromal cells in animal serum-free medium for transplantation and regenerative medicine, J. Cell. Physiol. **213** 1 (2007) 18–26.

[9] NEUILLY, M., CETAMA, Modélisation et estimation des erreurs de mesure, Lavoisier Technique et Documentation, Paris (1998) 406–425.

[10] INTERNATIONAL ATOMIC ENERGY AGENCY, Lessons Learned from Accidents in Industrial Radiography, Safety Reports Series No. 7, IAEA, Vienna (1998).

[11] FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS, INTERNATIONAL ATOMIC ENERGY AGENCY, INTERNATIONAL LABOUR ORGANIZATION, OECD NUCLEAR ENERGY AGENCY, PAN AMERICAN HEALTH ORGANIZATION, UNITED NATIONS OFFICE FOR THE CO-ORDINATION OF HUMANITARIAN AFFAIRS, WORLD HEALTH ORGANIZATION, Preparedness and Response for a Nuclear or Radiological Emergency, IAEA Safety Standards Series No. GS-R-2, IAEA, Vienna (2002).

ABBREVIATIONS

AFSSaPS	Agence française de sécurité sanitaire des produits de santé
BMMNC	Bone marrow mononuclear cell
CBC	Complete blood count
C.Ch.C.	Mutual de Seguridad insurance company of the Chilean Construction Chamber
CCHEN	Chilean Commission of Nuclear Energy
CT	Computed tomography
CTSA	Centre de transfusion sanguine des armées
DSNR	Nuclear and Radiological Safety Department of the CCHEN
ESR	Electron spin resonance
GCSF	Granulocyte colony stimulating factor
IEC	Incident and Emergency Centre of the IAEA
IRSN	Institut de radioprotection et de sûreté nucléaire
MINSAL	Chilean Ministry of Health
MSC	Mesenchymal stem cell
ONEMI	Chilean National Office for Emergencies, Ministry of Internal Affairs
PL	Platelet lysate
SEREMI	Regional Ministerial Secretariat of the Ministry of Health
TLD	Thermoluminescent dosimeter

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This report describes the radiological accident that occurred in Nueva Aldea, Chile, in December 2005, and the response to it by the IAEA under the Convention on Assistance in the Case of a Nuclear Accident or Radiological Emergency. The subsequent medical treatment of the workers who were injured is described in detail. The report will be of interest to, among others, emergency response planners, medical specialists, physicists and persons responsible for radiation protection.

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