Physical dose reconstruction in case of radiological accidents: an asset for the victims' management.

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Abstract. In most cases of radiological accidents caused by an external source, the irradiation is heterogeneous, even for a whole body irradiation. Therefore, more than a whole body dose, estimating the dose distribution in the victim's organism is essential to assess biological damages. This dose distribution can be obtained by physical dosimetric reconstruction methods.

The laboratory has developed several techniques based on experimental and numerical dose reconstruction and retrospective dosimetry by ESR in order to assess as accurately as possible and as quickly as possible the dose received and especially its distribution throughout the organism so that the physicians may fine tune their diagnosis and prescribe the most suitable treatment.

These last years, these techniques were applied several times and each time the results obtained proved to be essential for the physicians in charge of the victims in order to define the therapeutic strategy. This article proposes a review of the physical dose reconstructions performed in the laboratory for recent radiological accidents focusing on the complementarity of the methods and the gain for the victims' management.

KEYWORDS: radiological accident, dose reconstruction, experiments, numerical simulations, ESR.

1. Introduction

In the last fifty years, an increase of devices using radioactive sources has been noticed, especially in medical and in industrial areas. It led to an increase of radiological accidents involving external sources. Since 1945, around 600 accidents have been enumerated. 68% of them concern localised irradiation whereas the others involve whole body irradiation.

In most cases of radiological accidents caused by an external source, the irradiation is heterogeneous, even for a whole body irradiation. Therefore, more than a whole body dose, estimating the dose distribution in the victim's organism is essential to assess biological damage. The dose can be evaluated by integrating complementary data coming from different sources as: clinical observations, biological dosimetry and physical dosimetry.

The IRSN External Dosimetry Department has developed several techniques based on experimental and numerical dose reconstruction and retrospective dosimetry by ESR in order to assess as accurately as possible and as quickly as possible the dose received and especially its distribution throughout the organism so that the physicians may fine tune their diagnosis and prescribe the most suitable treatment.

These last years, these techniques were applied several times and each time the results obtained proved to be essential for the physicians in charge of the victims in order to define the therapeutic strategy.

In this article, the different techniques developed in the laboratory are presented. Then, physical dose estimations performed for three recent radiological accidents are described.

2. The dosimetric tools

2.1 Experimental dose reconstruction

An experimental dose reconstruction consists in irradiating a tissue-equivalent anthropomorphic dummy equipped with dosemeters in conditions as close as possible to those of the accident. In the laboratory, the Rando-Alderson dummy is used. As illustrated in Fig. 1, the Rando-Alderson dummy is made up of sections with locations provided for inserting dosemeters, thus enabling the distribution of the dose in the organism to be mapped. Depending on the radiation source,

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different types of dosemeters can be used: lithium fluoride, alumina, alanine, silicon diode or activation foils. For irradiations localised at hand, mouldings of victim's hand can be also performed (Fig. 1).

Figure 1: Photograph of RANDO tissue-equivalent dummy (a) and of a hand moulding (b)

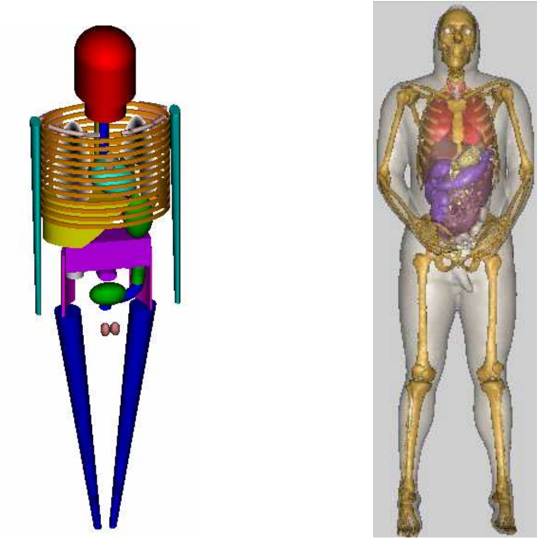

(a) (b)

2.2 Numerical dose reconstruction

The principle of dosimetric reconstruction of a radiological accident using numerical simulations is firstly, to model the person exposed to radiation using a numerical anthropomorphic phantom in the accident environment and secondly, to calculate the doses absorbed in the organism using a radiation-material interaction Monte Carlo computer code.

The victim can be modelled by a standard mathematical anthropomorphic phantom made up of simple geometric elements or by a so-called voxel phantom. In the laboratory, both are used. For global irradiation, the mathematical anthropomorphic phantom developed by Cristy and Eckerman [1], to which some modifications have been made [2], is generally used (Fig.2) whereas for localised irradiations voxel phantoms are used. This type of phantom is generated from computed tomography or magnetic resonance imaging (MRI) images of the victim. These phantoms are made up of a huge number of small volumes called voxels and provide a more realistic description of the human anatomy than mathematical phantoms, as they are based on real anatomical data (Fig. 2). The Monte Carlo code used in the laboratory for numerical dose reconstructions is MCNPX. This code is widely used in dosimetry as it can model the transport and interactions of charged or neutral particles in the material.

Figure 2: Numerical phantoms
(a) 3D view (visualised with SABRINA software) of the mathematical phantom used in the laboratory
(b) 3D view of the VIP-Man voxel phantom (RPI, USA)


(a) (b)

2.3 ESR measurements

Electronic Spin Resonance (ESR) is a spectroscopy technique used to observe the absorption of a microwave by unpaired electrons placed in a magnetic field. The interaction between the ionising radiation and the material generates phenomena of energisation and ionisation of atoms and molecules in its make-up, thus forming free radicals. The quantity of radio-induced free radicals is proportional to the dose delivered in the material and the absorption intensity of the microwave injected in the measured sample. ESR is capable of measuring a wide range of materials and numerous materials from the victim (tooth enamel, bone tissue, hair, nails) or found in his environment can be used (sugars, glasses from watch or display windows of mobile phone, plastic from glasses, button, mobile phone, etc.).

The lifetime of the radio-induced radicals varies according to the type of materials. The radio-induced radicals in the tooth enamel are the most stable, with lifetimes in the order of 10^9 years [3]. In bone tissue and dentin, a loss of signal can be noted several years after irradiation in living tissues. Most sugars show good signal stability over time [4]. The radio-induced signal from nails and hair, on the other hand, disappears completely in a few tens of hours depending on temperature and humidity conditions [5]. In the laboratory, the technique is operational in ex-vivo for bone tissue, tooth enamel and sugar with a good sensitivity.

3. Application to recent radiological accidents

3.1 Accident in Chile in December 2005

3.1.1 Description of accident

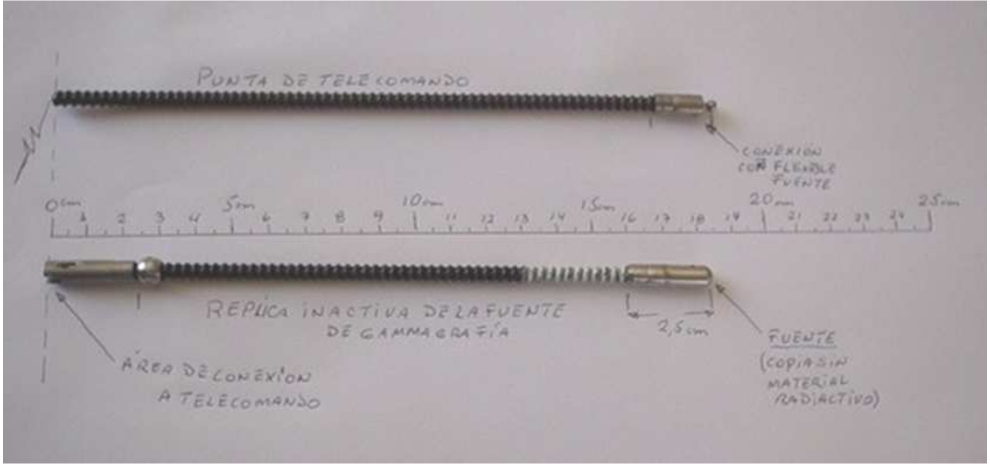
On 15 December 2005, in Chile, a worker in a cellulose plant picked up a ^{192}Ir source which had fallen inadvertently from a gammagraphy device. He handled it with his bare hands and also put it in the back left-hand pocket of his trousers before it was detected by someone with an electronic dosimeter, about forty minutes after the worker had found the source. An erythema very quickly developed on the victim's left buttock. Chile called on the IAEA for assistance which appointed a number of people on site to investigate. The victim was transferred to France on 29 December 2005 for treatment at the Percy Military Training Hospital in Clamart near Paris.

3.1.2 Material and methods

A numerical dosimetric reconstruction was performed in order to estimate the distribution dose on the left buttock. It was impossible to estimate the dose on the hands because the scenario was too inaccurate.

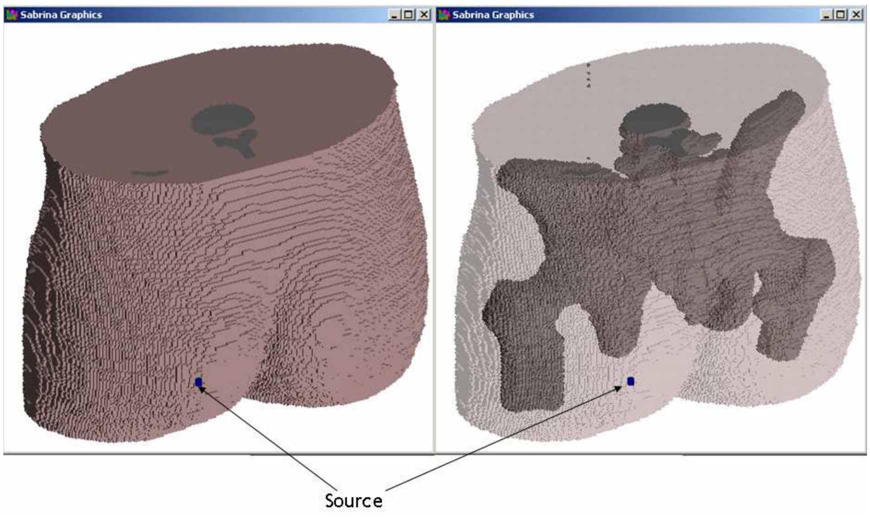
The source was a cylindrical ^{192}Ir source measuring 1 mm in radius and 2 mm in height enclosed in a steel cylinder measuring 2 mm in thickness and 6 mm in height. A photograph of the source is shown in Fig. 3. Source activity at the time of the accident was 3.3 TBq (90 Ci).

Figure 3: Photograph of the source



Once the victim had been hospitalised in France, we were able to obtain the CT and MRI images done at the Percy hospital. We selected 163 slices from mid-abdomen to mid-thigh. Then, using SESAME software [6], we generated a voxel phantom with external contours and bone structure, and defined and positioned the source. Lastly, we selected the area for which we wanted to calculate the isodoses, i.e. at the centre of the lesion. A 3D representation of the voxel phantom and the source is shown in Fig. 4. The deep and surface doses were calculated for the source at a distance of 2 mm from the skin surface and an exposure time of 10 minutes.

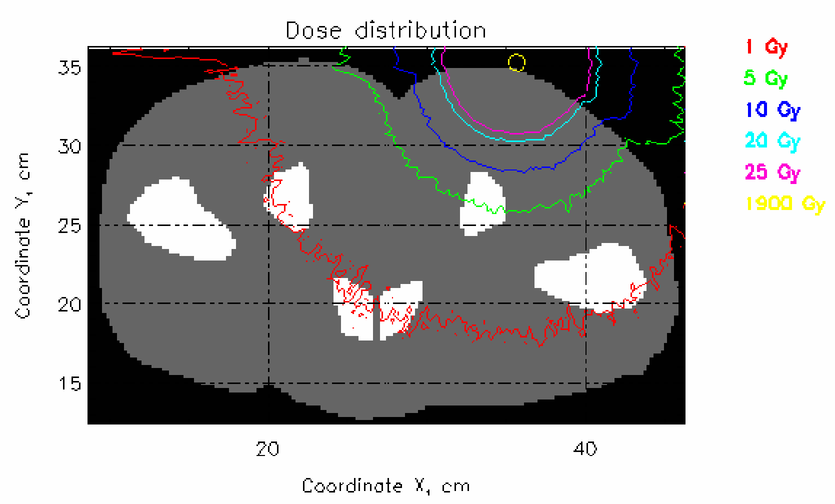
Figure 4: 3D View of the voxel phantom (external envelope and skeleton) and of the source using SABRINA software



3.1.3 Results

The results obtained for the dose distribution on the left buttock are given in Fig. 5. The dose absorbed at the skin surface is very high (1900 Gy) but drops rapidly at deep level due to the combined effect of distance and of tissue attenuation. At a depth of 5 cm, it is 20 Gy. The 25 Gy necrotic boundary isodose was situated at 4.5 cm in depth from the centre of the skin surface lesion.

Figure 5: Dose distribution obtained on the same level as the source plane using the voxel phantom



3.1.4 Conclusion

Based on the dosimetric mapping, and for the first time in a case of radiological burns, anticipatory surgery was performed. An excision measuring 5 cm in depth by 10 cm in diameter was performed on the buttock on 5 January 2006 by the plastic surgery team at the Percy Military Training Hospital in Clamart.

3.2 Accident in Belgium in March 2006

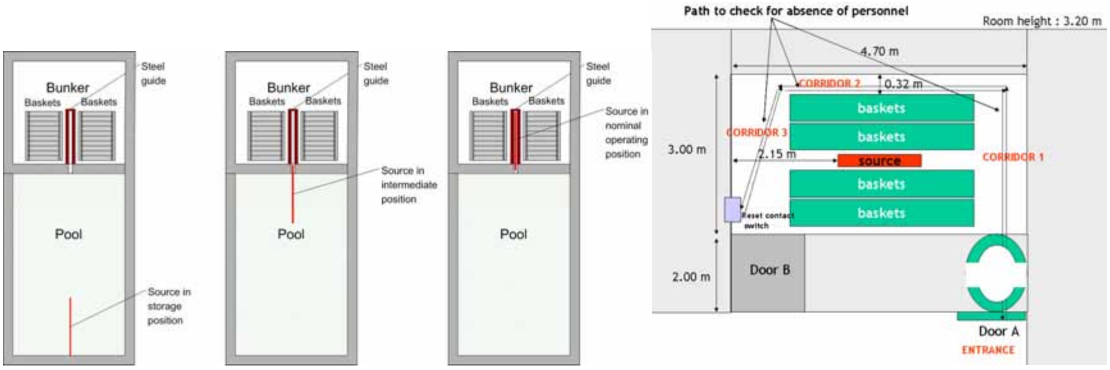
3.2.1 Description of accident

A severe irradiation accident involving a victim occurred on Saturday, 11 March 2006 in an industrial irradiation facility operated by Sterigenics at Fleurus in Belgium. This company uses irradiation to sterilise medical equipment and foodstuffs, with very high-level ionising radiation sources.

The accident occurred in the irradiation cell comprising a plane source made up of a set of rods 1.8 m high and 1 m wide in ^{60}Co with 30000 TBq activity. This cell includes a bunker, in which the material for irradiation is placed in baskets located either side of the source, and a 6 m-deep pool underneath the concrete slab acting as the bunker floor, in which the source is stored when not in use during irradiation phases. The source moves between the bunker and the pool through an opening in the concrete slab (Fig. 6a). A hydraulic jack raises the source vertically into the irradiation position; the source is lowered again by gravity and the jack combined. On Saturday, 11 March 2006, alarms went off in the radiological monitors at the entrance to the cell whilst this cell was no longer in irradiation phase and the access door was open. An operator was called and acknowledged the alarms. As they did not go off again, he then decided to close the cell access door. Under the safety procedure, the cell must be checked for the absence of personnel before the door is closed. The operator therefore went right to the back of the cell to validate the reset contact switch (Fig. 6b). It is during this operation lasting an estimated 20 seconds that the employee was irradiated. The irradiation of the operator was most probably due to the source not being in its storage position at the bottom of the pool, but in an intermediate position between the high position used for the irradiation phases and the storage position.

Figure 6: Dose distribution obtained on the same level as the source plane using the voxel phantom
(a) Schematic cross-sections of the pool and the bunker making up the cell and of the various positions of the plane source
(b) Diagram of the GAMMIR II cell and the path to follow to check for staff presence in the cell before closing the door.

(a) (b)



The radiological accident was suspected following an exploratory haemotological examination on 30 March 2006. The Occupational Health Doctor contacted IRSN on 31 March 2006. A team from the IRSN External Dosimetry Department travelled to the site on the same day to carry out an experimental dosimetric reconstruction. At the same time, the victim was transferred to the Haemotological Department of the Percy Military Training Hospital.

3.2.2 Material and methods

The strategy adopted to reconstruct the physical dosimetry in this accident was based on two complementary approaches ([7]):

- an experimental reconstruction on site in circumstances as close as possible to those of the accident, using an anthropomorphic dummy made of "tissue-equivalent" material fitted with dosimeters matching the type of radiation,
- a laboratory reconstruction using numerical simulations that with the use of a Monte Carlo computer code can estimate doses in a numerical anthropomorphic phantom placed in the accident environment.

Experimental dose reconstruction

It was not possible to reproduce on site the exact circumstances of the accident during this experimental reconstruction, as firstly, the position of the source at the time of the accident was unknown and secondly, it was technically impossible to place the source deliberately in an intermediate position. Therefore, it was impossible to estimate directly the dose received by the victim by experimental means. Then the experimental dosimetric reconstruction consisted in:

- mapping the facility in order to study the variation in radiation intensity using dosimeters placed along the path taken by the victim in order to provide input data for the numerical dosimetric reconstruction. It was carried out whilst the source was held constantly in the high position for several minutes. The facility was mapped using passive dosimeters arranged at 1.3 m from the floor on the cell walls. Seven measuring points representative of the entire path were chosen to study the variation in radiation intensity along the victim's path through the irradiation cell
- performing a first estimation of the heterogeneity of the distribution of the dose in the organism using an anthropomorphic dummy fitted with dosimeters. The measurements with the dummy were performed whilst the source was raised completely followed immediately by it being re-lowered. A dummy made of material equivalent to human tissue with respect to radiation and fitted with passive dosimeters was irradiated. The dummy was placed between the baskets and the wall, the most irradiating section of the path.

L-α-alanine pellets were used to map the facility dosimetrically as well as being fitted in the anthropormophous dummy. The dose is estimated from the analysis of the Electronic Spin Resonance (ESR) spectrum of the irradiated pellets.

Numerical dose reconstruction

Two main difficulties were encountered in this reconstruction:

- Firstly, the position of the source and therefore its effective activity during the accident were not well known. Initially, we carried out simulations with the source in its high position to constrain our model (source geometry) against the kerma air measured on site in this configuration. Secondly, numerical simulations were performed by considering the source placed in an intermediate position judged the most realistic.
- In addition, the victim moved around during his inspection and it is unrealistic to model each position of the victim in relation to the source over the entire path. Given the symmetry of the path taken by the victim in relation to the source, we modelled two of the victim's positions representative of the path, namely along the wall looking at the source and sideways to the wall perpendicular to the source. The mathematical anthropomorphic phantom developed by Cristy and Eckerman [1], to which some modifications have been made, was used. Given the lack of accurate information on the source position when the accident occurred, we produced reconstructions that took several source positions into account. We adopted a mid-height source position as the most likely and the only one that produced a dosimetric result in line with the first dose estimations obtained with biological dosimetry performed at IRSN [8].

3.2.3 Results

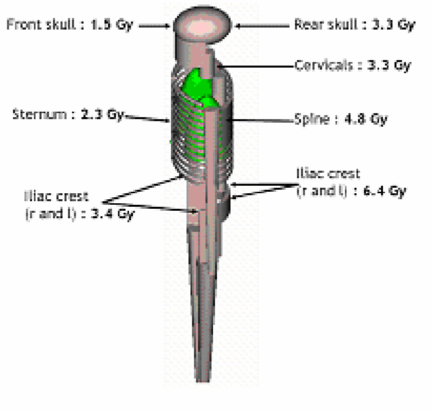
Experimental dose reconstruction

The measurements with the dummy indicated an anteroposterior gradient of around a factor of 3. No significant vertical gradient was observed at the scale of the trunk.

Numerical dose reconstruction

The absorbed doses calculated at various bone marrow sites are indicated in Fig. 7. The results reveal a relatively heterogeneity of the dose. As a matter of fact a gradient corresponding to a factor of 2 is observed as much in anteroposterior as between the pelvis and the skull, with the upper part of the body being the least exposed area. No significant side gradient was revealed.

Figure 7: Doses absorbed at various bone marrow sites



3.2.2 Conclusion

All the results from these experimental and numerical reconstructions show clearly that the accidental irradiation was heterogeneous. This information is crucial to adopting a treatment strategy. The fact that some areas of bone marrow are clearly under-exposed compared with others, given the dose levels, suggests spontaneous secondary resumption of bone marrow activity in these areas.

3.3 Accident in Dakar and Abidjan in summer 2006

3.3.1 Description of accident

A severe irradiation accident involving several victims took place between 3 June and 3 August 2006 in subsidiaries of the French group Bureau Veritas located in Senegal and in Ivory Coast.

On 3 June 2006, in Dakar, during a gammagraphy operation performed by Bureau Veritas employees on a site belonging to the Société Africaine de Raffinage whilst inserting the source in the storage container, the end of the remote control broke off for unknown reasons. Due to this technical failure, the ^{192}Ir radioactive source was lodged unexpectedly in the source ejection duct instead of being returned to its shielded storage container, without this malfunction being detected.

On 9 June, the assembly was taken to the Bureau Veritas premises in Dakar and the container supposedly containing the source was stored in a laboratory before being sent to the maintenance company in Belgium. The remote control and the ejection duct (holding the source) were stored temporarily under the stairs in the entrance hall where they remained until 31 July. Two individuals were principally exposed during this period (a daytime security guard (COL) and a night watchman (SE)): COL a few minutes every day when he put on and took off his shoes kept near the ejection duct and SE for about fifteen minutes every day when he was saying his prayers.

Following a request from the Bureau Veritas office in Abidjan to its counterpart in Dakar to send it a remote control and ejection duct system, two Dakar employees made up a parcel on 31 July. On the same day at around 10 a.m., the secretary placed the parcel comprising the ejection duct containing the source, and the remote control on the reception counter. COL immediately placed it on the shelf just above the partially circular counter to his left. Between 31 July from 10 a.m. to 6 p.m. and 31 August from 6 a.m. to 3 p.m., he was sitting behind the counter at the building entrance (with his left arm some 50 cm from the source) and lent on the parcel several times, for a few minutes every time, to fill in documents. SE upon his arrival at work on 31 July at 6 p.m. put the parcel at his feet and put it back on the shelf the following morning at 6 a.m.

A carrier fetched the parcel at around 3 p.m. on 1 August which was received in Abidjan at 10 a.m. on 3 August. Two persons were exposed in Abidjan before the source was detected and isolated on 4 August at 3 a.m.

The dosimetric techniques available in the laboratory were adapted individually to each of the four patients transferred at the Percy Military Training Hospital based on the knowledge of the scenario and the type of sample available and measurable using the ESR techniques ([9]). Only the dose estimation for patient COL, the most severe irradiated, is presented here. He was admitted to the Percy Military Training Hospital on 31 August. Clinical signs were a patent radiological burn on the left arm associated with an acute irradiation syndrome with major H3-classified medullar aplasia and partial alopecia of the left side.

3.3.2 Material and methods

The strategy adopted to reconstruct the dose received for patient COL using physical means was based on two complementary techniques: (1) measurements of doses received in teeth and bone samples from patient COL using the ESR spectrometry technique and (2) numerical simulation techniques using a Monte Carlo calculation code to estimate the dose distributions within a numeric anthropomorphic phantom modelling the victim placed in the accident environment.

ESR measurements

During this expertise, in the weeks following the arrival of the patient COL in France, biopsies of tooth enamel could be collected under dental care, thus providing an estimate of the doses received at the jaw. All these samples comprised molars with some cavities. The ESR measurement covered the healthy part of the dental enamel sample. The dental enamel measured was separated mechanically from the cavity part and the dentin with a dental drill. The samples were then reduced to 2 to 3 mm pieces using cutting pinchers before being soaked 5 minutes in a 20% acetic acid bath to eliminate spurious signals caused by the mechanical preparation. The samples were rinsed in distilled water and dried before being measured.

In addition, two bone samples were taken from the COL patient's arm by two surgical procedures at the beginning of 2007. Bone samples were washed in ultrasonic bath filled with distilled water. Samples were then prepared as tooth enamel samples.

To overcome variations in radiation dose sensitivity of bone tissue between samples, which limits the use of calibration curve, the doses were estimated using the dose additive method. This method involves post-irradiating the sample with known doses and measuring the sample after each irradiation. The samples were post-irradiated with the electronic equilibrium conditions from an IRSN ^{60}Co irradiator (gamma photon emitter, mean energy = 1.25 MeV) in terms of kerma (kinetic energy released per mass) in air. Measured doses were converted in the appropriate quantity (absorbed dose in bone) using conversion kerma coefficient from Hubble [10]. At least 24 hours elapsed between the irradiation and the measurement to limit the influence of short-lived EPR signals in estimation of signal intensity. A calibrating curve specific to the sample measured was thus constructed; it was used to determine the initial dose by calculating the intersection of the linear regression with the dose axis.

Numerical dose reconstruction

The mathematical anthropomorphic phantom representing a standard adult male developed by Cristy and Eckerman was used to estimate the dose distribution in the organism, the dose to the organs and the whole body mean dose. The source was identical to the one modelled for the accident in Chile. The source activity varied between 3.6 TBq (97 Ci) and 2.2 TBq (60 Ci) between 3 June and 3 August 2006. For the exposures considered, the source was found inside the ejection duct rolled as a torch. Failing information on the position of the source in this duct, the configuration adopted was to model the duct as a steel cylinder 2 mm thick and several centimetres long.

Two distinct exposures have been considered for the COL patient: (1) exposure from 9 June to 31 July when he put on and took off his shoes kept underneath the staircase close to the source and (2) exposure between 10 a.m. and 6 p.m. on 31 July and between 6 a.m. and 3 p.m. on 1 August when the package was on the reception desk shelf.

For the first exposure, it was considered that the victim was about 50 cm from the source, the most likely distance after the reconstruction and accounts from victims and that the exposure time was two minutes every day. The dose has been estimated by an analytical calculation.

For the second exposure, two types of data source were available: the account by the victim used to specify his various positions in relation to the source, supplemented by a video film, and secondly, the dosimetric data obtained using the ESR technique from a tooth and bone samples taken from the arm during surgery. Based on the victim's account, two representative positions of a working day at the reception desk were adopted: a sitting position leaning on the parcel and a sitting position facing the desk. To simulate these two positions, the source was placed in the vertical direction 50 cm above the start of the trunk, in other words a few centimetres below the shoulder, and in the horizontal direction at 10 cm, then 50 cm from the arm of the phantom. The exposure time was then adjusted for these two positions, whilst respecting the information taken from the victim's account, so that the dose calculated at 3 cm deep in the arm corresponded to the dose measured by ESR on the bone sample located at this same depth.

3.3.3 Results

The mean whole body dose, linked to the two-minutes-a-day exposure from 9 June to 31 July when he put on and took off his shoes was calculated analytically at 0.3 Gy.

For the victim's left arm, the doses absorbed in the biopsy tissue, measured by ESR, were estimated respectively at 53.5 ± 3.7 Gy for the first biopsy and 44.4 ± 4.9 Gy for the second biopsy. These results led to determine exposure times of 2.5 hours and 13.5 hours for the source located 10 cm and 50 cm away respectively. The accumulated doses to organs and to the whole body from the two positions at the reception desk are presented in Table 1.

Table 1: Mean doses to organs and whole body mean dose relating to the exposure at the reception desk for the COL patient

Organ	Mean dose (Gy)
Kidneys	3
Liver	1.3
Stomach	6.1
Right lung	1.7
Left lung	7.6
Heart	4.1
Brain	3.9
Whole body	3.3

3.3.4 Conclusion

ESR measurements and numerical dose reconstruction found to be complementary in order to estimate the dose distribution within the COL patient's body. The dosimetric results have been communicated and discussed with the medical team during the on-going care of the patient.

4. Conclusion

The IRSN External Dosimetry Department has developed different techniques in order to assess as accurately as possible the dose distribution in the body of victims of radiological accidents involving external sources. These techniques are experimental and numerical dose reconstruction and retrospective dosimetry with ESR. It is an addition to data produced by clinical and biological investigations.

These techniques were applied to recent radiological accidents. These different approaches were found to be necessary and complementary to be able to reconstruct the accident scenario as accurately as possible. The results obtained proved to be essential for the physicians in charge of the victims in order to define the therapeutic strategy.

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