PHYSICAL DOSIMETRIC RECONSTRUCTION OF A RADIOLOGICAL ACCIDENT AT NANJING (CHINA) FOR CLINICAL TREATMENT USING THUDOSE

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Abstract—A severe radiological accident involving an industrial radiography source containing $^{192}$Ir occurred in China. A worker was seriously exposed, which resulted in acute radiation syndrome. Initial whole-body dose was estimated at 1.51 Gy (95% Confidence Interval: 1.40–1.61 Gy) using biological dosimetry. This work performed a physical dosimetric reconstruction to provide more detailed exposure information for clinical treatment, using sitting and standing posture phantoms constructed by adjusting the Chinese reference adult male polygon surface phantoms to the worker body. A 3D view of photon flux in the body and dose distribution of local tissue with isodose lines in his legs were displayed by THUDose, and the absorbed doses of organs were present. These results were compatible with clinical symptoms and analysis, and they were helpful in assisting in the planning of therapy and in alerting physicians of potential high-risk organs. The physical dosimetric reconstruction could provide more detailed information for clinical treatment in a radiological accident with respect to obtaining local dose estimates.

Key words: accident analysis; dose assessment; phantom, mathematical; radiation protection

INTRODUCTION

On 7 May 2014, a radiological accident involving a worker occurred due to a radiography equipment accident at Nanjing, China. The radioactive source was a cylindrical $^{192}$Ir source encapsulated by stainless steel and attached to a pigtail. The accident happened when operators failed to return the source back to its shielding storage container. A worker picked up the source with bare hands and put it in his right trousers pocket. He was exposed for 3.25 h with initial clinical manifestations of exposure and was admitted to a hospital for specialized treatment of radiation-induced injuries.

In this accident, a personal monitoring dosimeter was not available for the worker as he was from the contracting oil company rather than a radiography employee. The initial dose evaluation was performed using biodosimetry 5 d after the accident (Dai et al. 2016). A chromosome aberration analysis revealed that the distribution of dicentrics did not follow a Poisson distribution, indicating the worker had been exposed inhomogenously, which was in agreement with clinical symptoms. However, biodosimetry is limited to assessing the average whole-body dose without information on organ doses and local tissue dose distribution. KTMAN-2 was used to calculate the absorbed doses of organs and tissues, and two concentric cylinders were used to calculate local dose distributions in the legs (Sun et al. 2016). These approximations would potentially alter the final results, as the mass and height of KTMAN-2 are 38.1% and 7.5% greater than the worker phantom, respectively (Lee et al. 2006), and the concentric cylinders were used to represent the soft tissue and bone instead of using the realistic voxel phantom. Thus, further investigation was required to obtain the detailed results as accurately as possible.

This paper presents the sequence of the accident events and the detailed physical dosimetric reconstruction of the worker in the accident.

CHRONOLOGY OF THE ACCIDENT EVENTS

At 3:00 a.m. local time on Day 1 (7 May 2014), radiographers working at the site dismantled the radiography equipment (as shown in Fig. 1) after the radiography operation and disconnected the source guide tube without noticing that the source had fallen out of the tube. A survey instrument was used to monitor the surface dose rate of the equipment, and an alarm sounded. The radiographers mis-took that the radioactive source was returned to its shielded

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storage container instead of realizing that the survey instrument was not far from the lost source.

At 7:50 a.m., a worker found the source but did not recognize it as being such, and he picked it up with his bare hands. Then he put it into his right trousers pocket and stayed in the lounge for an hour. From 9 a.m., he handled materials with other workers. The source was carried in his pocket for a total of 3.25 h before he dropped it into the junk in the yard outside his house.

At 7:00 p.m. on Day 2 (8 May), the source was found to be lost when the radiography equipment was in maintenance, and the accident was reported at 1 a.m. on Day 3 (9 May). A search for the source was carried out with detectors by experts. The worker realized the metal he found was the source but did not tell anyone; instead, he threw it into the brushwood near his house at 6 a.m. on Day 4 (10 May). On the same day at around 9 a.m., the location was found, and efforts to recover the source pellet lasted until 6:00 p.m.

In an accident, routine blood examination is performed for people potentially involved in the radiation exposure. On Day 5 (11 May), early radiation injuries of the skin, such as erythema and edema, could be seen on the worker’s right leg. He was transferred to a specialized hospital in Suzhou for further therapy, and peripheral blood samples were taken for biological dosimetry with the results obtained on Days 9 and 10.

During the treatment, clinical symptoms induced by overexposure were observed. For example, the survival rate of the worker’s sperm decreased from 23.00% on Day 9 to 0 on Day 92; bone marrow edema induced by radiation was found by MRI, and a surgery with an excision area of 10.7 cm by 9.3 cm in size was performed to remove the necrotic derma and tissue on Day 62. The worker was discharged from the hospital on Day 378.

MATERIALS AND METHODS

Numeric simulations have been conducted to estimate the absorbed dose received by the worker (hereinafter referred to as “the patient”). In order to make an accurate estimate, the main factors required are:

1. The radioactivity of the source;
2. A personalized phantom of the patient;
3. The relative position of the source to the patient; and
4. The length of time for which the patient was exposed.

Precise data are available for (1) and (4), as the source was registered and the sequence of events is based on interviews with the radiographers and the patient. Item (2) can be achieved to a reliable approximation by using the Chinese adult male phantom family with similar weight and the same height as the patient (Liu et al. 2009); in this paper, both sitting and standing posture phantoms are constructed to approximate the movement of the patient. Details for (3) are not precise enough to permit an accurate simulation. The uncertainties come mainly from the relative movement of the source in the pocket due to the posture changing when the patient moved. For example, when the patient stands, sits, or moves around handling materials, the distances between the source and the organs or tissues differ, since the dose rate decreases rapidly with distance; when the pigtail shape changes, the shielding effect of the pigtail differs.

The radioactive source $^{192}$Ir

The radioactive source involved in the accident was a cylindrical $^{192}$Ir source encapsulated by stainless steel, as shown in Fig. 2. The source and the radioactive pellet are 5.0 mm × 6.0 mm and 3.0 mm × 3.0 mm in size, respectively. The source capsule is attached to a pigtail about 15 cm long and 8 mm in diameter. Two segments of the pigtail are made of tungsten (W) alloy and are 45 mm long. The stainless steel (1Cr18Ni9Ti)* consists of nine elements with a mass fraction (C: 0.12%, Si: 1.00%, P: 0.035%, S: 0.03%, Ti: 0.50%, Cr: 18.00%, Mn: 2.00%, Fe: 69.315%, Ni: 9.00%), and the density is 7.85 g cm$^{-3}$.

The radioactive half-life of $^{192}$Ir is 73.8 d. Data on energy and corresponding yield are from the program DECDATA.

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*1Cr18Ni9Ti refers to stainless steel in Chinese steel grades. Numbers 18 and 9 represent chemical composition (mass fraction) of Cr and Ni.
provided by International Commission on Radiological Protection (ICRP) Publication 107 (ICRP 2008). The initial loading of the irradiator was 3.77 TBq on 14 December 2013, and by the time of the accident, its radioactivity had decayed to approximately 0.96 TBq.

**THUDose and phantoms**

THUDose is a toolkit for simulating radiation protection quantities using human phantoms developed by Tsinghua University based on Geant4 (Asai et al. 2015). It integrates a wide range of functionality, including phantom conversion, physics simulation, statistics, and visualization components. It can automatically convert the polygon phantom to a voxel phantom (Chen et al. 2016), simulate the particle transportation in the voxel phantom, calculate the absorbed doses of organs or tissues, compute the doses of voxels in parts of the phantom, visualize the result in conjunction with the phantom, and display the isodose or isoflux lines in the phantom. The ICRP and Chinese adult male and female reference phantoms are integrated into the toolkit so far, and the phantom can be chosen in the user interface.

THUDose has been verified by comparing the conversion coefficients of organs and tissues with those of ICRP publication 116 (ICRP 2010), and a relative deviation of less than 3% is found for idealized occupational irradiation using ICRP adult reference male and female phantoms.

The reference adult voxel phantom is limited in terms of its abilities to alter the body posture and body size for individuals (Hurtado et al. 2012), and hybrid computational phantoms have been studied widely in recent years (Xu and Eckerman 2011). The Chinese adult male phantom family is constructed with different heights and total body masses, which is suitable for the simulation of the patient in the accident (Chen et al. 2016). In this paper, the patient “personalized” phantoms are adjusted from the Chinese reference adult male polygon surface (CRAM_S and CRAM_Ssit) phantoms, as shown in Fig. 3, and two voxel phantoms of sitting and standing postures are constructed. The height of the phantoms is 160 cm, which is the same as the patient; the mass is 52 kg, which is slightly different from the patient’s mass of 48 kg.

In the simulation, the source is assumed to be in parallel with the right leg, and the center of the source is placed 6.5 mm from the skin of the patient’s leg. The interval between the skin and the outer surface of the source is 2.5 mm.

Photons are assumed to emit isotropically at the center of the source, and 100 million photons are simulated so that the derived organ doses have an acceptable level of statistical uncertainty (<1% in most organs).

**Flux mapping and absorbed dose**

In the accident, the patient was exposed under the situation of non-uniform irradiation. A physical dosimetric reconstruction would help to provide information to improve the understanding of the radioactive effects in the patient and to identify the critical organs of the body for clinical decisions. An isodose line at different dose values is also of interest for medical staff. In the simulation, photon flux of the whole body is simulated, the absorbed doses of organs or tissues and local dose distribution near the source are calculated, and the time of exposure for the patient is assumed to be 3.25 h with the source carried in his pants pocket.

The simulation was conducted with Intel i7-4510 (two cores, four threads) using THUDose, and the time spent on the computation of whole body absorbed dose and local dose were about 2 h and 24 h, respectively. The above results are displayed in THUDose.

**RESULTS AND DISCUSSION**

**Photon flux in the phantoms**

Figs. 4 and 5 show the photon flux of the whole body for sitting and standing postures, respectively. Photons are mainly distributed in the region near the source and thus will result in higher absorbed doses for organs and tissues close to the source. In addition, a comparison of the flux distributions in Figs. 4 and 5 shows that the sitting posture has a wider range of exposure than the standing posture, which will result in different absorbed doses for organs and tissues as discussed later.
Absorbed doses of organs and tissues

Absorbed doses of the organs and tissues for which weighting factors are specified in the ICRP 2007 Recommendations (ICRP 2007) are shown in Fig. 6 for sitting and standing postures.

It can be found that organs or tissues close to the source, such as the colon, bladder, testes, and skin, receive higher doses for both postures. For most of the organs and tissues, the absorbed doses are smaller for the standing posture compared to the sitting posture due to the decrease in dose rate as the distance from the source to the organs increases. However, the absorbed doses of testes and bladder in a standing posture are greater by a factor of 2.8 and 1.2 compared to a sitting posture, respectively, due to tissue attenuation differences between sitting and standing postures. For standing posture, the positions of testes and bladder in the phantom have less shielding from the right leg as shown in Fig. 3.

The maximum absorbed dose is 10.5 Gy to the testes for the standing posture. A threshold value of 3.5 to 6.0 Gy to testes will induce permanent infertility (GBZ107-2015 2015). During clinical treatment, hydrocele of tunica vaginalis was found by MRI, and an analysis of the patient’s semen also showed that the survival rate of sperm decreased from 23.00% on Day 9 to 0 on Day 92. In addition, there was still no survival of sperm when he was discharged from the hospital on Day 378 (Guo et al. 2016).

Local dose mapping

Fig. 7 shows the local dose distributions at the legs around the source for standing posture. The deep and surface dose distributions are almost concentric circles, as shown in Fig. 7b–d.

The maximum local dose at the right leg is 3,092 Gy but with a steep decrease in depth due to effect of distance and tissue attenuation. Isodose lines at different doses are shown in Fig. 7d, and special interest is paid to the 20-Gy isodose, which is the threshold limit value for the excision area. The dose at 20 Gy is about 5.6 cm in depth and 10.2 cm in diameter on skin surface, which is compatible with the excision area of 10.7 cm by 9.3 cm in size performed to remove the necrotic derma and tissue on Day 62 (Bian et al. 2016). The wound after radical surgical debridement on Day 65 is shown in Fig. 8 (Zheng et al. 2016). For most of the right leg, the dose is above 5 Gy in depth, whereas the dose is below 1 Gy for the left leg due to the effect of distance and tissue attenuation.
In addition, voxel doses of the femora are obviously above 20 Gy as shown in Fig. 7d, which exceed the reference threshold dose of 20 Gy for radiation-induced bone injuries (GBZ100-2010 2010). During the treatment, bone marrow edema was also found by MRI.

**Shielding effect of the pigtail**

In the accident, the relative positions of the pigtail and the radioactive source in the pants pocket were uncertain, which would form different geometric shapes of the pigtail and subsequently result in different exposure scenarios received by the patient. Thus, in addition to the calculation above, which represented a conservative estimate for the patient, the source was also defined at a location farther away from the skin to permit direct comparison due to the effects of shielding of the pigtail and distance attenuation by locations of the source. The center of the source is moved from 6.5 mm to 16.4 mm from the surface of the leg. A tungsten cylinder, 8 mm in diameter by 20 mm in height, is added between the source and the skin to simulate one representation of the shielding effect by the pigtail.

Figs. 9 and 10 show the absorbed doses of organs and tissues for sitting and standing postures. The absorbed doses of organs and tissues near the source, such as colon, testes, bladder, red bone marrow and bone surface, become smaller due to the shielding of the pigtail for both postures.
changes in the skin are different due to different photon flux and incident angle between sitting and standing postures.

**Dose comparisons**

A comparison of the results from clinical symptoms, physical dose reconstructions and biososimetry are presented in Table 1.

The biological dose was estimated by counting the yields of dicentrics and rings (dic + r), cytokinesis-block micronuclei assay (CBMN) and nucleoplasmic bridge plus FHC (NPB + FHC). The dose estimated by dicentrics and rings was 1.51 Gy [95% Confidence Interval (CI): 1.40–1.61 Gy]. Moreover, dose estimates of the fraction of photons absorbed by organs and tissues for a sitting posture with (white pattern) and without (black) shielding from tungsten cylinder of the pigtail between the source and the skin.
irradiated lymphocytes was 2.62 Gy, with irradiated blood percentages of 60% (sampling date: On Day 5).

The estimated doses obtained by physical dosimetric reconstruction are 1.18–2.20 Gy, considering different setting scenarios in the simulation. Actually, it is impractical to record the realistic shape of the pigtail in the patient’s right trousers pocket and the corresponding total time, as the patient kept moving during exposure. In addition, a lack of detailed information about the relative time the patient spent standing, sitting, or walking makes it difficult to improve the accuracy of whole body absorbed dose. However, the results obtained by physical dosimetric reconstruction effectively mark the range of expected dose for the accident.

**CONCLUSION**

Following the radiological accident on 7 May 2014 at Nanjing, a physical dosimetric reconstruction was performed using THUDose. A quick and accurate physical dosimetric calculation of the patient was crucial for clinical treatment.

The average whole-body dose is comparable to the results obtained using biodosimetry, and the exposure was a non-uniform irradiation, which is confirmed by the absorbed doses of organs and tissues. The absorbed dose of testes agreed with the clinical symptoms of the patient. The isodose line of the skin and the leg tissue at 20 Gy was consistent with the boundary of the excision area, and bone marrow edema found by MRI during the treatment was also verified by the voxel doses of the femora. As a complement to biological dosimetry and clinical symptoms, physical dosimetric reconstruction can provide more detailed information about the exposure distribution, for example, with respect to obtaining dose estimates for local vs. whole body exposure and being able to obtain estimates for the uncertainties or ranges of local doses.

The uncertainties in the simulation are mainly due to the movement of the patient, which include the postures of the patient and the pigtail position relative to the patient. Both sitting and standing postures were simulated, and the effects of shielding from the pigtail are discussed in the paper. The differences are mainly for organs and tissues near the source, such as the colon, testes, bladder, and skin. The dose received by the patient was finally determined by the actual settings of exposure scenarios in the accident.

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

![Fig. 10. Absorbed doses of organs and tissues for a standing posture with (white pattern) and without (black) shielding from tungsten cylinder of the pigtail between the source and the skin.](image)

Table 1. Comparison of clinical symptoms, biological and physical dosimetric reconstruction for the patient.

<table>
<thead>
<tr>
<th>Clinical symptoms</th>
<th>Physical dosimetric reconstruction</th>
<th>Biodosimetry (95% CI)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Whole body dose (Gy)</td>
<td>Sitting + pigtail shielding</td>
<td>Standing + pigtail shielding</td>
</tr>
<tr>
<td>—</td>
<td>2.20</td>
<td>1.63</td>
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<tr>
<td>Maximum local dose</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Excision area (cm)</td>
<td>10.7 x 9.3</td>
<td>—</td>
</tr>
<tr>
<td>Femora</td>
<td>Bone marrow edema by MRI Threshold dose: 20 Gy</td>
<td>—</td>
</tr>
<tr>
<td>Testis</td>
<td>Survival rate of sperm: 23.00% on Day 9, 0 on Day 92 and 0 on Day 378 Permanent infertility threshold: 3.5 ~ 6 Gy</td>
<td>3.81 Gy</td>
</tr>
</tbody>
</table>

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All the results show that physical dosimetric reconstruction is an effective method of assisting in the planning of therapy and in alerting the medical staff to organs with potentially high risks that could occur in the following weeks and months.

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