EVALUATING THE RADIATION FROM ACCIDENTAL EXPOSURE DURING A NONDESTRUCTIVE TESTING EVENT

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Abstract—**Industrial radiography is a common nondestructive testing (NDT) method used in various industries. An investigation was conducted for a 1999 incident in Taiwan where two workers (Operators A and B) were accidently exposed to an unshielded ^{192}Ir source while conducting industrial radiography. Operators A and B experienced acute close-range radiation exposure to a source of ^{192}Ir for 3 h at a strength of 2.33 × 10^{12} Bq. The health of mammary glands, bone marrow, thyroid glands, eyes, and genital organs of these two workers after radiation exposure was examined. Subsequently, Operator A experienced severe radiation injury, including tissue necrosis and keratinization in the fingers, chromosomal abnormalities, reduced blood cell count, diffuse hyperplasia of the thyroid gland, opaque spots in the crystalline lens, and related radiation effects. The results showed that the left index finger and thumb, eyes, and gonads of Operator A were exposed to a radiation dose of about 369–1,070, 23.1–67.4, 2.4–5.3, and 4.2–11.6 Gy, respectively. Effective dose for Operator A was estimated to range from 6.9 to 18.9 Sv. The left fingers, thumb, eyes, and gonads of Operator B were exposed to a radiation dose of 184.9–646.2, 11.8–40.7, 0.49–3.33, and 0.72–7.18 Gy, respectively, and his effective dose was between 2.5 and 11.5 Sv. This accident indicated a major flaw in the control and regulation of radiation safety for conducting NDT industrial radiography in 1999; however, similar problems still exist. Modifications of the Ionizing Radiation Protection Act in Taiwan are suggested in this study to regulate the management of NDT industries, continually educate the NDT workers in radiation safety, and enact notification provisions for medical care systems toward acute radiation exposure events.**
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Key words: ^{192}Ir; accident analysis; exposure, radiation; radiation damage

INTRODUCTION

NONDESTRUCTIVE TESTING (NDT) is defined as the use of various methods to test a component, material, or system without damaging its function and structure. Currently, this method is widely used in various industries, such as those that investigate the properties of materials used in industrial products and large-scale projects. Specifically, NDT is a diverse scientific application technology that involves using physical means to investigate the physical performance and internal structures of an object, thereby determining whether the object meets the qualification criteria. Common testing methods include ultrasonic testing, microwave scanning, infrared scanning, liquid penetrant, magnetic-particle testing, and radiation testing. Among these methods, radiation testing necessitates a high level of safety awareness because inattentive use of this method may injure both the operators and the public.

In principle, the application of radiation in NDT involves measuring material defects based on the presented radiation scattering characteristics when radiation penetrates the tested materials. Currently, NDT industrial radiography in Taiwan makes use of x-ray machines (in kV range) and radioactive sources, of which ^{192}Ir is the most common. Although accidental radiation exposure during industrial radiography has been reported in various countries, these accidents are rare. In 1968, an Indian worker placed an ^{192}Ir radioactive source (5.18 × 10^{10} Bq) into his hip pocket for 2 h, exposing the skin of the hip to a radiation dose of approximately 130 Gy, causing severe radiation burns. Furthermore, the bone marrow in the pelvic bone and testicle (located 3 and 10 cm from the radioactive source, respectively) were exposed to a radiation dose of 14 and 1.3 Gy, respectively, resulting in temporary infertility for about 2 y (Annanalai et al. 1978). In 1971, a Japanese worker accidentally exposed his hand to a 1.92 × 10^{11} Bq source of ^{192}Ir for 2–7 min and received a dose of 20–90 Gy. His whole body dose was calculated to be 1.3 Gy, and the right fingers were severely damaged and developed contracture, necessitating amputation (Nakagawa et al. 2001). In 1985, a Bengali worker conducted industrial radiography using a

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1.85×10^{11} Bq ^{192}Ir source. At that time, the radioactive component was obstructed during the radiography process and failed to return to a safe position. Unaware of the problem, the worker continued to capture 18 radiographic images. Consequently, his fingers were exposed to a radiation dose of about 24 Gy and were subsequently amputated. Moreover, the effective dose was 2–3 Sv (Jalil and RabMolla, 1989, 1992). Jacobson et al. (1977) reported an accidental radiation-exposure incident in which an American worker received 15 Sv effective dose when accidentally exposed during industrial radiography using a 2.89×10^{12} Bq ^{192}Ir source. Approximately 1 wk after the incident, a decrease was found in the worker's white blood cell count (from 6.4×10^3 to 4.8×10^3 mL^{-1}) and hemoglobin level (from 15.2 to 13.6 g dL^{-1}); 1 mo later, his platelet count also declined.

The current study investigated primarily two Taiwanese male operators aged 40 y who were accidentally exposed to gamma radiation during a nondestructive examination event in 1999. These two operators (Operators A and B) were examined for the damage caused by the exposure and treated by a regional teaching hospital, Changhua Christian Hospital, in Taiwan. Radiation dose information was lacking because they did not wear dosimeters during the incident. Also, before the Ionizing Radiation Protection Act of Taiwan [enacted by the Atomic Energy Council (AEC) of Taiwan] was proclaimed in 2002, the radiation safety standards for the NDT proprietors were not strictly observed. In apparent consideration of related penalties, the NDT proprietor did not notify the AEC at the occurrence of this event yet reached an agreement on indemnification and health care with these two operators. In addition, the hospital treated the patients but did not inform the AEC either, since no associated legislation regulated the actions for medical care systems. Accordingly, the investigation was not performed immediately after the occurrence but rather not until the event was exposed by a retiree. Based on detailed statements of these two operators, the absorbed dose to their fingers and various organs during the accident were estimated. Moreover, the effective doses for Operators A and B were also assessed using tissue weighting factors recommended by ICRP Publication 60 (ICRP 1991) for sensitive organs.

MATERIALS AND METHODS

The accident

In January 1999, two operators (referred to as Operators A and B) collaborated to conduct NDT radiography for weld joints in oil (gas) pipelines with a 2.33×10^{12} Bq ^{192}Ir source. At the time, the alarm device for radiation exposure was undergoing maintenance; however, these two operators were required to meet an urgent deadline. Thus, despite the absence of the alarm device, Operators A and B proceeded with work without wearing alarming devices or thermoluminescent dosimeters (TLDs). When another worker walked passed them, his electronic alarming device raised an alarm. Finally, they realized that the radioactive source did not return to its storage position. This accident was primarily caused by a mechanical error such that the crank controlling the position of the radioactive source was reversed. Hence, when the operators selected the active mode, the source was actually in the storage position; whereas when they switched the source to the safe mode, the source was actually in the irradiation position.

Subsequently, during the night of the incident, Operator A experienced symptoms such as nausea, dizziness, visual impairment and physical discomfort. However, he continued working on the following day. On the third day, Operator A experienced a burning sensation and pain in his fingers. The pain intensified on the fourth and the fifth day, so that he sought medical attention at a clinic in Southern Taiwan. About 2 wk later, he was transferred to the Changhua Christian Hospital in Taiwan for a medical checkup. The examination results showed a reduced blood lymphocyte and platelet count, slight decline in white blood cell (WBC) count, reduced sperm count and activity, diffuse hyperplasia of the thyroid gland, and severe radiation burns to his fingers. Eventually, his left index finger was amputated in August 1999 because of ulcerations and necrosis (Fig. 1). Approximately 4 y following the accident, the amputated area and left thumb continued to exhibit deterioration and necrosis; his left middle finger was enlarged and right index finger and thumb presented keratinization.

Fig. 1. Radiation damage to the left fingers of Operator A (2 wk after exposure).

Dose evaluation

The radioactive source involved in this accident was ^{192}Ir encapsulated by aluminum 2 mm thick (which eliminated the beta radiation and somewhat hardened the beam). Irridium-192 (^{192}Ir) emits β^- particles and gamma photons via β^- decay and electron capture with a half-life of 74.02 (Johnson and Birky 2012). The photon energy ranges between 0.136 and 1.06 MeV (averaged 0.38 MeV) and is characterized by a 0.317 MeV γ ray (82.8%) with a gamma rate constant (Γ) of 1.85×10^{-11} Gy cm^{-2} Bq^{-1} min^{-1} and a half-value layer of 4.8 mm in aluminum (Khan 2010).

Based on the event described by Operator A, he did not receive effective or relevant training before working with the source and thus lacked knowledge regarding ways to decrease radiation exposure and the risks of radiation exposure. To derive the received dose, the total exposure time for each operator is required, which can be estimated from individual film exposure time. Generally, an operator needs 1.5–2.5 min, including 0.5 min to transport the radioactive source to the irradiation position via the guide tube, to capture one film in the NDT by radiation. However, the operation time of Operator A was prolonged due to deficient training; about 3 min was spent in capturing each film. In comparison, Operator B averaged 1.5–3 min for each film. The expected time the source was to be exposed for each film averaged 0.5 min; however, since the cable crank was reversed, the ^{192}Ir source was in the storage position and no dose was received during this period. Also, considering the transport time (0.5 min) from storage to the irradiation position, the operators were exposed for about 1 min while attempting to take a film. Because of the error, Operators A and B were exposed to radiation for, respectively, 2 min and 0.5–2 min while attempting to capture a radiographic image. Over the duration of the radiography operation, within 0.5 m of the ^{192}Ir source, Operator A was exposed for 2–2.5 h while attempting to capture 40–50 images, and Operator B was exposed for 0.5–1 h while taking 20–30 films. Additionally, before commencing radiography operations, the operators directed the front end of the guide tube toward the object to be irradiated (the contact time for fingers is typically 3–7 s per film). Because of the mechanical error in attaching the crank, the source was exposed rather than stored during this time, and the exposure time was 2.0–5.8 min and 1.0–3.5 min, respectively, for the left index finger and thumb of Operators A and B. The distance from the source was 0.5 cm (the thickness of the guide-tube wall) to the left index finger and 2 cm to the left thumb for both operators. Close contact with the radioactive source was accordingly concluded to be the cause of severe left finger damage to Operators A and B. During the exposure period, the radioactivity of ^{192}Ir decayed by approximately 0.08%; therefore, the radioactivity of the radioactive source during exposure could be considered to be constant. Consequently, the absorbed dose for each body area can be estimated using the following equation:

$$D(Gy) = \frac{\Gamma \times A \times t}{d^2} \times \frac{\mu_{\rho,t}}{\mu_{\rho,a}}, \qquad (1)$$

where:

D = absorbed dose (Gy);
Γ = gamma exposure rate constant; ($Gy\ cm^{-2}\ Bq\ min^{-1}$),
A = source radioactivity (Bq);
t = exposure time (h); d = distance between the radioactive source and body surface (cm);
$\frac{\mu_{p,t}}{\mu_{p,a}}$ = ratio for mass energy absorption coefficient of tissue to air, equal to 1.07 (Khan 2010).

Subsequently, doses were assessed to individual fingers and the 12 organs listed in the ICRP Publication 60. The effective dose can be calculated as follows:

$$D_{eff} = \sum D_i W_i, \qquad (2)$$

where:

D_{eff} = effective dose,
D_i = absorbed dose in each tissue, and
W_i = weighting factor of a specific tissue.

Radiation exposure conditions when Operator A was working within 0.5 m from the radioactive source

Operator A was exposed to radiation in two conditions: (a) first, when he pointed the guide tube of the radioactive source toward the regions where radiation exposure was to occur. The distance between the radioactive source and various body parts was 30–40 cm for the eyes, 32–42 cm for the lungs, 23–33 cm for the stomach, and 20–30 cm for the gonads; and (b) second, Operator A was exposed during the preparation for radiography. The distances between the radioactive source and various body parts were estimated as shown in Table 1.

Radiation exposure conditions when Operator A was working within 0.5–6 m from the radioactive source

In addition to working within 0.5 m of the radioactive source, Operator A also worked in an area within 0.5–6 m from the source for 0.5–1 h. Since Operator A could only approximate where he stayed around the work area, the body position and time spent were not detailed. Therefore, the body position and time spent were estimated by dividing the distance between 0.5 and 6 m from the radioactive source equally into 56 intervals. The spent time at each position during an interval was thus averaged to be 0.54–1.07 min. Assuming that the body is completely exposed to radiation at each interval, the organ dose can be estimated using the following equation:

Table 1. Exposure parameters and tissue/organ doses for operator A.

Organ	Distance (cm)	Exposure time (min)	Absorbed dose (Gy)
Left index finger	0.5	2.0–5.8	369–1070
Left thumb	2	2.0–5.8	23.1–67.4
Eyes	30–40	80–100	2.4–5.3
Gonads	20–30	80–100	4.2–11.6
Red bone marrow	25–35	80–100	3.1–7.5
Colon	30–40	80–100	2.4–5.2
Lungs	32–42	80–100	2.1–4.6
Stomach	23–33	80–100	3.4–8.8
Urinary bladder	24–34	80–100	3.3–8.1
Mammary glands	30–40	80–100	2.4–5.2
Liver	23–33	80–100	3.4–8.8
Esophagus	32–42	80–100	2.1–4.6
Thyroid gland	32–42	80–100	2.1–4.6
Skin (except finger skin)	20–30	80–100	4.2–11.6
Bone surface	20–30	80–100	4.2–11.6
Other tissues	32–42	80–100	2.1–4.6

$$D = \sum_{\substack{k=50 \\ \triangle k=10}}^{600} \left(\frac{\Gamma \times A \times t}{{d_k}^2} \times \frac{\mu_{\rho,t}}{\mu_{\rho,a}}\right), \qquad (3)$$

where:

D = absorbed dose (Gy);

Γ = gamma exposure rate constant; ($Gy\ cm^{-2}\ Bq\ min^{-1}$),

A = source radioactivity (Bq);

t = exposure time (h); and

d_k = distance k (cm) between the radioactive source and the surface of an organ or tissue, and

$\mu_{\rho,t}/\mu_{\rho,a}$ = ratio for mass energy absorption coefficient of tissue to air (=1.07).

Radiation exposure conditions for Operator B

Since both operators were collaborating in the same work when the accident occurred, it was assumed that the distance (within 0.5 m from the radioactive source) from the source to Operator B was similar to Operator A. However, the exposure time for Operator B was shorter compared to that for Operator A; thus, the period that Operator B spent working was estimated to be 0.5–1 h within 0.5 m from the source and 2–2.5 h within 0.5–6 m from the source. The time spent at each position was calculated to be 2.14–2.68 min using the aforementioned approach. Subsequently, eqns (1) and (3) were used to estimate the absorbed dose in individual tissues, and the effective dose was calculated using eqn (2).

According to eqns (1) and (3), time spent and distance to the source are the key parameters contributing to absorbed dose. However, since the dose rates, distances, and time spent during the movement in operation were indeterminate, detailed assessment for the dose with distance and time as well as that for tissue attenuation were not considered. In addition, body self-shielding was also ignored since the operators were irradiated without shielding.

RESULTS AND DISCUSSION

Based on the evaluation, the absorbed dose in the individual organ tissues of Operators A and B was estimated as shown in Tables 1 and 2, respectively. The doses that both Operator A and B received were primarily from irradiation when working within 0.5 m of the radioactive source. Therefore, the effective doses for Operators A and B, calculated using the tissue weighting factors recommended in the ICRP Publication 60 (1991), were 6.9 to 18.9 and 2.5–11.5 Sv, respectively. The organ doses to the left index finger, thumb, eyes, and gonads of Operator A were 369–1,070, 23.1–67.4, 2.4–5.3, and 4.2–11.6 Gy, respectively, and the dose to the same organs in Operator B were 185–646, 11.8–40.7, 0.49–3.33, and 0.72–7.18 Gy. This high exposure caused various acute radiation damage in Operator A, including finger tissue necrosis, lens opacity, and reduced sperm count.

Neither Operator A nor B was wearing a dosimeter during the incident, so precise absorbed doses could not be determined. Therefore, the radiation doses to Operators A and B could only be estimated based on their personal descriptions of the event. Operators A and B could not recall details about working time and relative distances, so the assessment resulted in wide dose ranges according to approximate ranges provided by the operators. Overall, the estimated doses corresponding to the radiation damages agreed with the minimum threshold values for the

Table 2. Exposure parameters and tissue/organ doses for operator B.

Organ	Distance (cm)	Exposure time (min)	Absorbed dose (Gy)
Left index finger	0.5	1.0–3.5	185–646
Left thumb	2	1.0–3.5	11.8–40.7
Eyes	30–40	10–60	0.49–3.33
Gonads	20–30	10–60	0.72–7.18
Red bone marrow	25–35	10–60	0.58–4.68
Colon	30–40	10–60	0.49–3.33
Lungs	32–42	10–60	0.46–2.69
Stomach	23–33	10–60	0.63–5.49
Urinary bladder	24–34	10–60	0.60–5.06
Mammary glands	30–40	10–60	0.49–3.33
Liver	23–33	10–60	063–5.49
Esophagus	32–42	10–60	0.46–2.96
Thyroid gland	32–42	10–60	0.46–2.96
Skin (except finger skin)	20–30	10–60	0.72–7.18
Bone surface	20–30	10–60	0.72–7.18
Other tissues	32–42	10–60	0.46–2.96

Table 3. Threshold doses estimated from the ICRP-60 publication for deterministic effects of radiation.

Tissue/Organ	Effects	Acute exposure dose (Gy)	Chronic exposure dose (Gy y^{-1})
Testicles	Temporary infertility	0.15	0.40
	Permanent infertility	3.50–6.00	2.00
Ovary	Permanent infertility	2.50–6.00	0.20
Crystalline lens	Cataract Low LET[a]	5.00 (2.00–10.00)	0.15
	Lens opacity	0.50–2.00	0.10
Hematopoietic organs	Hypo-function	0.50	>0.40
Fetus	Deformity	0.10	
	Severe dementia	0.12–0.20	

[a]Low linear energy transfer (LET).

deterministic effects of radiation according to ICRP Publication 60 (Table 3).

Nearly 4 y after the incident, Operator A had gradually recovered from the various acute radiation damage, exhibiting a normal blood cell count, increased sperm number (from 13 million to 135 million), and increased sperm activity (from 20% to 60%). Moreover, his thyroid gland was recovering. However, delayed effects began to appear: (1) partial chromosomal abnormalities; (2) lens opacities; (3) severe keratinization in the area where the left index finger was amputated and in the left thumb; (4) dry patches, broken skin, blisters, and minor keratinization in the right index finger; (5) poor finger motility; and (6) increased sensitivity and pain in the fingers. The effects on the health status of the two workers, such as the stochastic effects that may occur in 3 to 5 y or more than 10 y following the accident, carcinogenic effect, and severe genetic effect should be carefully examined. The most common cancers developing after accidental exposure include leukemia, thyroid cancer, stomach cancer, lung cancer, colorectal cancer, and breast cancer. Specific attention should be paid to the high risk of leukemia 5 y after exposure and the increased risk of an inherited cancer in the patient's offspring. According to ICRP Publication 60 (1991), the nominal probability coefficient for fatal cancer is approximately 5.0×10^{-2} Sv^{-1} and that for severe hereditary effects is 1.3×10^{-2} Sv^{-1}. Therefore, monitoring the carcinogenic and genetic effects in Operators A and B is vital. Furthermore, according to the Ionizing Radiation Protection Act of Taiwan, both operators must receive appropriate medical care and psychological counseling.

According to the Statistics of Annual Occupational Exposures in Taiwan in 2012 (Atomic Energy Council 2014), there were 48,225 national radiation workers, and 455,118 TLDs were used. Thus, on average, each worker wears 9.44 TLDs annually. Furthermore, the overall number of industrial radiation workers was 19,576, 5.21% of which are industrial radiographers. In addition, 13.3% of the industrial radiation workers engaged in radiation measurements. Industrial radiography accounted for 35.9% of the industrial worker population. However, the collective dose for industrial radiographers was 67.9% of all industrial radiation workers (451 person-mSv). Based on these results, workers in industrial radiography are at higher risk of exposure. Thus, considering radiation safety for these workers is critical.

The evaluation of this accident suggests that a critical flaw existed in NDT radiation safety standards for domestic industrial radiography in 1999 when the Ionizing Radiation Protection Act of Taiwan had not yet been enacted. Numerous workers were engaged in radiation-related operations without relevant certifications, the knowledge of radiation protection or comprehending the importance of dose monitoring. The radiation exposure case of Operators A and B was typical of conditions at the time, as their employer instructed them to commence radioactive operations without providing relevant orientation training. Consequently, the two operators were ignorant of radiation risks and the significance of wearing dosimeters. A deficiency in radiography training also impeded their work progress and contributed to the radiation overexposure. In addition, Operators A and B did not sense the severity of radiation exposure, did not report this event to the proprietor or AEC, and did not seek medical attention until their physical conditions deteriorated.

Today, according to radiation safety regulations of AEC in Taiwan for NDT employees, workers at industrial radiographic facilities are required to possess relevant operational certifications and wear dosimeters at work. However, although the Ionizing Radiation Protection Act of Taiwan has been in effect more than a decade, similar problems still exist in NDT industries (e.g., the proprietor employed uncertified workers, operator did not establish controlled areas and supervised areas, the operator did not perform related radiation monitoring or wear dosimeters, the radioactive source was lost during transportation) as indicated by cases fined by the AEC from 2005 to 2012 (Atomic Energy Council 2014).

However, the basic rights of employees (e.g., dose monitoring during routine work and follow-up medical care after inadvertent high exposure) may be sacrificed due to deficient education in radiation safety. Accordingly, modification of the enforcement rules of the Ionizing Radiation Protection Act of Taiwan is imperative. Several suggestions are made for changes to the implementing regulations. First, procedures should be established within the medical care systems to inform the AEC when patients have been injured by radiation to prevent concealment of radiation exposure accidents. Second, the NDT proprietors should be required to perform routine training for radiological operations and to provide their workers ongoing education in radiation protection. Third, to help prevent unnecessary radiation exposure and radiation detriment in the industrial radiography workforce, it is recommended the AEC educate the consignors to refuse uncertified operators for NDT work.

CONCLUSION

A 1999 radiation overexposure accident involving two NDT operators was investigated in this study and was determined to have resulted mainly from deficient education in radiation protection and unskillful operation. Diffuse hyperplasia of the thyroid gland and a decrease in the number of blood lymphocytes, platelets, white blood cells, as well as sperm cells and activity were found. Operator A's left index finger was amputated in August 1999. Deterioration and necrosis occurred at the amputated region and the left thumb while keratinization presented at the right index finger and thumb. Operator B also received considerable radiation doses to his left fingers, thumb, eyes, and gonads.

This accident occurred before related radiation protection regulation was enacted in Taiwan; however, similar violations are still occurring even after the Ionizing Radiation Protection Act of Taiwan was declared on 2002. Therefore, recommendations are made to regulate the NDT proprietors to provide training and radiation protection education for workers. In addition, provisions should be enacted for medical care systems to notify the AEC in the event of radiation overexposures to prevent such events from being concealed and to help the NDT workers cope with follow-up health care and medical treatments.

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