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Special Contribution

# Radiation Doses to Practitioners Caring for Victims of a Radiological Accident

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1. Introduction: Nuclear and Radiological incidents present unique patient care challenges. Traditionally, the focus of radiological incident preparedness has been nuclear power plant accidents. Emergency response planning now has a broader focus and addresses a range of nuclear and radiological emergencies including acts of terrorism.
Basic actions of responders to radiological emergencies should not differ, in general, from those taken in response to emergencies involving other hazardous material. The purpose of this project was to model the potential radiation exposure to first responders and in receiving healthcare facilities.
2. Methods: Radiation doses to medical personnel were modeled both empirically and via computer modeling. Simulated isotopes were selected based on their likelihood of being present during a radiological incident, as well as their radiological characteristics. Working backward from a regulatory dose limit, the amount of material on or in a victim's body needed to produce such a dose was determined.
3. Results: Calculations estimate a dose rate of 0.67 mSv $h^{-1}$ to a practitioner caring for a Chernobyl accident victim with 1,400 MBq of I-131 in the thyroid. A practitioner caring for a hypothetical patient uniformly contaminated with $^{60}$Co, $^{137}$Cs, or $^{192}$Ir would be able to stay in close proximity to the patient for 18.1, 33.7, or 54.7 hours, respectively, before they reached the IAEA threshold dose for lifesaving activities.
4. Conclusion: Information presented here may be used to educate healthcare workers on the relative risk of lifesaving activities following a radiological or nuclear incident. The research presented here can also be used to provide additional information that an Incident Commander can use to make more informed decisions about evacuation, sheltering-in-place, defining radiation hazard boundaries, and in-field radiological dose assessments of the radiation workers, responders, and members of the public.

*Key words*: emergency response, accident, dose assessment

## 1. Introduction

Radiological materials and radiation generating devices are used in numerous industries throughout the world[1]. As the use of radiological materials continues to expand, the probability of a physician or responder encountering someone with a real or suspected radiological injury

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grows. When incidents do occur, they tend to illicit a powerful fear and concern in the public and even emergency responders[2].

Practitioners that have not been trained in radiological emergency response may not recognize the difference between a radiological and a chemical incident, and are likely to have concerns about the risk a potentially contaminated patient could pose to the response team[3]. All-hazards training tend to emphasize that patients involved in chemical, biological, radiological, nuclear, and explosive (CBRNE) events pose potentially serious problems for hospital emergency departments and emergency care providers[4], and some practitioners studied have indicated a reluctance to treat a patient before decontamination efforts have been undertaken[5]. These concerns may unnecessarily delay care if personnel opt to decontaminate a patient prior to first aid, medical stabilization, or treatment of serious injuries[5, 6]. Select agencies have implemented prohibitions on the transport of patients involved in CBRNE events out of concerns that the treatment staff may be injured or incapacitated, or that the transport equipment will need to be taken out of service due to the spread of contamination[7].

Following a radiological or nuclear incident, the responders arriving on scene first will need to make rapid decisions about how to manage the event. Once victims have been assessed, individuals with life-threatening injuries or medical conditions need to be treated without delay[8]. In order to prepare providers and emergency responders to comfortably and reliably administer care in these situations, it is important that they understand the relative risk that handling a potentially contaminated patient poses to them and their colleagues[9].

The purpose of this paper is to demonstrate, both by example case studies and through computer modeling, the minimal hazard posed to medical practitioners during the handling of radiologically-contaminated patients.

## 2. Review of selected cases

Despite the widespread use of radiological materials, serious radiological or nuclear incidents occur infrequently, and serious incidents involving the spread of radioactive contamination at levels harmful to people are even more uncommon[10]. Out of 465 radiological accidents in the Radiation Emergency Assistance Center and Training Site (REAC/TS) registry, 59 involve the incorporation of radiological material into the body. The majority of these cases involve the intake of alpha-emitting radionuclides that pose no risk when outside the body. Three cases involve internal and/or external contamination at levels high enough to deliver a measurable dose to those in close proximity[11].

To illustrate the minimal hazard posed to medical practitioners during the handling of radiologically-contaminated patients, a description of some notable historical incidents is presented in this section and summarized in Table 1.

**Table 1.** Maximum dose to medical personnel at three large-scale contamination events

| Event | Practitioner Maximum Dose |
|---|---|
| SL-1 Reactor Criticality | 140 mSv |
| Chernobyl Criticality | 10 mSv |
| Goiania Source Rupture | 3 mSv |

### *2.1. The Stationary Low-Power Plant Number 1 (SL-1) accident (1961)*

On December 23, 1960, the reactor was shut down for routine maintenance, including instrument calibration, installation of valves, minor plant modifications, and installation of flux wires in the core. A group of 3 men reported to the SL-1 reactor on the evening of 3 January, 1961 to reconnect the reactor's control rods to the drive mechanism, which had been disconnected to allow for the installation of the flux wires. At 9:01 p.m. the reactor went "prompt critical" with the three men in the reactor silo, two of them directly over or very close to the top of the reactor, working with the central control rod[12].

The criticality produced enough thermal energy that the water surrounding the fuel vaporized within four milliseconds. Twenty percent of the fuel melted in the absence of cooling water, and iron pellets packed near the reactor as thermal insulation and radiation shielding scattered all over the floor as the reactor vessel jumped and sheared off its piping connections. The violence of the explosion killed all three of the men. Two of them died instantly, with one thrown sideways against a shielding block and the other straight upwards, where one of the shield plugs pinned his body to the ceiling. The third man suffered head wounds that would prove ultimately fatal, but his pulse continued for another two hours. Shards of radioactive metal were thrown by the blast into the men's bodies[13].

The first individual to enter the facility after the accident was the assistant fire chief who noted radiation levels up to 25 R/hr, prompting him to retreat from the building. Three men (two firemen and a health physicist) approached the reactor building approximately fifteen minutes later, observed radiation levels adjacent to the reactor floor of the order of 500 R/hr, and withdrew[13].

Of the several hundred people engaged in recovery operations, 23 persons received whole-body radiation exposures in the range of three to 27 R. Of those 23, 14 received exposures between three and 12 R, six were in the 12-25 R range, and three received exposures above 25 R. The nurse that attempted resuscitation of one of the victims and the physician that declared that victim dead received whole body exposures of 15 and 16 R, respectively[14)].

### 2.2. The Chernobyl Nuclear Power Plant accident (1986)

On the evening of 26 April, 1986, a combination of flawed reactor design and the intentional bypassing of safety features and protocols led to an explosion and the release of more than 50 tons of radioactive material into the atmosphere[15)]. Approximately 600 persons were involved in the emergency response during the first day of the accident and 134 people received doses resulting in acute radiation sickness. Two individuals were killed by the force of the explosion and 28 died shortly after the accident as a result of their radiation exposures[16)].

Although patients presented with body burdens of $^{131}I$ and $^{134/137}Cs$ as high as 1,400 and 80 MBq, respectively[16)], medical practitioners received a dose of less than 10 mGy[17)]. The notable exceptions are the first two physicians that responded to the scene of the accident and suffered from Acute Radiation Syndrome. Both worked treating victims at the scene of the accident and traversed fuel fragments that had been ejected during the explosion as they went into the reactor building to retrieve victims[18, 19)].

### 2.3. Scrap metal scavenging and contamination spread at Goiânia, Brazil (1987)

Theft and dismantlement of a rotating assembly of the shielding head of a teletherapy unit led to four fatalities, injuries to many people, and the widespread contamination of the central part of Goiânia, Brazil in September 1987. Scrap metal scavengers did not recognize the contents of the capsule, 50.9 TBq of $^{137}Cs$, as radioactive. Fascination with the pale blue light emitted by the cesium salt convinced the scrapyard owner to distribute small amounts of the material to several family members[20)].

Out of approximately 112,000 people that were monitored for contamination, 249 were found to be either internally or externally contaminated. Of that number, 50 required close medical surveillance at either the Goiânia General Hospital (20 people), or a local primary care unit. The 14 victims that required the most intensive medical care were transferred to a specialized unit in Marcílio Dias Navy Hospital in Rio de Janeiro[21)]. During transfer, medical and radiation protection teams, medical transporters, and aircraft crews were all required to wear protective clothing to protect patients from microbial contaminants, as well as to prevent possible radionuclide contamination of the aircraft, ambulances, and personnel by the patients[22)]. Estimated intakes for the 20 people treated at Goiânia General Hospital were between $4.5\times10^6$ and $1.0\times109$ Bq[21)]. Maximum dose-equivalent rate at the thorax of the patient with the highest body burden was measured at 1 mSv $h^{-1}$, and 5 mSv $h^{-1}$ at the hands and feet[22)]. Local lesions induced by $^{137}Cs$ were observed in 28 people[20)], and dose rates as high as 15 mSv $h^{-1}$ were measured over some of these lesions[20)].

During the 4-month period in which the patients were hospitalized, patient treatment areas were controlled as radiological areas, and all medical and radiation protection staff that entered these areas wore standard medical precautions and were monitored for external radiation using film, TLD, and pen-type dosimeters. The highest dose integrated over the entire 4-month period was 3 mSv[22)]. For comparison, the average annual background dose worldwide is 2.4 mSv[23)].

## 3. Methods

Because there is little information available in the literature related to exposures of emergency personnel from radiologically-contaminated victims, simulations were run to determine the doses that could be expected from plausible contamination scenarios. Estimation of exposure to responders following a radiological dispersal device (RDD) resulting in large fragments embedded in tissue have been previously described in the literature[24)] and are not discussed here.

### 3.1. Calculation background

Estimates of the maximum dose rate (in μSv $h^{-1}$) to medical staff from a patient with a small, localized area of contamination can be developed using the point source approximation:

$$\dot{D} = \frac{A\times\Gamma}{d^2} \tag{1}$$

Where $A$ is the administrated activity (MBq), Γ is the exposure rate constant for the radionuclide of interest (μSv $m^2$ $MBq^{-1}$ $h^{-1}$), and d is the distance from the between the practitioner and the area of contamination (m). Doses delivered to medical practitioners from radioiodine concentrated in the thyroid can generally be modeled as point sources[25)]. Note, however, that there is some variation in doses to individual organs as the distance between the source and the area of the body receiving the dose is not constant across the entire body.

If the patient is contaminated fairly uniformly over their entire body, the practitioners' dose rate can be estimated by treating the patient's body as a line source:

$$\dot{D} = \frac{A\times\Gamma}{a\times d}\left[\tan^{-1}\left(\frac{l_1}{d}\right) + \tan^{-1}\left(\frac{l_2}{d}\right)\right] \tag{2}$$

Where $A$ is the total activity uniformly distributed in the line segment (MBq), is the exposure rate constant for the radionuclide (μSv $m^2$ $MBq^{-1}$ $h^{-1}$), a is the patient's height (m), and d is the distance between the center of the patient and the practitioner (m). Under the line source approximation, $l_1$ and $l_2$ are the distances between a point lying at the intersection of the line source and a line orthogonal to that source and extending parallel to the ground to the practitioner, and the patient's head and feet, respectively.

A variation of equation 3 can be used to more precisely estimate the dose to the practitioner from a point source:

$$\dot{D} = \frac{A \times \Gamma}{d}\left[\tan^{-1}\left(\frac{l_3}{d}\right) + \tan^{-1}\left(\frac{l_4}{d}\right)\right] \quad (3)$$

Where $A$ is activity in the thyroid (MBq), $\Gamma$ is the exposure rate constant for the radionuclide ($\mu$Sv m$^2$ MBq$^{-1}$ h$^{-1}$), and d is the distance between the patient's thyroid and the practitioner (m). In this case $l_3$ and $l_4$ are the distances between the practitioner's head and the elevation of the patient, and the elevation of the patient and the practitioner's feet, respectively.

For photons with energies above 150 keV, the line source approximation has been shown to provide reasonably accurate estimates of the maximum dose rate to practitioners[26)]. However, for lower-energy photons and beta particles, this approximation overestimates the practitioner doses by neglecting the attenuation of emitted radiation by the patient's tissues and the intervening air.

### *3.2. Radionuclide selection*

In 2012, a series of experiments known as the Full-Scale Radiological Dispersal Device Field Trials were conducted by Defense Research and Development Canada. Results of these field trials were used to estimate the fraction (approximately 10%) of a source that, if uniformly dispersed, would be expected to deposit over a specified area[27)]. These results were applied to the source strength of the teletherapy source from the Goiânia incident (50.9 TBq) to produce a uniform contamination level of 50.9 GBq m$^{-2}$. This contamination level was used for each of the computer simulations.

The International Atomic Energy Association (IAEA) has developed guidelines for radioactive source security for radionuclides pose the greatest health hazard. These guidelines are based on the commercial radioactive sources that contain significant amounts of radioactivity, and are frequently used in various industries. The sources considered highest risk include $^{241}$Am, $^{252}$Cf, $^{137}$Cs, $^{60}$Co, $^{192}$Ir, $^{238}$Pu, and $^{90}$Sr[28)]. Of these radionuclides, $^{60}$Co, $^{137}$Cs, and $^{192}$Ir emit the most energetic gamma photons, as shown in Table 2.

Radioactive cobalt and iridium are generally used in their metallic form, making them less of a dispersible hazard and more of a concern due to the intense radiation they emit as a discrete source. There are, however, refining and industrial processes that may lead to dispersible oxide and halide forms of these elements. Cesium, on the other hand, is used in older teletherapy units in the form of a soluble salt, making it a contamination risk of the source capsule is compromised. Simulations were run using $^{60}$Co, $^{137}$Cs, and $^{192}$Ir as the contaminants.

### *3.3. Monte Carlo simulation geometry*

External dose rate estimates presented here were developed using the Monte Carlo code MCNPX[29)] with the patient represented by a horizontally-oriented, cylindrical phantom standing 130 cm tall and with a radius of 18 cm. The cylinder was modeled as being uniformly contaminated on its outer surface. A female practitioner was simulated using the PIMAL (Phantom with Movable Arms and Legs) phantom[30)], previously developed by Oak Ridge National Laboratory (ORNL) and the United States Nuclear Regulatory Commission (US-NRC). The practitioner was assumed to be standing at mid-torso of the patient, with the midline axis of the patient 40 cm away from the midline axis of the practitioner.

An energy deposition tally was taken in each of the cells (organs) of the practitioner phantom, yielding results in MeV g$^{-1}$ per unit activity. These results were converted to Gy h$^{-1}$ and multiplied by the ICRP 103 tissue weighting factors to produce an effective dose rate:[31)]

$$\dot{E}_T = \sum_T w_T \dot{H}_T \quad (4)$$

Where $\dot{E}_T$ is the effective dose rate (Sv), $w_T$ is the tissue weighting factor, and $\dot{H}_T$ is the equivalent dose rate (Sv), which is accounts for the relative biological effectiveness of different types of radiation.

## 4. Results

For the point source estimate, a distance of 50 cm was estimated between the patient's thyroid and the practitioner's midline, and the practitioner was assumed to be 170 cm tall. The 1,400 MBq thyroid from the Chernobyl accident was used as a test case[16)], which would have delivered an estimated dose rate of 0.67 mSv h$^{-1}$ to a practitioner.

Effective dose rates resulting from contamination levels of 50.9 GBq m$^{-2}$ $^{60}$Co, $^{137}$Cs, and $^{192}$Ir are presented in Table 3. Because of the proximity of this organ to the patient, the female practitioner's bladder was the organ receiving the highest dose in each case.

The IAEA recommends that emergency workers performing life-saving activities not exceed 500 mSv. A healthcare provider would need to be in direct proximity to a patient contaminated with 50.9 GBq m$^{-2}$ of $^{60}$Co for 18.1 hours to reach this dose threshold. A practitioner

**Table 2.** Radiological and physical characteristics of gamma-emitting radionuclides of concern

| Isotope | Half Life | Gamma Energy (MeV) | Primary Form |
|---|---|---|---|
| $^{60}Co$ | 5.27 y | 1.1732 (99.90%); 1.3325 (99.98%) | Metal pellets |
| $^{137}Cs$ | 30.17 y | 0.662 (85%) | Salt (CsCl) |
| $^{192}Ir$ | 74.02 d | 0.317 (83%); 0.468 (48%); 0.604 ( 8%) | Metal pellets or disks |

**Table 3.** Effective dose rates for uniform contamination of 50.9 GBq $m^{-2}$

| Isotope | Effective Dose Rate ($mSv\ h^{-1}$) | Equivalent Dose Rate To Bladder ($mSv\ h^{-1}$) | Time to Reach IAEA Lifesaving Dose Limit of 500 mSv (h) |
|---|---|---|---|
| $^{60}Co$ | $27.6 \pm 0.42$ | $55.6 \pm 3.2 \times 10^{-5}$ | 18.1 |
| $^{137}Cs$ | $14.8 \pm 2.2$ | $30.7 \pm 4.7 \times 10^{-4}$ | 33.7 |
| $^{192}Ir$ | $9.13 \pm 0.15$ | $19.6 \pm 1.1 \times 10^{-5}$ | 54.7 |

could treat a patient contaminated with $^{137}Cs$ or $^{192}Ir$ for 33.7 or 54.7 hours, respectively, before they reached the IAEA threshold dose for lifesaving activities.

## 5. Conclusions

In a radiation emergency, standard guidance is that life-saving measures take priority over concerns about radioactive contamination[8]. Other studies[24] have indicated that special precautions may need to be taken in cases of embedded radioactive debris with high activity. However, uniform contamination across the body with a high-activity source is unlikely to deliver a dose to a practitioner that would be of immediate medical concern.

In this paper, it is demonstrated both by example case studies and through computer modeling, that the hazard posed to medical practitioners during the handling of radiologically-contaminated patients is minimal. It is emphasized that, even accounting for the most serious radiological and nuclear accidents on record, no healthcare provider or first responder has been known to receive a dose higher than 27 mSv as a result of handling a contaminated patient[14]. Two physicians have been seriously injured while responding to radiological accidents, but in both cases, their exposure was largely due to contamination at the site and not that on the patients being treated[18].

## Conflict of Interest

The author declares that they have no conflict of interest

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