Risk assessment for occupational potential exposure at cobalt teletherapy units

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ABSTRACT

The occupational potential exposure risk that could occur due to source stuck event at \textsuperscript{60}Co teletherapy facility is estimated. Such risk estimation has been carried out quantitatively and qualitatively using probabilistic safety assessment and risk matrix methods, respectively. The event consequences for workers are evaluated by measuring the effective dose from the occupational potential exposure during the event response. Sets of thermoluminescent dosimeters are placed at different positions corresponding to worker locations while performing the event response procedure. Both of the two estimation methods gave low and acceptable risk as a result of several safety barriers in the facility design and low event consequences. In view of the obtained results in this paper, it is recommended to use the risk matrix method in the future for risk analysis of \textsuperscript{60}Co teletherapy units. Such a safety assessment process is an essential stage for licensing/renewal decision making.

1. Introduction

Safety assessment is a matter of interest for both the operators and regulatory bodies which need formal and credible assurance that the safety objectives are achieved and meets the current safety measures for licensing/renewal decision making. In radiotherapy units, safety assessment aims to ensure that the medical exposure of patients is not over or below the intended ones and the occupational exposure is kept as low as reasonably achievable (ALARA) and below the relevant dose limit. The occupational exposure of any worker should be controlled in order that it does not exceed 20 mSv/year averaged over five consecutive years and does not exceed 50 mSv in a single year (International Atomic Energy Agency, 2014).

In the past, safety assessment did not consider probabilities. It was performed within the facility design basis using Deterministic Safety Assessment (DSA) method. Nowadays, probabilistic safety assessment (PSA) integrated with DSA is the most widespread efficient safety assessment method which is applied to quantify the risk beyond facility design basis including all possible accident scenarios. PSA was established to determine the undesired consequences with its occurrence frequencies and finally implement any required reduction measures. Although PSA has become a standard tool in the safety assessment of Nuclear Power Plant (NPP), it can also be applied to Non-Reactor Nuclear Facilities (NRNFs), e.g. \textsuperscript{60}Co teletherapy units which still find a place in developing countries (International Atomic Energy Agency, 2002). PSA has already been carried out for \textsuperscript{60}Co external beam therapy (Vilaragut et al., 2004), high dose rate Brachy-therapy (Thomadsen et al., 2003) and electron accelerators (Vilaragut et al., 2008).

PSA method has been used to assess both the occupational and medical potential exposure risk resulted either from \textsuperscript{60}Co source teletherapy or sequence of event of a probabilistic nature including equipment failure and operating errors.

The risk matrix method as a risk analysis approach was proposed by the American Forum of nuclear and radiation safety regulatory agencies (FORO) (International Atomic Energy Agency, 2017). Even this method has been used extensively for safety assessment in the industry. It was adapted lately for the safety assessment of \textsuperscript{60}Co teletherapy. It is based on a logical sequence of accidents occurrence while it is characterized by being systematic and simple (International Atomic Energy Agency, 2017).

For the radiological protection of patients, some of the accidents which may cause deviation of the prescribed dose were evaluated where the initiation events (IEs) and contributing factors were analyzed. The frequencies of such accidents vary in dependence on the extent to which the error affect the individual treatment, individual patients, or all patients treated in a specific unit. The highest probabilities are that a patient receives a high dose than prescribed during the whole treatment course or in only one day of the treatment nevertheless, there is low probability that all the patients receive an overdose. Regarding the occupational protection, the

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annual personnel doses received by workers as well as the like hood of potential exposures shall be assessed as part of facility safety assessment which is required for licensing/renewal decision making. The occupational potential exposure risk probabilities should be low as a result of several safety barriers exists in the facility design. The risk that may be occurred due to source stuck accident in $^{60}$Co teletherapy have to be considered where safety assessments focused only on major accidental exposures the overlook of others with significant, but with less severe consequences, which due to their higher probability of occurrence and the absence of sufficient barriers, and hence their combined risk may be higher than that of the major accidental exposures. The failure to maintain cobalt machines in safe operating conditions may result in unnecessary exposures (International Atomic Energy Agency, 2017).

In the present study, PSA and risk matrix methods are applied to assess the occupational potential exposure risk which may be occurred due to source stuck event in $^{60}$Co teletherapy unit such assessment process is useful to decide which method is mostly recommended for risk analysis and required for licensing/renewal decision making.

2. Material and methods

2.1. Consequences of occupational potential exposure during source stuck event

The International Nuclear and Radiological Event Scale (INES) (International Atomic Energy Agency, 2008) is applied to rate source stuck event that result in potential exposure of workers. It is based on the received dose and defense in depth criteria.

The effective dose is measured as a criterion of the event consequences. The source stuck event was simulated in off beam condition to measure the total elapsed time until the worker exercise the following procedure according to (Best-Theratronics, 2013):

(a) Enters the treatment room
(b) Release the patient and
(c) Get the source back into its shielding position.

This event simulation is repeated for different three gantry angles $0^\circ$, $90^\circ$ & $270^\circ$ with a fixed field size $(12 \times 15)$ cm$^2$. In order to measure the average absorbed dose, thermoluminescent dosimeters (TLDs) are placed at different points corresponding to the worker locations in the treatment room. Both PSA and risk matrix methods are applied to estimate the risk quantitatively and qualitatively, respectively, as follow:

2.2. PSA method

This method is performed to estimate the risk quantitatively following the general major procedural steps (International Atomic Energy Agency, 2002):

(i) Facility familiarization: This step requires data collection of the facility depending on the objective of the study. Generally, it should include facility design, different operational processes, and modes, emergency procedures, maintenance, safety analysis reports, etc. Besides sufficient knowledge on safety systems form the basis for the subsequent definition of accidents scenarios. The current study is performed for external beam therapy system/Gamma beam 100–80 model Figure 1. The device is loaded with a $^{60}$Co radioactive source with activity 407 TBq in cylindrical form with a diameter of 2 cm. The device has several incorporated safety features which are source drawer system, off-shield interlock, operational interlocks, inhibited interlocks, emergency stop system and other safety features to reduce the risk of injury or damage. A large air reservoir tank is provided with a pneumatically driven allows the source to cycle from the fully shielded to fully exposed position. A mechanical indicator is retracted in the head when the source is in the fully shielded position and protrudes from the head when the source is in or near the fully unshielded position. Audible and visual indicators are located inside the treatment room and at the control console reflect the source position and unit status. Treatment room door interlock inhibits treatment when the treatment room door is open.
When emergency stop switches is activated, it removes the power from the unit and table motion drive circuits causing the source to return to or remain in the fully shielded position (Best-Theratronics, 2013).

(ii) **Hazards analysis and IEs selection:** Hazards analysis includes hazard identification and evaluation. Radiological and/or non-radiological hazards are identified according to the study objective. Then it should be evaluated through two different analytical methods Failure Modes Effects Analysis (FMEA) or Preliminary Hazards Assessment (PHA) method. The FMEA is a system based on a structured examination performed according to the consequences of systems element failure modes, where the PHA is an accident scenario-based analysis. In PHA, hazardous situations are first postulated then it is followed by a structured investigation of how such a situation could occur. In this present work, the direct radiological hazard; occupational potential exposure which may occur due to source stuck event; is considered. The PHA is applied to postulate the different scenarios which may lead to such hazard. The postulated scenarios could be initiated due to source stuck event.

(iii) **Event sequences modeling and reliability data estimation:** According to the postulated event scenario, event sequence modeling is developed using Event Tree (ET) and Fault Tree (FT) to identify the possible event failure paths. Boolean logic gates are used to construct ET begins with the selected IE and followed by the successive function events that define the success or failure of mitigating functions. FT is a logical model of fault combinations that could cause a mitigating system failure to perform its function, when required it could be incorporated with ET. CAFTA (computer software version 6) is used for logic modeling design and reliability data estimation (Mishra, 2006).

(iv) **Risk Quantification:** The risk is defined in terms of accident probability of occurrence and its consequences where:

\[
\text{Risk} = \text{accident occurrence probability} \times \text{consequences} \tag{1}
\]

A criterion for risk acceptability and management in radiotherapy was proposed as shown in Figure 2; the quantified risk for workers is categorized into three regions (International Atomic Energy Agency, 2017):

(i) Unacceptable region, more than $10^{-4}$ per year
(ii) Tolerable region, from $10^{-4}$ to $10^{-6}$ per year
(iii) Broadly acceptable region, less than $10^{-6}$ per year

2.3. **Risk matrix method**

Risk matrix method is a systematic approach which combines the following relevant potential event features (International Atomic Energy Agency, 2017)

(i) IE frequency (f),
(ii) Consequence for potential event (C),
(iii) Probability of failure of the set of safety measures (P).

Once these features are determined, the risk can be qualitatively categorized into four levels ($R_{VH}$) Very High, ($R_{H}$) High, ($R_{M}$) Medium, or ($R_{L}$) Low using Equation (2) and parameters listed in Tables 1 and 2 where:

\[
\text{Risk} = f \times C \times P \tag{2}
\]
Table 1. Criteria to assign levels for frequency of initiation events (f), consequences (C) and probability of barriers failure (P) ([IAEA, 2017]).

| Qualitative Frequency (f) | Number of events per year | High (f_H) | Medium (f_M) | Low (f_L) | Very Low (f_VL) |
|--------------------------|---------------------------|-----------|-------------|-----------|----------------|
| Consequences (C)         |                           | f ≥ 50    | 1 ≤ f < 50  | 0.05 ≤ f < 1 | f < 0.05       |
| Of workers               |                           |           |             | Medium (P_M) | Low (P_L)       |
| Failure probability of the set (P) | High (P_H)      | No safety barriers in the set |           | Three        |                |
| Number of safety barriers in the set | No safety barriers in the set |           |             | Four or more  |                |

Table 2. Risk matrix ([Ibero and IAEA, 2017]).

3. Results and discussions

3.1. Consequences estimation due to source stuck event scenario

The measured effective dose is presented in Table 3 as a measure of consequences estimation due to source stuck event. The obtained data show that the average effective dose varies with the gantry angle and the worker positions related to beam direction. Also it depends on the time taken by the worker to perform the event response procedure.

3.2. Risk analysis methods

The risk is estimated quantitatively and qualitatively using PSA and risk matrix methods, respectively.

Table 3. Effective dose measured during source stuck event response at different gantry angles and fixed field size of (12 × 15) cm²

| Gantry Angle (degree) | Averaged response total time measured (Sec.) | Exposure time (one minute) | Averaged Absorbed Dose Measured (mSv) |
|----------------------|---------------------------------------------|---------------------------|----------------------------------------|
| Vertical (0°)        | 29.17 ± 3.1                                 | 0.45 ± 0.07               | R_H                                      |
| Lateral (90°)        | 26.55 ± 2.3                                 | 0.3 ± 0.07                | R_H                                      |
| Lateral tangential   | 30.86 ± 4.9                                 | 0.27 ± 0.07               | R_H                                      |

3.2.1. PSA results

The PSA study has been performed, applying the above-described methodology, as the following:

Hazard analysis and IE selection: only the direct radiological hazard (occupational potential exposure) is considered. PHA was applied to postulate the different accident scenarios which may lead to the hazard. Such hazard could be initiated due to the source stuck event during normal operations. According to the facility records, the average source stuck events are 36 events per year.

Event scenario modeling and reliability data estimation: The postulated event scenario ET is shown in Figure 3. ET is constructed based on the facility safety features incorporated into the event response procedure as described in Table 4. Source stuck detection FT shown in Figure 4 is constructed and incorporated into the event scenario ET. Systems/components failure data ([International Atomic Energy Agency, 1988, 1997; Paul and Solanki, 2006]) are used to estimate different safety systems/components failure rates incorporated into event scenario FT& ET and preceded by CAFTA software, in order to obtain the frequency of each event path.
3.2.2. Risk quantification

According to the effective dose measured during source stuck event response where:

1. The measured response time varies from $29.17 \pm 3.1$ to $30.86 \pm 4.9$ s with average $28.86 \pm 3.4$, which is required to enter the treatment room, release the patient and get the source back into its shielding position.

2. The average effective dose calculated per event is $0.17 \pm 0.07$ mSv.

3. The average number of source stuck events recorded per year is $36$ events.

The results show that the occupational potential exposure during performing the source stuck event response procedure due to drawer system failure may reach $6.48$ mSv/year. The effective dose is conservatively calculated on the basis of the maximum time of response.

Although this dose is below the occupational annual dose limit, it is considered as an unjustified dose to the worker and could be avoided. With the passage of time, the systems/components must be checked periodically to prevent its deterioration and failure. Thus, the required maintenance to the source drawer system should be done and the staff adequate training should be maintained to decrease the annual frequency and required time.

The data obtained from the event scenario ET shows that the occurrence probability (annual frequency) of the undesired end state is $3.15E-13$/year, which represents the access to the treatment room combined with safety systems failure and/or human error. This result illustrates that such event scenario rarely occurs. The risk is very low and broadly acceptable by applying the criteria of risk acceptability and management.

3.2.3. Risk matrix results

The risk matrix method is applied to estimate the occupational potential risk exposure due to source stuck accident (as mentioned at Equation (2)). The values of source stuck IEs annual frequency are recorded in average equal $36$/year. The safety system failure probability is selected for three safety barriers sets. The consequences are determined according to the effective dose ranging from $0.27 \pm 0.07$ mSv to $0.45 \pm 0.07$ mSv as it was measured during performing the event response procedure. According to Table 1, the frequency, probability, and consequence are estimated as $f_M$, $P_L$, and $C_L$, respectively. The resultant potential exposure risk as listed in Table 3 is considered as a low risk where: $R_L = f_M \times P_L \times C_L$.

The obtained results from the two methods show that the source stuck event at radiotherapy units has low risk. The low occurrence probability and frequency should be kept by applying periodic maintenance plan for different safety barriers and device components. The keeping of low event consequence required an adequate personnel training for workers in order to maintain low exposure during event response. Results showed that the use of risk matrix method was easier
and simple applicability and had lowering invested efforts during risk assessment in $^{60}$Co teletherapy units.

4. Conclusion

In view of the obtained results, it is concluded that:

1. The occupational potential exposure risk of direct radiological hazard due to source stuck event at $^{60}$Co teletherapy unit has been found of low occurrence probability and low consequences.
2. The source stuck event at $^{60}$Co teletherapy unit is considered as low risk and no reduction measures were recommended for licensing/renewal.
3. The periodic maintenance of different safety barriers and adequate personnel training for workers are required to maintain the low occupational risk.
4. It is recommended to use the risk matrix method in the future for risk analysis of $^{60}$Co teletherapy units and such a safety assessment process is an essential stage for licensing/renewal decision making.

Disclosure statement

No potential conflict of interest was reported by the authors.

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