Radiotherapy Reliability Analysis Based on PSA Method (Postprint)

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Abstract

The reliability of radiotherapy was evaluated and effective approaches were obtained in order to improve radiotherapy quality by using the Probabilistic Safety Assessment (PSA) method. This study investigated the feasibility of the PSA method being applied to radiotherapy through Image-guided Radiotherapy (IGRT) and chest tumor irradiation. A fault tree has been constructed after analyzing causal relationship of the events. After calculating RiskA, a total inaccuracy radiotherapy probability and the importance of all base events were obtained. The probability of inaccurate radiotherapy was 2.87%. Under the condition that the target delineation was perfectly right, the accuracy of radiotherapy significantly improved. With the calculation without Cone-beam Computed Tomography (CBCT) being corrected before irradiation, the accuracy significantly decreased. The most important events were connected with the human factor. Improving human technical level could enhance radiotherapy quality control efficiently.

Full Text

Preamble

Radiotherapy Reliability Analysis Based on PSA Method

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This study evaluated radiotherapy reliability using the Probabilistic Safety Assessment (PSA) method to identify effective approaches for improving radiotherapy quality. We investigated the feasibility of applying PSA to radiotherapy through Image-guided Radiotherapy (IGRT) for chest tumor irradiation. After analyzing the causal relationships of events, we constructed a fault tree and calculated the total probability of inaccurate radiotherapy and the importance of all base events using RiskA. The probability of inaccurate radiotherapy was 2.87%. Radiotherapy accuracy improved significantly when target delineation was perfectly accurate, while accuracy decreased substantially without Cone-beam Computed Tomography (CBCT) correction before irradiation. The most critical events were related to human factors, indicating that improving technical proficiency could efficiently enhance radiotherapy quality control.

Keywords: Probabilistic safety analysis, Accurate radiotherapy, Reliability, Quality control, RiskA
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INTRODUCTION

Accurate radiotherapy focuses on enhanced reliability and safety. Ideal accuracy requires precise planning of the target volume, actual dose delivery, and dose distribution [1]. Despite numerous efforts to improve radiotherapy reliability, cases of inaccurate irradiation still occur in clinical practice due to unskilled staff or equipment issues. Currently, there is no quantitative definition of accurate radiotherapy—only descriptive terms exist. Meaningful analysis requires a reasonable definition of accuracy, with standards that depend on tumor location, though tumors in the same location share the same accuracy standard. Additionally, an effective method was needed to analyze the entire radiotherapy process, particularly for the complex dynamic system of interactions between human and machine factors.

The Probabilistic Safety Assessment (PSA) method has been widely applied in nuclear power stations for many years. As an efficient approach for complex system analysis, PSA has been used in aerospace, aviation, chemical engineering, and the nuclear field. The authors have previously applied PSA to assess radiotherapy reliability and safety [2]. The advanced nuclear energy research team, FDS (Fusion Design and Study), has conducted extensive research on nuclear safety [3-7] and developed a Reliability and Probabilistic Safety Assessment Program named RiskA [8-10]. This software was the first probabilistic safety assessment program applied to real-world nuclear power plants in China. Building on preliminary studies of accurate radiotherapy physics and technology [11-15], this paper analyzes radiotherapy reliability based on the PSA method. After calculation with RiskA, we obtained the total probability of inaccuracy and the importance of all base events, along with all minimum cut sets. This quantitative data is crucial for radiotherapy quality control, enabling clinicians and physicists to improve irradiation efficiency by focusing on the most important events.

METHODS

A. Experiment Conditions

This study is based on chest tumor cases and an Image-guided Radiotherapy (IGRT) system with online Cone-beam Computed Tomography (CBCT) correction. The cases were obtained from a static hospital radiotherapy center. The experimental conditions were: patients received chemotherapy before mid-tumor treatment; an Elekta linear accelerator (Precise) with KV magnitude CBCT; Electronic Portal Imaging Device (EPID) radiation field validation performed once weekly; and use of the same simulation machine, treatment planning system, and treatment team.

B. Definition of the Top Event

In this paper, the top event is defined as inaccurate radiotherapy. Based on clinical experience and various synthesized documents of radiotherapy quality requirements, IGRT inaccuracy for chest tumors is defined as follows.

1. Irradiation targets stray from planned target by more than 1 cm. While millimeter-level accuracy is widely recognized in modern radiotherapy, the specific deviation limit is not universally determined. In conventional radiotherapy, human movement up to 2–3 cm in the cranio-caudal direction was common [16]. Without respiratory gating or other approaches to compensate for breathing, a total deviation within 1 cm is acceptable. The dose distribution to Gross Tumor Volume (GTV) and organs at risk (OAR) would be seriously affected if the position strayed more than 1 cm [17]. Baler et al. [18] noted that the target would lose 6 cm if setup errors exceeded 1 cm.

2. Deviation of dose delivery to planned target exceeds $±$5% and dose distribution does not satisfy plan assessment.
ICRU Report No. 24 indicates that if the deviation of dose delivery to a planned target exceeds $±$5%, the primary tumor lesion would be uncontrolled and complications would increase. The Radiation Therapy Oncology Group (RTOG) documents 0225 and 0615 provide target dose limitations to OAR. RTOG No. 0418 protocols list requirements for dose plan assessment and prescription dose [19].

C. Building Fault Tree

We first analyzed the process of all selected radiotherapy cases. The general stages of IGRT radiotherapy in this study are shown in Fig. 1 [Figure 1: see original paper]. A fault tree was built retrospectively by analyzing the whole process down to specific procedures or device functions, known as basic events. The resulting fault tree is shown in Fig. 2 [Figure 2: see original paper].

D. The Probabilities of Base Events

Every base event has a probability, even if it was not recorded at the time. The probabilities for each event are shown in Table 1 . Probabilities were obtained through the following methods: (1) Empirical data: Most base event probabilities were derived from clinical experience. For example, the probability of misdiagnosis was calculated as the frequency of misdiagnosis divided by irradiation times over past years. (2) Maintenance data: Some equipment data came from examination and repair records, where probability was based on fault frequency. (3) Hindsight analysis: Some mistakes were not realized at the time, requiring retrospective analysis. (4) Analog statistics: This simulation approach involved multiple users outlining the same tumor. For instance, ICRU reported that the World Health Organization (WHO) organized 12 clinical experts to sketch the same tumor, and the difference in volumes they outlined nearly doubled [20]. (5) Literature review: Summarizing results from related literature and data.

E. Calculation Using RiskA

We constructed a fault tree in RiskA with the same configuration as Fig. 1. All basic data was input into the tree leaves (base events) and calculated. The analysis focused on uncertainties and importance measures, including Fussell-Vesely importance (cut-set importance), RAW (Risk Achievement Worth) importance, and RRW (Risk Reduction Worth) importance. The final outcomes were obtained through the calculation and analysis functions. The entire calculation process was very convenient.

RESULTS

A. The Probability of Top Event

Based on the data in Fig. 1 and Table 1, the probability of the top event was 2.87%, as shown in Table 2 . If the probability of target delineation errors is set to "0" (assuming completely accurate target delineation), the probability of the top event decreases to 1.18%, representing a significant drop in overall probability. Without online CBCT correction, the probability of the top event increases to 5.09%, with cases of inaccuracy rising substantially.

B. The Importance of Minimal Cut Sets

Minimal cut sets represent the minimal combination of base events that lead to the top event. All key paths and their importance rates are listed in Table 3 . The top event will be reduced accordingly if any base event is eliminated. This effect is called Risk Reduction Worth (RRW). Contribution rates for reducing main base events were calculated using RiskA' s importance function. As shown in Table 4 , the most important event was inaccurate delineation, followed by lesion diagnosis error, and third, misoperation in dose delivery. In the calculation results, the Risk Achievement Worth (RAW) values of base events were almost identical, so RAW data is not listed in this paper.

DISCUSSION AND CONCLUSION

A. Assessment of Accurate Radiotherapy

Accurate radiotherapy requires expensive equipment and complex operations, making accuracy critically important for cancer patients and physicians. The 2.87% probability of inaccuracy warrants significant attention. These results demonstrate that the PSA method should be applied in the radiotherapy field to assess reliability.

B. The Important Reasons Leading to Inaccuracy

Table 3 shows that the most important event was inaccurate delineation, with an importance percentage of 14.68% in the minimal cut sets. Assuming completely accurate target delineation would reduce the probability of the top event by half. Table 4 demonstrates that improving delineation technical level is the most efficient method to enhance radiotherapy accuracy. However, at a given delineation technical level, quality can be improved by better approximating the biological target [23]. In the future, biological target recognition technology could further improve irradiation accuracy [24]. Overall, almost all important factors are closely related to human factors. For example, the most important events in the fault tree structure were inaccurate delineation and diagnostic error. As reported in the literature, most radiotherapy errors are attributed to human mistakes or inattention [25].

C. The Importance of CBCT to Positioning Accuracy

Literature has demonstrated the importance of CBCT for positioning accuracy [26, 27]. As shown in Table 2, without CBCT correction, the probability of inaccuracy increases to 5.69%, nearly doubling. CBCT can correct most organ deviations before actual treatment, addressing positional errors for the target and critical structures immediately prior to or during treatment. Sometimes it can even identify the wrong patient, leading to safer treatment [28]. As shown in Table 1, based on clinical experience, the probability that deviation error would exceed 1 cm after CBCT correction was only 0.8/1000.

D. Guidance to Clinical Radiotherapy and Quality Assurance

This research verified that the PSA method can be applied more broadly to provide quantitative data for engineering quality control. As a credible software application [29], RiskA should serve as an assessment platform for radiotherapy reliability. Focus on safety and reliability is an important feature of ARTS [30, 31]. The quality control function could be improved by integrating quantitative data from this study. Hospital and administrative management should use this method at different levels with different combinations to analyze radiotherapy reliability and assess the quality of accurate radiotherapy. Based on results calculated by RiskA, weak links can be identified and radiotherapy quality improved by addressing these vulnerabilities. For example, dose reliability can be developed by improving the dose calculation method [32]. Additionally, analyzing human factor reliability can reveal methods to improve operational reliability. By verifying the reliability of multiple radiotherapy units, the overall radiotherapy reliability level can be assessed. This data can then be combined with clinical opinions to establish an expectative radiotherapy standard pattern for guiding practice. In conclusion, analyzing radiotherapy reliability based on the PSA method is of great significance for formulating objective standards and quality assurance.

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