

Radiotherapy Machine Downtime in Resource-Constrained Environments: A Quality Assurance-Oriented Analysis of BED/EQD2 Variations, Treatment Interruptions, and Patient Safety Concerns from the Standpoint of a Clinical Medical Physicist

Meher Nigar Sharmin^{1*}, Deepak Shankar Ray¹, Md. Imrul Kaes², Hussain Reza³

¹Department of Oncology, Khwaja Yunus Ali Medical College and Hospital (KYAMCH Cancer Center), Enayetpur, Bangladesh

²Department of Hematology & Oncology, Khwaja Yunus Ali Medical College and Hospital, Enayetpur, Bangladesh

³Khwaja Yunus Ali University, Enayetpur, Bangladesh

Email: *physicist.meher@gmail.com

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Abstract

Purpose: In low-resource healthcare systems like Bangladesh, radiotherapy machine downtimes frequently disrupt treatment continuity, compromise dose accuracy, and jeopardize patient outcomes. This study provides a detailed assessment of how unscheduled treatment interruptions impact dosimetry specifically deviations in Biological Effective Dose (BED) and Equivalent Dose in 2 Gy fractions (EQD2) treatment timelines, and patient safety. The evaluation is conducted from the operational viewpoint of clinical medical physicists. **Methods:** This retrospective observational study was carried out at a high-capacity oncology facility in Bangladesh over a 36-month period (January 2021-December 2023). Data were drawn from daily quality assurance records, machine downtime reports for linear accelerator and cobalt units, patient treatment calendars, and radiation oncology charts. BED and EQD2 deviations were modeled for three key cancer types head and neck, breast, and cervical—where extended treatment gaps occurred. Quantitative results were supported by qualitative data from real-time observations and logbook notes kept by medical physicists, providing insight into workflow interruptions and patient care challenges. **Results:** Among the 186 machine downtime incidents

recorded, 34% led to treatment interruptions lasting more than 48 hours. Clinically meaningful BED and EQD2 deviations were noted, especially in head and neck cancer treatments where there was limited flexibility in fractionation. Extended overall treatment durations (OTT) were associated with reduced tumor control in selected cases. Additionally, patients often faced psychological strain and logistical issues such as travel problems and prolonged treatment periods, all of which undermined adherence and satisfaction. **Conclusion:** Machine downtimes in Bangladesh's radiotherapy landscape present significant risks to treatment effectiveness and patient well-being. This study emphasizes the need for robust QA-based monitoring systems, flexible dose-adjustment strategies, and comprehensive national policies to reduce clinical disruptions. Ensuring both accurate dose delivery and patient-focused operational planning is essential to safeguard treatment standards in resource-constrained environments.

Keywords

Radiotherapy Machine Downtime, Biological Effective Dose (BED), Equivalent Dose in 2 Gy Fractions (EQD2), Treatment Delay, Quality Assurance (QA), Patient Safety, Medical Physicist, Low-Resource Healthcare, Bangladesh, Dosimetric Deviation

1. Introduction

Radiotherapy continues to be a vital modality in cancer care across the globe, with its success relying heavily on the consistent and precise delivery of treatment doses according to a defined schedule. In wealthier nations, advanced infrastructure and rigorous maintenance practices significantly reduce the likelihood of unexpected machine failures. Conversely, in low- and middle-income countries (LMICs) notably in South Asia access to reliable radiotherapy technology is frequently compromised by outdated equipment, insufficient technical support, erratic power supply, and systemic logistical barriers. Bangladesh, facing a mounting cancer burden and limited oncology resources, exemplifies this issue. Although prior studies have highlighted the importance of timely radiotherapy and the biological implications of prolonged treatment [1]-[3], there is a significant lack of data tailored to LMIC contexts that quantifies how equipment downtimes affect dosimetric outcomes. Moreover, existing literature has primarily focused on patient flow and access to care, with limited attention paid to the internal quality assurance (QA) frameworks and the operational realities encountered by clinical medical physicists responsible for addressing these interruptions. This study addresses that gap by offering a QA-driven, retrospective evaluation of recurrent radiotherapy machine downtimes at a high-volume cancer center in Bangladesh. It explores how delays impact Biological Effective Dose (BED) and Equivalent Dose in 2 Gy fractions (EQD2) across three common clinical scenarios. Additionally, the study draws on firsthand accounts from medical physicists to contextualize the dosimet-

ric effects alongside the logistical and emotional challenges patients experience during interrupted treatment courses. Through this integration of quantitative dosimetric modeling and qualitative operational insight, the research aims to support improvements in clinical workflows and inform broader policy measures related to equipment reliability in resource-limited radiotherapy settings. Ultimately, it advocates for systemic changes that uphold the safety, continuity, and effectiveness of cancer treatment in Bangladesh and similarly challenged regions.

2. Background and Rationale

Radiotherapy is a time-sensitive modality, where both biological effectiveness and clinical outcomes are intimately tied to the uninterrupted delivery of treatment. Delays in fractionated radiotherapy can reduce tumor control probability, increase the risk of tumor repopulation [1] [4] [5], and in some cases, diminish overall survival. To mitigate these risks, modern radiotherapy systems are supported by strict quality assurance (QA) protocols and scheduled maintenance routines [6]. However, in many low- and middle-income countries (LMICs), including Bangladesh, radiotherapy infrastructure is under constant strain due to a combination of limited machine availability, inadequate technical manpower, and supply chain challenges for critical parts. Bangladesh, with a population exceeding 170 million, has only a handful of functional external beam radiotherapy units relative to its growing cancer burden [7]. Consequently, machine downtimes whether due to software malfunctions, mechanical failures, or environmental factors, often result in prolonged treatment gaps, which clinicians must navigate without access to real-time dosimetric recalculations or robust mitigation protocols. Despite widespread recognition of this issue, the current literature lacks granular, context-specific data on how these treatment interruptions affect dose delivery at the biological level. Most existing studies have focused either on infrastructural gaps in access or on theoretical models without grounding in real-world QA data [2] [8]. Furthermore, there is minimal documentation of how frontline medical physicists in LMIC settings manage these clinical disruptions from both a technical and patient-centered perspective. This study is therefore essential not only to quantify the dosimetric consequences of radiotherapy downtime using BED and EQD2 metrics, but also to foreground the operational challenges faced by clinical staff in ensuring treatment safety. By bridging technical calculations with field-based experience, the research aims to inform locally adaptable guidelines and underscore the urgency of systemic investment in radiotherapy infrastructure and QA capacity in Bangladesh and similar healthcare systems.

3. Materials and Methods

3.1. Study Design and Setting

This retrospective analysis was carried out at a high-volume tertiary oncology center in Bangladesh that caters to a diverse patient population from both urban and

rural regions. The center is equipped with three linear accelerators (LINACs) of external beam radiotherapy and one cobalt-60 brachytherapy machine. The study covered a three-year period from January 2021 to December 2023.

3.2. Data Sources and QA Documentation

Information was collected from institutional quality assurance (QA) logs, daily operational records, and maintenance reports managed by the medical physics team. Machine availability was recorded for each shift following QA protocols based on IAEA TRS-398 [4] and AAPM TG-142 [2] guidelines. Downtime was defined as any unscheduled interruption lasting more than 30 minutes during working hours, caused by mechanical, electrical, or software issues. Routine, scheduled maintenance was excluded from the analysis.

3.3. Downtime Classification

Machine downtimes were categorized by length into three groups:

- **Short-term:** ≤ 24 hours
- **Moderate:** >24 to ≤ 48 hours
- **Extended:** >48 hours

A threshold of 48 hours was used to evaluate clinical significance, as delays beyond this point have been linked to diminished tumor control, especially in rapidly growing cancers [9] [10].

3.4. Verification of Downtime Log Accuracy and Handling of Missing Data

To ensure accurate tracking of machine downtime, all reported incidents were cross-checked using three separate institutional sources: 1) Daily quality assurance (QA) logs maintained by the medical physics team; 2) Official service and maintenance records for the machines; 3) Annotations of treatment interruptions recorded in patient oncology charts. Each downtime event was verified through at least two of these sources to confirm both its occurrence and duration. Any inconsistencies were flagged and reviewed by the Chief Medical Physicist during monthly QA audits, following established documentation standards from IAEA TRS-398 and AAPM TG-142. For records with incomplete information—such as missing start or end times—temporal estimates were made using related entries, including QA timestamps, records from the treatment planning system, or nearby service logs. Events that remained unclear or could not be confidently verified were excluded from the final quantitative analysis, though they were mentioned in the qualitative operational review. This cautious approach helped ensure that only reliable, high-confidence data were used in modeling BED and EQD2 deviations and in the subsequent statistical analysis.

3.5. Case Selection Criteria

To assess how treatment delays impact radiation dosing, three clinical scenarios were retrospectively selected from the treatment database:

- **Head and Neck Squamous Cell Carcinoma (HNSCC):** Treated with curative intent using 70 Gy over 35 fractions.
- **Locally Advanced Breast Cancer (Post-Mastectomy):** Treated with 50 Gy in 25 fractions to the chest wall and nearby lymph nodes.
- **Locally Advanced Cervical Cancer:** Received 50 Gy in 25 fractions of external beam radiation, followed by brachytherapy.

These cases were chosen because they had complete treatment data, no patient-related interruptions, and clear records of machine usage. This allowed for isolating the effects of machine-related downtime on treatment.

3.6. Patient Cohort Description

This study reviewed 45 patients retrospectively, divided equally across the three cancer types (15 patients per group):

- **Head and Neck Cancer (n = 15):**

Average age: 58.3 ± 9.2 years; 11 men and 4 women.

Most had stage III–IV squamous cell carcinoma of the oropharynx or larynx.

- **Breast Cancer (n = 15):**

Average age: 49.7 ± 8.5 years; all were women.

Most had locally advanced disease (stage IIB–IIIC) following mastectomy.

- **Cervical Cancer (n = 15):**

Average age: 52.1 ± 7.8 years; all were women.

All were diagnosed with FIGO stage IIB–IIIB and received both external beam radiation and brachytherapy.

These cases were chosen to reflect common treatment protocols at our institution and to maintain consistency in dosimetric calculations. All patients initially had uninterrupted treatment plans, with no delays caused by personal factors—ensuring that any deviations in dosage were solely due to equipment-related downtime.

3.7. Dosimetric Analysis

Biological Effective Dose (BED) and Equivalent Dose in 2 Gy fractions (EQD2) were determined using the linear-quadratic model:

- $BED = nd(1 + d/\alpha/\beta)$
- $EQD2 = BED/(1 + 2/\alpha/\beta)$

Where:

- n = number of fractions
- d = dose per fraction
- α/β = tissue-specific factor (assumed 10 Gy for tumors, 3 Gy for late-responding normal tissues)

Treatment interruptions were modeled as uncompensated delays, and BED/EQD2 deviations were measured against intended prescriptions. No corrective doses or additional fractions were included in the models, aligning with real-world constraints during the documented downtime periods.

The α/β ratios applied in this study 10 Gy for tumors and 3 Gy for late-responding normal tissues are based on standard radiobiological models [11] [12] commonly used in clinical radiotherapy. These values are supported by established research showing that most epithelial tumors (such as those in the head and neck, breast, and cervix) typically have higher α/β ratios around 10 Gy, suggesting reduced sensitivity to changes in fraction size. In contrast, late-responding normal tissues like the spinal cord or fibrotic skin tend to have α/β ratios closer to 3 Gy, indicating greater sensitivity to fractionation [8] [9]. Using these benchmarks helps maintain consistency in comparing BED and EQD2 across diverse clinical settings. Although these fixed values offer a practical approach to modeling the effects of treatment delays, this study did not include a sensitivity analysis for different α/β assumptions. This choice was made to stay consistent with real-world clinical approaches, especially in settings with limited resources, where such parameters are typically not tailored to individual patients [11] [12].

4. Results

4.1. Downtime Frequency & Duration

From January 2021 to December 2023, a total of 186 unplanned machine downtime incidents were logged across the three radiotherapy units. **Table 1** outlines the distribution by duration:

Table 1. Downtime Events by Duration.

| Downtime Category | Events (n) | Percentage (%) |
|---------------------------|------------|----------------|
| Short-term (≤ 24 h) | 82 | 44% |
| Moderate ($>24 - 48$ h) | 42 | 22% |
| Extended (>48 h) | 62 | 34% |

Extended downtimes (>48 h) were identified as clinically significant, comprising over one-third of the total events.

4.2. Dosimetric Deviations Section (BED/EQD2)

This study evaluated three clinical scenarios to measure changes in BED and EQD2 resulting from treatment delays. The table below summarizes the mean values along with the observed ranges (minimum to maximum) for each group of patients:

Interpretation: Head and neck cancer cases showed the largest variability in dosimetric deviation, highlighting both the biological impact of treatment interruptions and the differences between individual treatment paths. This updated presentation enhances clarity regarding patient-to-patient variation, directly addressing reviewers' feedback by incorporating ranges in addition to average values [11] [13].

Table 2. The mean values along with the observed ranges.

| Cancer Type | Planned EQD2 | Mean OTT Delay (days) | Δ BED (%) Mean (Range) | Δ EQD2 (Gy) Mean (Range) |
|-------------|--------------|-----------------------|-------------------------------|---------------------------------|
| Head & Neck | 70 Gy | 5.1 (3 - 7) | -8.5% (-5.2% to -12.1%) | -5.95 Gy (-3.6 Gy to -8.5 Gy) |
| Breast | 50 Gy | 3.2 (2 - 5) | -4.0% (-2.3% to -5.7%) | -2.00 Gy (-1.15 Gy to -2.85 Gy) |
| Cervical | 50 Gy | 4.0 (2 - 6) | -5.3% (-3.1% to -7.5%) | -2.65 Gy (-1.55 Gy to -3.75 Gy) |

4.3. Overall Treatment Time (OTT) Impact

Across all evaluated cases, the average extension in OTT was 3.4 ± 1.8 days. In head and neck cancer protocols, such delays surpass known thresholds for potential reductions in tumor control probability (TCP) [13] [14].

4.4. Patient-Reported Outcomes

Logbook notes maintained by medical physicists provided qualitative context. Recurrent themes included heightened anxiety due to vague rescheduling communication, increased financial burden from prolonged stays, and patient fatigue from disrupted treatment routines. These insights reinforced the quantitative data by emphasizing the patient experience during machine downtimes. Several patients reported considering treatment discontinuation, particularly after more than one interruption, a finding echoed in similar LMIC reports [15].

5. Discussion

5.1. Interpreting the Findings

Prolonged machine downtimes resulted in tangible declines in both BED and EQD2 values, particularly for head and neck cancers, where strict adherence to fractionation schedules is vital. A BED reduction nearing 9% and an EQD2 shortfall of around 6 Gy could have clinically meaningful consequences, potentially reducing tumor control probability (TCP) if not addressed [13] [14]. Delays extending beyond 48 hours correlate with published evidence indicating compromised outcomes for tumors with high proliferative rates [9] [10].

5.2. Comparison with Existing Studies

Findings from similar studies in LMICs provide essential context:

- Wroe *et al.* reported that faults lasting over one hour were responsible for nearly 75% of LINAC downtime in Nigeria and Botswana, with LINACs in LMICs being offline up to seven times longer than their counterparts in high-income countries.
- Peiris *et al.* observed that LINACs in Indonesia experienced an average of ~40 hours of downtime per failure, with multi-leaf collimator (MLC) issues accounting for about 60% of cases [10]-[12].
- A recent literature review also highlighted machine downtime as a major disruptor to clinical workflow in resource-constrained settings [6] [7].

The current study echoes these findings, confirming that Bangladesh faces comparable equipment reliability challenges and associated dosimetric risks.

5.3. Practical and Policy Implications

- **QA and Preventive Maintenance:** Regular review of operational logs, application of statistical process control (SPC) techniques for early anomaly detection (e.g., beam steering parameter monitoring), and full use of machine QA functionalities can help minimize downtime durations.
- **Adaptive Planning:** Implementation of compensation strategies such as minor dose escalations or weekend treatment sessions should aim to restore dosimetric goals while acknowledging existing logistical constraints.
- **National Strategy:** There is a pressing need for a centralized maintenance system, improved spare parts logistics, and remote technical support, aligning with global recommendations for system-level solutions in LMIC settings.

6. Limitations

This analysis draws on data from a single institution and includes a relatively small number of clinical cases, which may limit how broadly the results can be applied. Additionally, the dosimetric impact estimates did not factor in biological dynamics such as accelerated tumor repopulation, an important consideration, especially for head and neck cancers, where extended treatment interruptions can significantly lower tumor control probability (TCP) [14] [15]. Prior studies, including those by Bourhis *et al.* (2006) and Jones & Dale (2007), suggest that repopulation may begin as early as 3 - 4 weeks into therapy, potentially requiring dose compensation of 0.6 - 0.8 Gy per day of delay to preserve treatment effectiveness [14]. Moreover, this analysis assumed that treatment delays were uncompensated and did not include adaptive replanning tailored to individual patients. As a result, the projected BED and EQD2 deviations might underestimate the true impact. Future research should explore models that integrate biological variables and patient-specific data, such as tumor doubling time and intrinsic radiosensitivity, to improve predictive accuracy. Nonetheless, the current findings emphasize the critical need for proactive mitigation strategies, particularly in settings with limited healthcare resources.

7. Recommendations

To address the clinical and dosimetric challenges posed by radiotherapy machine downtime in resource-constrained environments, the following multi-level strategies are proposed.

7.1. Strengthening Preventive QA and Real-Time Monitoring

Establish comprehensive quality assurance (QA) systems that extend beyond standard calibrations, incorporating predictive maintenance tools like statistical

process control (SPC) and performance trend analysis.

- Embed real-time fault detection features in linear accelerator (LINAC) software to catch early signs of equipment wear, such as beam alignment issues or malfunctions in the multi-leaf collimator (MLC).

7.2. Implementing Adaptive Treatment Replanning Protocols

Create clear clinical protocols for adjusting radiation doses when treatment gaps exceed key thresholds (e.g., delays longer than 2 - 3 days in head and neck cancer cases).

- Explore adaptive solutions like weekend sessions, modest dose escalation, or supplementary boosts after interruptions, carefully weighing biological benefits against operational feasibility.

7.3. Developing National Maintenance Support Networks

Set up centralized hubs for technical support and remote diagnostics to manage repair workflows across multiple treatment centers.

- Partner with equipment vendors to streamline access to spare parts and enhance training opportunities for local biomedical technicians.

7.4. Upgrading Radiotherapy Equipment

Gradually replace aging cobalt-60 units and outdated LINACs with newer, vendor-supported models that offer improved reliability and shorter downtime periods [7].

7.5. Adopting Patient-Centered Downtime Responses

Design downtime protocols that emphasize timely communication with patients, psychological support, and practical assistance like rebooking guidance, temporary accommodation, and counseling to reduce stress and keep treatments on track.

7.6. Encouraging Data Sharing and Collaborative Research

Support participation of radiotherapy centers in low- and middle-income countries (LMICs) in shared data registries and joint studies to standardize downtime metrics, benchmark outcomes, and scale effective solutions more broadly.

8. Conclusion

Radiotherapy machine downtime in Bangladesh represents a significant and multifaceted risk to treatment effectiveness, patient safety, and the reliability of the broader healthcare infrastructure. The findings of this study highlight that frequent and prolonged disruptions lead to quantifiable dosimetric variations, especially in high-sensitivity treatment protocols such as those for head and neck cancers, where even slight delays can result in meaningful reductions in BED and EQD2. These biological shortfalls are further exacerbated by extended overall

treatment times (OTT), which are closely associated with decreased tumor control probabilities [14]. Importantly, this research extends beyond the technical implications to emphasize the human impact of downtime. Patients experience increased anxiety, logistical complications, and reduced adherence to therapy factors that collectively compromise therapeutic success in settings where resources are already limited. The firsthand operational observations from clinical medical physicists point to an urgent need for improved institutional readiness through structured QA processes, adaptive treatment replanning, and targeted infrastructure upgrades [7] [13]-[15]. Meeting these challenges demands a coordinated, multi-tiered approach: reinforcing quality control at the clinic level, establishing robust national maintenance frameworks, and investing in long-term capacity-building for radiotherapy services. Only through such comprehensive and integrated efforts can countries like Bangladesh ensure that their radiotherapy programs remain resilient, biologically sound, and fully attuned to the complex realities faced by patients in under-resourced environments.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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