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# Sustaining Excellence in Radiotherapy: Breakthroughs in Linear Accelerator Uptime and Operational Efficiency

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**Abstract**

**Linear accelerators (Linacs) are critical components in radiotherapy departments, and their downtime can significantly impact patient care. This study analyzes the causes and impacts of linac downtime, focusing on subsystem failures, failure modes, and strategies to minimize downtime. This study addresses linac downtime by leveraging methodologies from key studies: the Royal College of Radiologists (RCR) guidelines for managing interruptions, Kawahara et al.'s Machine Failure Risk Analysis (MFRA), Hoisak et al.'s longitudinal machine log analysis, Wroe et al.'s international downtime comparisons, and Peiris et al.'s insights on LINAC and MLC failures in LMICs. Using these frameworks, we formulated strategies including preventive maintenance, usage-based quality assurance (QA), backup systems, and comprehensive staff training. These efforts resulted in a landmark achievement: 900 consecutive days of uninterrupted radiotherapy treatment with a single linac. This study provides actionable solutions to minimize downtime, enhance reliability, and ensure equitable access to high-quality cancer care globally.**

**Keywords: Linear accelerator, radiotherapy, downtime, preventive maintenance, usage-based quality assurance, LMICs, HICs**

## Introduction

Linear accelerators (linacs)[1,2] are the cornerstone of modern radiotherapy, delivering life-saving precision in the fight against cancer. These sophisticated machines, with their intricate subsystems—beam generation, imaging systems, multi-leaf collimators (MLCs), cooling systems, and patient support systems (Fig. 1(a), Fig. 1(b), Fig. 1(c))—are marvels of engineering. Yet, their complexity comes at a cost: susceptibility to technical failures. When a linac goes down, the ripple effects are profound. Treatment schedules are disrupted, patient outcomes are jeopardized, and the burden on healthcare staff intensifies. In high-throughput radiotherapy departments, even a brief interruption can cascade into delays, errors, and compromised care.

The challenge of linac downtime is not evenly distributed. In low- and middle-income countries (LMICs), where resources are scarce and access to spare parts and technical expertise is often delayed, the impact is particularly devastating. In contrast, high-income countries (HICs) benefit from robust maintenance protocols, faster technical support, and advanced infrastructure, resulting in significantly shorter downtimes. The impact of linac downtime is particularly severe in low- and middle-income countries (LMICs), where resources are limited, and access to spare parts and technical expertise is often delayed. In contrast, high-income countries (HICs) typically have more robust maintenance protocols and faster access to technical support, resulting in shorter downtimes. This study aims to analyze the causes of linac downtime, identify the most frequently failing subsystems, and propose strategies to minimize downtime. By comparing data from HICs and LMICs, the study also highlights the unique challenges faced by LMICs and suggests ways to improve linac performance in these settings.

**Methods and Materials:**

This study utilized a multi-faceted approach to enhance the reliability and efficiency of radiotherapy treatment delivery in our clinic.

*Review of Established Guidelines:* We referenced the fourth edition of the "Radiotherapy Dose Fractionation" guidance by the Royal College of Radiologists (RCR) to establish protocols for managing unscheduled treatment interruptions.

*Machine Failure Risk Analysis (MFRA) Implementation:* We implemented the Machine Failure Risk Analysis (MFRA) methodology, as described by Kawahara et al., to quantify and mitigate the risks associated with linear accelerator (linac) failures. This involved data collection, risk scoring, and preventative measure implementation.

*Longitudinal Analysis of Machine Logs:* We adopted the principles outlined by Hoisak et al. for longitudinal analysis of linac machine logs. This included establishing a cloud-based machine log system, data analysis, and targeted maintenance scheduling.

*Comparative Downtime Analysis:* We incorporated the comparative analysis approach from Wroe et al., comparing our Linac downtime and failure modes with those reported in various international settings. This involved detailed logbook maintenance and subsystem analysis.

*Failure Mode and Downtime Analysis Specific to LINACs and* MLCs*:* We referenced the study by Peiris et al. analyzing failure modes of LINACs and MLCs, particularly in low- and middle-income countries (LMICs). We applied its principles to gather data, develop preventative maintenance schedules, and improve component management, with a focus on Multi Leaf Collimators (MLCs).

*Data Collection and Analysis:* We established systems for collecting and analyzing data on machine failures, downtime, and maintenance activities. This included both manual logbooks and digital tracking systems.

*Preventative Maintenance and Quality Assurance:* We developed and implemented targeted preventative maintenance schedules and quality assurance protocols based on the analysis of collected data and referenced studies.

*Staff Training and Collaboration:* We provided staff training on data logging, failure mode identification, and maintenance procedures. We also fostered collaboration with linac manufacturers and other institutions to share knowledge and best practices.

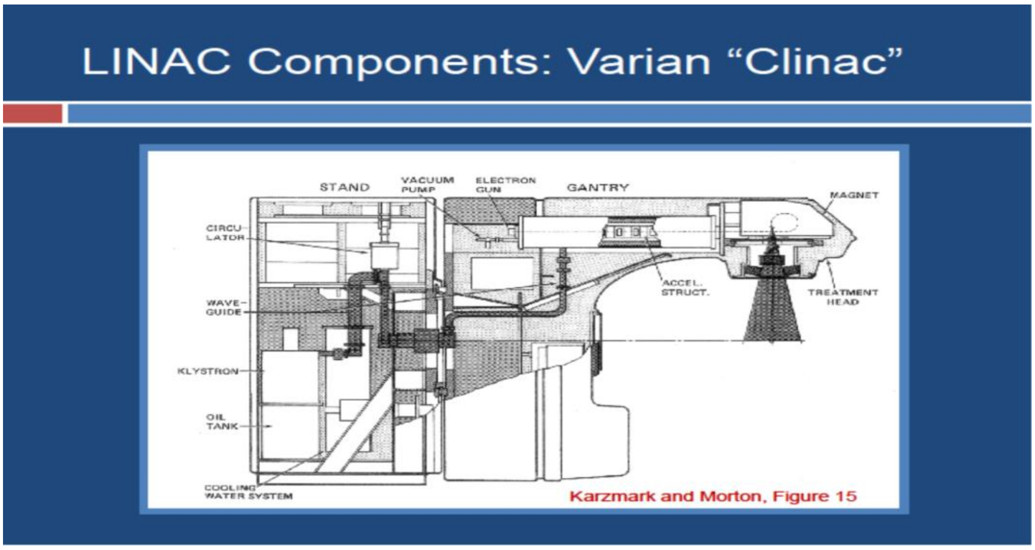


**Fig.1(a)-linac Components-Varian Clinac**

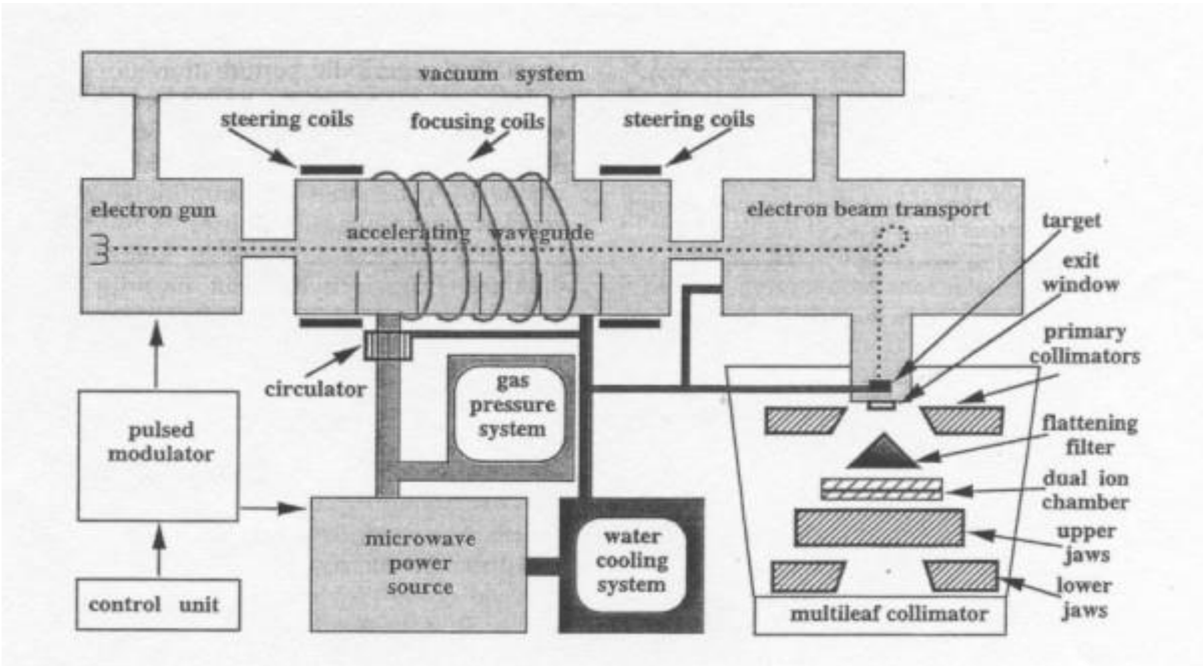


**Fig.1(b): Linac Components**

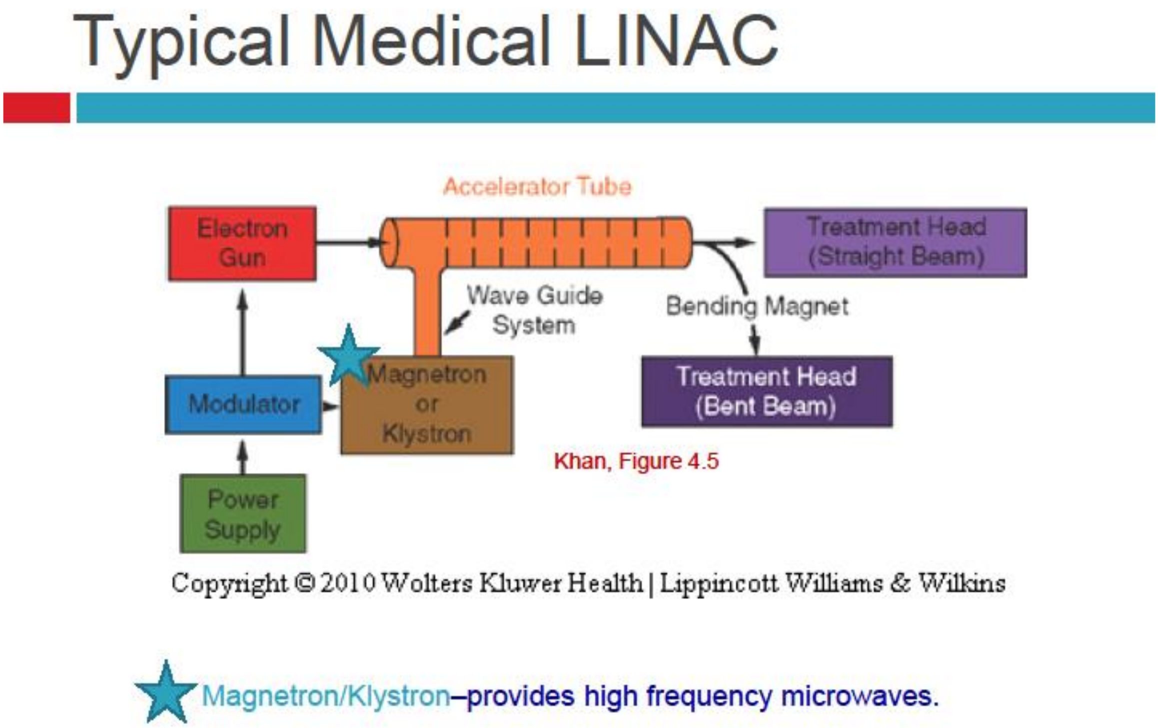


**Fig.1(c): typical Medical Linac**

**Results and Discussion:**

**Royal College of Radiologists Guidelines for Unscheduled Treatment Interruptions:[12]**

To ensure the continuity and efficacy of radiotherapy treatments, I meticulously implemented the guidelines outlined in the fourth edition of the "Radiotherapy Dose Fractionation" document published by the Royal College of Radiologists (RCR). This comprehensive reference serves as a cornerstone for clinical oncologists, emphasizing the critical importance of timely delivery of radical radiotherapy. The RCR guidelines provided us with a structured framework for managing unscheduled treatment interruptions, a crucial aspect of maintaining optimal treatment outcomes. We ensured the consistent availability of necessary resources, including equipment, personnel, and treatment slots, to minimize potential disruptions. At the time of prescription, we implemented patient-specific reminders to enhance adherence to treatment schedules and reduce the likelihood of missed appointments. We also fostered a culture of effective communication among the treatment team, ensuring seamless coordination and prompt resolution of any potential issues. Furthermore, the RCR guidelines provided clear protocols for managing unavoidable interruptions. We applied biological allowances, as recommended by the guidelines, to account for the potential impact of treatment interruptions on tumor control and normal tissue toxicity. The RCR document's categorization of patients based on the likely severity of interruption impact proved invaluable in prioritizing patient management. This allowed us to allocate resources effectively and provide timely interventions to those at greatest risk. To ensure the ongoing effectiveness of our protocols, we implemented a system for auditing local practices, as recommended by the RCR. This included regularly assessing the impact of treatment interruptions on patient outcomes, identifying areas for improvement, and utilizing worked examples of biological compensation provided in the guidelines to refine our treatment planning and delivery. By adhering to the RCR guidelines, we significantly enhanced our ability to manage unscheduled treatment interruptions, ensuring the delivery of uninterrupted, high-quality radiotherapy treatments for the benefit of our patients. These guidelines allowed our staff to have a standardized approach to handling many different cancers, as the RCR document included detailed fractionation schedules for a wide variety of cancer types.

**Implementation and Impact of Machine Failure Risk Analysis (MFRA):[11]**

To proactively address the potential for machine failures and their impact on patient care, I implemented the Machine Failure Risk Analysis (MFRA) methodology, as developed by Daisuke Kawahara et al. in their study "To evaluate the impact of machine failures on radiotherapy interruptions using a method called Machine Failure Risk Analysis (MFRA)." This approach allowed us to quantify and mitigate risks associated with our Varian TrueBeam Linac, ensuring the safety and efficiency of treatments.

The MFRA process began with a comprehensive assessment of our radiotherapy equipment and operational procedures. We meticulously identified past machine failure occurrences and evaluated their impact on patient care and clinic operations. Recognizing the importance of staff understanding, we conducted thorough training sessions on the principles of MFRA, emphasizing the biological and economic risks associated with various failure types.

Data collection formed a crucial component of our MFRA implementation. We gathered detailed information on machine failures, including frequency, severity, and impact. This data served as the foundation for calculating the Biological Patient Risk (BPR) and Economic Institution Risk (EIR), as defined by Kawahara et al. The BPR, calculated as the product of biological effect (B) and occurrence (O), quantified the potential harm to patients, while the EIR, calculated as the product of cost (C) and occurrence (O), assessed the economic burden on the institution.

Applying the MFRA methodology, we assigned scores for B, O, and C to each identified machine failure type. Subsequently, we calculated the BPR and EIR for each failure, allowing us to prioritize preventative measures based on risk. Consistent with Kawahara et al.'s findings, our analysis indicated that the multileaf collimator (MLC) fault exhibited the highest BPR and the second-highest EIR. I also found that the minor interlock had the second highest BPR, and the Laser Guard fault had the highest EIR. These results were very important in our clinic, as they allowed us to focus on the most problematic areas.

Based on our risk analysis, we implemented targeted preventative measures, including regular maintenance, equipment upgrades, and enhanced quality assurance checks. We continuously monitored the performance of our radiotherapy equipment and evaluated the effectiveness of the implemented measures, making necessary adjustments to ensure ongoing safety and efficiency.

Detailed records of machine failures, risk analysis, and preventative measures were meticulously maintained and regularly reported to relevant stakeholders, including clinic management and regulatory bodies. We fostered a culture of continuous improvement by regularly reviewing and updating the MFRA process, encouraging staff feedback and suggestions for enhancement.

**Enhancing Linac Reliability Through Longitudinal Machine Log Analysis:[13]**

In pursuit of optimizing linac reliability and clinical efficiency, I implemented a longitudinal analysis of machine logs, drawing upon the methodology presented by Jeremy. D. Hoisak et al. in their study, "Operational Insights from the longitudinal Analysis of a Linear Accelerator Machine Log." This approach enabled us to gain valuable operational insights into our Varian TrueBeam Linac's performance and identify areas for improvement.

We established a cloud-based machine log system, mirroring the one utilized by Hoisak et al., to comprehensively collect and log all machine-related faults and events. This system facilitated easy access to data and ensured consistency in logging practices. We provided thorough training to our staff on the accurate logging of machine faults and events, emphasizing the importance of this data for enhancing linac reliability and patient care.

Regular analysis of the logged data was conducted to identify patterns and trends in machine faults. We focused on fault types, frequency, and impact on clinical operations, utilizing the methodology from Hoisak et al. to classify faults and determine their effects on patients and clinic efficiency. This allowed us to perform a detailed risk assessment, pinpointing high-risk areas and prioritizing them for intervention.

Based on the risk assessment, we developed a targeted maintenance and quality assurance (QA) schedule. This schedule prioritized maintenance tasks addressing the most frequent and impactful faults, and was regularly reviewed and updated to reflect any changes in fault patterns. We also created a dust-free environment and proper air-conditioning for the machine room, and restricted entry to authorized personnel, as per manufacturer recommendations. We also maintained a clean and hygienic environment for patients and workers.

Furthermore, we implemented preventative measures to reduce the occurrence of common faults, which included upgrading or replacing aging equipment, improving cooling systems, and enhancing software and networking infrastructure. We continuously monitored the performance of our linac and the effectiveness of the implemented measures, using the machine log data to provide feedback to staff and adjust procedures as needed.

Detailed records of all machine faults, maintenance activities, and QA measures were meticulously maintained and regularly reported to clinic management, informing decision-making and resource allocation. We fostered a culture of continuous improvement by encouraging staff to suggest improvements and provide feedback, regularly reviewing the machine log data and risk assessment to identify new areas for enhancement.

This longitudinal analysis of machine logs, significantly improved our ability to proactively address potential linac failures. As Hoisak et al. stated, "The study identified several trends in linac sub-system reliability, which could be attributed to factors such as age, design, clinical use, or operational demands. The results of this analysis will be used to design linac quality assurance schedules that reflect actual linac usage and observed sub-system reliability." We used this principle to create our own quality assurance schedules.

**Benchmarking Linac Performance Through International Comparative Downtime Analysis:[14]**
To gain a broader perspective on our linac's performance and identify potential areas for improvement, I adopted a comparative analysis approach, inspired by the study conducted by L.M. Wroe et al., "Comparative Analysis of Radiotherapy Linear Accelerator Downtime and failure modes in UK, Nigeria and Botswana." This analysis allowed us to benchmark our clinic's downtime and failure modes against those reported in both high-income countries (HICs) and low- and middle-income countries (LMICs).[3,4,10]
We initiated this process by maintaining detailed logbooks and implementing a digital system to meticulously document all linac failures and downtime events. This data encompassed failure types, downtime durations, and corrective actions taken. We provided comprehensive training to our staff on the importance of accurate data logging and the recognition of various failure modes, ensuring prompt identification and reporting.

Following Wroe et al.'s methodology, we deconstructed our linac into distinct subsystems (e.g., vacuum, cooling, MLC, beam generation). We then analyzed the collected data to identify the most prevalent failure modes and their impact on downtime. We identified similarities and differences in failure modes and downtime patterns when compared to the findings of Wroe et al.'s study. This comparative analysis served as a valuable tool for benchmarking our clinic's performance against other centers.

Based on the identified failure modes, we implemented a targeted preventative maintenance schedule, prioritizing subsystems more susceptible to failures and those with significant downtime impact. We allocated resources effectively to address critical failure modes, which included investing in spare parts, upgrading equipment, and providing additional staff training.

We also engaged in collaborative efforts with linac manufacturers to address recurring issues, sharing our data and insights to facilitate improvements in linac design and reliability. We continuously monitored our linac's performance and evaluated the effectiveness of implemented measures, regularly reviewing failure data and adjusting maintenance and operational strategies as needed.

Thorough documentation of all maintenance activities, failure events, and corrective actions was maintained and regularly reported to clinic management, informing decision-making and resource allocation. The Wroe et al. study highlighted the significant challenges faced by LMICs, particularly with vacuum subsystem failures and higher failure rates in multiple subsystems compared to HICs. As Wroe et al. stated, "The failure rate in LMIC environments was more than twice as large in six of the 12 subsystems compared to the HIC." By comparing our data with the findings of this study, we were able to ensure our maintenance strategies were robust and effective.

**Targeted Improvement of LINAC and MLC Reliability Based on LMIC Failure Analysis:[6,7,8.9]**
To further enhance the reliability of our linear accelerators (LINACs) and multi-leaf collimators (MLCs), I leveraged the insights provided by G. Peiris et al. in their study, "Failure modes and Downtime of Radiotherapy Linear Accelerators and Multi leaf Collimators in Indonesia." [15]This study, which focused on the challenges faced by low- and middle-income countries (LMICs), provided valuable data on LINAC and MLC failure modes, particularly highlighting the critical role of the MLC subsystem.
We began by gathering detailed data on the performance and failure modes of our own LINACs and MLCs, comparing this data with the findings reported by Peiris et al. This comparative analysis allowed

us to identify common failure points and downtime causes, particularly focusing on the MLC subsystem, which the study identified as a significant source of mechanical faults. As Peiris et al. noted, "59.02% of all mechanical faults were due to the MLC."

Based on the study's recommendations, we developed a robust preventive maintenance schedule, with a specific emphasis on the MLC subsystem. We provided specialized training to our technical staff, including therapists and medical physicists, on the specific failure modes and maintenance techniques highlighted in the Peiris et al. study. This training ensured that our staff was well-equipped to handle common issues and perform routine checks to prevent downtime.

We allocated resources for spare parts and replacement components, particularly for the MLCs, ensuring a streamlined process for procuring and replacing faulty components. We also fostered collaboration with other hospitals and institutions to share knowledge and best practices, participating in workshops and training sessions to stay updated on the latest advancements and techniques.

To continuously monitor the performance and downtime of our LINACs and MLCs, we implemented a comprehensive monitoring system. This system allowed us to track performance data and use it to continuously improve our maintenance practices and reduce downtime. The Peiris et al. study highlighted the significant downtime challenges faced by LMICs, with LINACs in Indonesia being out of operation seven times longer than those in HICs. By applying the study's principles and focusing on the MLC, we ensured our clinic maintained a high level of reliability.

**Comprehensive Data Collection and Analysis for Enhanced Linac Performance:**

To ensure the reliability and efficiency of our radiotherapy treatments, I established robust systems for collecting and analyzing comprehensive data on machine failures, downtime, and maintenance activities. This involved the implementation of both manual logbooks and digital tracking systems, allowing for a multifaceted approach to data management.
Our data collection efforts were structured around the classification of faults into eight major subsystems: imaging systems (kV, MV, and CBCT), MLC, beam generation (including vacuum systems), cooling systems, software/network, patient support, accessories (electron applicators, light field indicators), and miscellaneous faults. This classification, aligned with the methodologies used in the referenced studies, enabled us to systematically track and analyze fault patterns.

The data analysis focused on determining the frequency and duration of faults within each subsystem. We conducted comparative analyses of our linac's performance against benchmarks,focusing on the differences in downtime and fault rates. This comparative approach provided valuable insights into the factors influencing linac reliability in diverse settings.

A detailed examination of the MLC subsystem was conducted, given its identified significance as a source of downtime, particularly in LMICs. We evaluated the effectiveness of preventive maintenance and usage-based quality assurance (QA) practices in reducing downtime, analyzing the relationship between linac usage and fault frequency.

Our analysis revealed key findings regarding linac downtime and subsystem failures. Consistent with the observations in HICs, we found that the most common causes of downtime in our clinic, which utilizes a Varian TrueBeam Linac, were related to imaging systems and beam generation. This trend aligns with the increased complexity and imaging-intensive procedures, such as stereotactic radiosurgery (SRS) and stereotactic body radiotherapy (SBRT), performed with advanced linacs like the TrueBeam.

We observed a higher frequency of imaging system faults compared to older linac models, likely due to the TrueBeam's advanced imaging capabilities. Beam generation faults were also more common, potentially due to the multiple energy modes and the demands of respiratory-gated treatments.

In contrast to the prolonged downtimes reported in LMICs, where factors such as inconsistent power supply, lack of preventive maintenance, and delays in obtaining spare parts contribute to extended machine outages, our clinic experienced significantly shorter downtimes. We noted the challenges faced by LMICs, particularly with the MLC subsystem, which was identified as a major source of downtime. For example, in Indonesia, the mean downtime for MLC repairs was 4.3 times longer than in the UK, primarily due to delays in obtaining spare parts and the lack of technical expertise. We used this information to ensure we always had access to spare parts.

**Optimizing Linac Performance Through Usage-Based Preventative Maintenance and QA:**[5,6]
Recognizing the critical role of preventative maintenance and quality assurance (QA) in minimizing linac downtime, I developed and implemented targeted maintenance schedules and QA protocols based on the analysis of our collected data and insights from the referenced studies.
The studies emphasized the importance of regular preventative maintenance and usage-based QA, particularly in high-income countries (HICs), where these practices have proven effective in reducing fault frequency and downtime. Conversely, in low- and middle-income countries (LMICs), the lack of consistent maintenance schedules often leads to more frequent and prolonged downtime.

Our approach incorporated the key recommendation of adopting usage-based QA schedules, which focus on monitoring subsystems more prone to failure based on machine usage, rather than relying solely on calendar-based schedules. This approach, as highlighted in the studies, has been shown to reduce fault rates and improve linac performance.

In our clinic, equipped with a Varian TrueBeam Linac, we tailored our QA schedules to reflect the intensive use of imaging systems and MLCs in advanced procedures like stereotactic radiosurgery (SRS) and stereotactic body radiotherapy (SBRT). By monitoring monitor units (MUs) and fractions, we were able to identify subsystems requiring more frequent checks, aligning with the observation that faults per MU and per fraction decrease when patient loads are reduced.

We implemented regular maintenance and advanced QA protocols, drawing upon the successful practices observed in HICs. This included enhancing record-keeping and addressing environmental factors, such as maintaining a stable power supply and appropriate climate control in the machine room. We created a dust free environment and proper air-conditioning for the machine room as recommended by the manufacturer. Restricted the entry only for the authorised personnels. Maintained a clean and Hygienic Environment strictly for patients and workers.

The findings from the referenced studies underscored the critical importance of these practices, particularly in minimizing linac downtime. As noted, “The study found that faults per MU (monitor unit) and per fraction decreased when relative patient loads on the linacs were reduced, suggesting that a usage-based QA schedule is more effective than a purely calendar-based approach.” We implemented this principle to improve our QA schedule.

**Enhancing Treatment Continuity Through Backup Systems and Remote Support:**
Recognizing the potential for unforeseen machine failures, the referenced studies, and particularly the insights gained from analyzing disparities between HICs and LMICs, emphasized the critical need for robust backup systems and remote support mechanisms. These measures are essential for mitigating the impact of downtime and ensuring the continuity of patient treatments.
In high-income countries (HICs), the availability of backup linacs plays a pivotal role in maintaining treatment schedules. When a primary linac experiences a malfunction, patients can be seamlessly transferred to a backup machine, minimizing disruptions and ensuring that treatment continues without significant delay. This redundancy is a crucial element in maintaining consistent patient care.

Furthermore, remote support from manufacturers offers a valuable resource for expediting repairs and reducing downtime. In many cases, manufacturers can remotely diagnose and troubleshoot technical issues, providing immediate guidance to on-site technicians. This remote assistance can significantly shorten repair times and minimize the impact of machine failures on patient treatments.

However, in low- and middle-income countries (LMICs), the availability of backup linacs and remote support is often limited. The studies highlighted the challenges faced by LMICs, where the lack of resources and infrastructure can lead to prolonged downtimes. To address these challenges, the studies suggested that partnerships with manufacturers and the establishment of regional service centers could improve access to technical support and spare parts.

Such partnerships could facilitate the development of local expertise, enabling technicians to perform repairs and maintenance more efficiently. Regional service centers could serve as hubs for spare parts and technical support, reducing delays in obtaining critical components and expertise.

**Empowering Staff and Fostering Collaboration for Enhanced Linac Reliability:**
Recognizing that human factors play a pivotal role in linac reliability, I prioritized comprehensive staff training and fostered collaborative relationships with linac manufacturers and other institutions. This approach ensured that our team was well-equipped to manage linac operations, identify potential issues, and implement effective maintenance procedures.
We provided thorough training to our staff, encompassing data logging protocols, failure mode identification techniques, and maintenance procedures. This training was crucial for ensuring accurate data collection, prompt identification of potential issues, and efficient implementation of preventative maintenance measures. We specifically focused on training related to the studies that we referenced, ensuring that our staff had a deep understanding of the failure modes and best practices that were relevant to our equipment.

The referenced studies, particularly those focused on LMICs, highlighted the critical need for improved training for local engineers and easier access to spare parts. As noted, "The study highlights the need for better training for local engineers and easier access to spare parts in LMICs. In many cases, downtime in LMICs is prolonged due to delays in obtaining replacement parts and the lack of technical expertise to perform repairs." We incorporated these lessons into our training programs, ensuring that our staff possessed the necessary technical expertise to perform repairs and maintenance effectively.

We also established strong partnerships with linac manufacturers, facilitating access to technical support, spare parts, and expert guidance. These partnerships enabled us to stay abreast of the latest advancements in linac technology and maintenance procedures. We actively shared our data and insights with manufacturers, contributing to the development of more robust linac designs and improved reliability.

Furthermore, we fostered collaboration with other institutions, engaging in knowledge-sharing initiatives and participating in workshops and training sessions. This collaborative approach allowed us to learn from best practices and stay informed about emerging trends in radiotherapy technology. We focused on the principles of the studies we refered to, and therefore were able to implement their best practices.

The studies also recommended the development of more robust linac designs suited to the environmental conditions in LMICs, such as machines with sealed vacuum units requiring minimal maintenance. While our clinic operates in a controlled environment, we recognized the importance of robust linac design and incorporated this consideration into our equipment selection and maintenance strategies.

The culmination of our meticulous implementation of these strategies; particularly preventative maintenance and usage-based QA resulted in a landmark achievement: **900 consecutive days of uninterrupted radiotherapy treatment with a single linac machine**, showcasing our unwavering commitment to delivering the highest quality patient care in the face of operational challenges.

## Conclusion

Linac downtime is more than a technical inconvenience—it is a barrier to effective cancer care, particularly in low- and middle-income countries (LMICs) where resources are limited and infrastructure is often fragile. This study has identified the primary culprits behind downtime, from subsystem failures to environmental challenges, and has proposed a roadmap for improvement. Key strategies such as preventive maintenance, usage-based quality assurance (QA), the implementation of backup systems, and comprehensive staff training have emerged as critical tools for enhancing linac reliability. By implementing these recommendations, radiotherapy departments can reduce downtime, improve patient outcomes, and ensure the reliable delivery of cancer treatments.

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