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Development and implementation of a wireless real-time radiation monitoring system for LINAC beam delivery monitoring

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ABSTRACT

Introduction: In this work, we developed a wireless, remote, real-time radiation monitoring system designed to oversee beam delivery in a radiation therapy room equipped with a medical linear accelerator (LINAC). **Methods**: This system utilizes a Geiger-Müller detector paired with embedded electronic hardware to accurately record radiation count rates in real-time. The data collected by this system are transmitted through LAN/WAN networks to the internet, ensuring instantaneous accessibility. In addition, a web server and mobile application were developed to display, receive, and archive the data from the radiation counter. **Results**: Our system was deployed in the radiation therapy room of the Oncology Hospital in Ho Chi Minh City, demonstrating a remarkable data reception rate of up to 99.8% over a three-day test period from June 27th to 29th, 2022. The system effectively identified beam-on instances and provided precise measurements of the number and duration of beam-on events. **Conclusion**: This study demonstrates the feasibility of remote real-time radiation monitoring in medical settings and highlights the potential for enhancing radiation safety and treatment efficacy in external beam radiotherapy.

Key words: LINAC, beam delivery, embedded electronic, real-time monitoring, GM counter

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INTRODUCTION

In 2023, the International Agency for Research on Cancer (IARC) updated its estimates and reported nearly 20 million new cancer cases, including non-melanoma skin cancers (NMSCs), and 9.7 million cancer-related deaths (including NMSC) across 185 countries[1]. Given these conditions, radiation therapy has become a fundamental component of cancer treatment, in addition to chemotherapy and surgery. It leverages devices such as linear accelerators (LINACs) and cobalt therapy machines, which are essential for delivering high-energy X-rays or electrons to target cancers and tumors effectively[2].

The adoption of LINACs has increased significantly due to their ability to generate photon and electron beams across a wide range of energy levels, allowing advanced treatment techniques. This technology allows for precise control over beam delivery, which is typically managed and monitored from an operator room adjacent to the treatment space[2,3]. Beam delivery can be assessed through an ionization chamber within the LINAC head or radiation dosimeters in the treatment room. However, there are scenarios where remote monitoring of beam delivery becomes crucial, such as monitoring from outside the local treatment building or from considerable distances. Despite the growing need, current technologies still have limitations in enabling remote real-time beam delivery monitoring.

The technological progress of wireless electronics and the importance of real-time communications have been increasingly recognized across various sectors, including environmental monitoring, agriculture, healthcare, and industry[4–7]. The ability of these technologies to provide real-time data is crucial for enabling timely responses to emergent situations, optimizing operational processes, and enhancing safety and efficiency. In the field of nuclear radiation monitoring, systems have been developed to facilitate remote, real-time monitoring for security and early warning purposes[8–12].

This study aims to improve remote beam delivery monitoring by developing a wireless, real-time radiation monitoring system specifically for medical linear accelerators. By integrating automatic radiation monitoring that can be accessed remotely via a web or mobile application interface, the system enables comprehensive, real-time (in second) surveillance of radiation levels, enhancing radiation safety and treatment management in radiation therapy.

SYSTEM DESIGN AND EXPERIMENTAL SETUP

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Wireless remote real-time radiation monitoring system

A schematic overview of the system, illustrated in Figure 1, includes the following primary components: a wireless real-time radiation counter, a cloud server for real-time data transmission, and a mobile application/website for monitoring. Additionally, a cloud database is incorporated for data storage.

- *Wireless real-time radiation counter*

The counter, shown in Figure 2, includes a Geiger-Müller (GM) detector for radiation detection, an ESP8266 NodeMCU module for network connectivity and data transmission, and an SD card reader for local storage. These components are interconnected via digital input/output (DIO) standards. Custom firmware on the ESP8266 enables Wi-Fi connectivity, time synchronization, pulse interpretation, and data management.

- *Data Transmission and Cloud Server*

Figure 3 illustrates the data transmission and cloud server components, which are essential for the operation of the real-time radiation monitoring system. The server architecture is designed to receive, store, and manage radiation data, providing an application programming interface (API) for easy data access through web or mobile applications. Utilizing Node.js [13] and the Socket.IO library [14], the server enables efficient, low-latency, bidirectional communication between the detection system and the user interface. This configuration enables users to access up-to-date radiation data instantly via the web or mobile applications, offering insights into radiation levels and related information. The inclusion of the API extends the system's applicability, allowing for the development of custom applications or integrations to interact with the radiation data stored on the server.

Experimental setup

The system was deployed in a medical linear accelerator treatment room at the Oncology Hospital in Ho Chi Minh City. Figure 4 illustrates the setup, with the real-time radiation detector positioned at the entrance corridor of the treatment room. The data, measured in counts per second (cps), are wirelessly transmitted to the outside using a Wi-Fi router and LAN cable, connecting the treatment and control rooms for seamless real-time communication. Figure 4b and Figure 4c show the accelerator treatment room and the installation of the detector at the entrance corridor, respectively.

MEASUREMENT DATA

The system's response to beam delivery

The system's response to beam delivery is tested for several beam-on delivery energies. Figure 5 shows the system's response in terms of the count rate versus time. The system clearly records radiation peaks during beam activation, distinguishing them from the lower radiation background levels when the beam is off, with a notable response time of less than a second to beam toggling. The peak heights indicate different beam energies.

Monitoring of LINAC beam delivery

Over the course of three days, from June 27th to June 29th, 2022, we assessed the performance of the wireless real-time radiation monitoring system installed in the medical linear accelerator treatment room. The duration of the measurements was 250,828 seconds. During this period, the system encountered only 559 seconds of network disconnection, which ensures an uptime of 99.8%. This high level of reliability is crucial for ensuring continuous monitoring of radiation levels within the treatment environment.

The data collected in terms of counts per second (cps) were recorded and are presented in Figure 6. These data clearly mark the instances of beam activation as identified by significant peaks in the count rate. The system's ability to detect changes quickly and accurately in radiation levels allowed for the precise identification of the background radiation and various phases of beam delivery.

DATA ANALYSIS AND DISCUSSION

In the beam-on delivery analysis shown in Figure 6, we set a threshold of 5 cps to determine the beam-on duration and perform a statistical overview of beam-on durations for beam deliveries over the three-day observation period. The results, presented in Figure 7a-c, corresponding to beam-on duration, and Figure 7d-f, corresponding to a statistical overview of beam-on durations, for each respective day, reveal patterns in LINAC usage. Specifically, the operator conducts beam tests at approximately 6:00 AM, followed by patient radiation treatments from 8:00 AM to nearly 12:00 PM. On June 27th, additional beam deliveries observed at approximately 6:30 PM were likely attributed to the LINAC's quality assurance (QA) checks.

Based on a statistical overview of beam-on durations, shown in Figure 7d-f, the beam-on duration varied from a few seconds to up to 30 seconds, reflecting

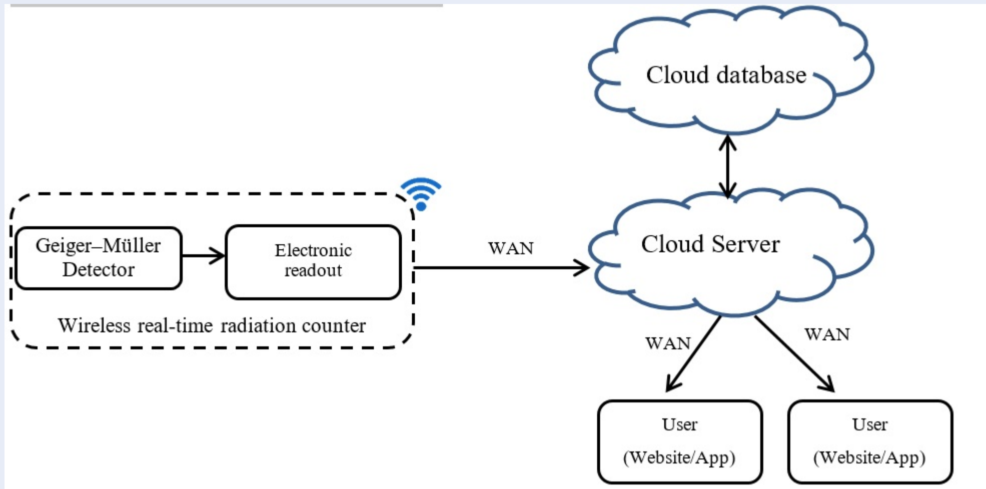

Figure 1: Schematic overview of the wireless remote real-time radiation monitoring system.

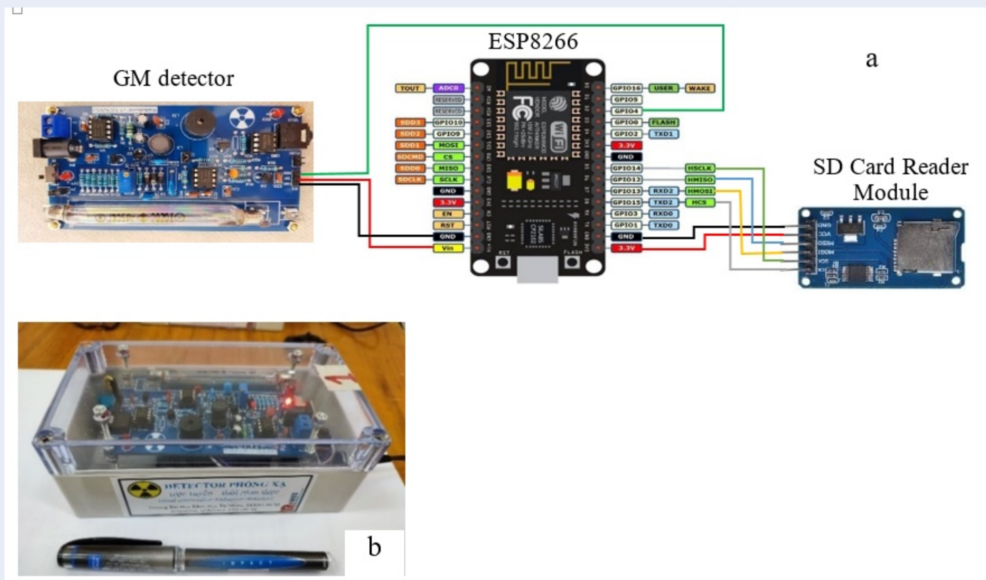

Figure 2: Wireless real-time radiation counter. (a) Components of the GM detector, ESP8266 and SD reader. (b) Assembled Unit.

different treatment protocols and procedures. Specifically, shorter beam-on lengths of 3-4 seconds were used for patient positioning verification before initiating treatment irradiation. This highlights the system's ability to ensure accurate patient alignment, which is a critical factor in the operation and safety of radiation therapy.

To provide a quantitative overview, we compiled the data of the three-day period, as summarized in Table 1. This compilation provides detailed insight into the beam delivery patterns, indicating an average of 359 occurrences and 2,618 seconds of beam-on time during treatment within the observed days. This analysis demonstrated the effectiveness of our system in monitoring and distinguishing between various operational phases of the LINAC, thereby contributing to the optimization of treatment schedules and ensuring patient safety.

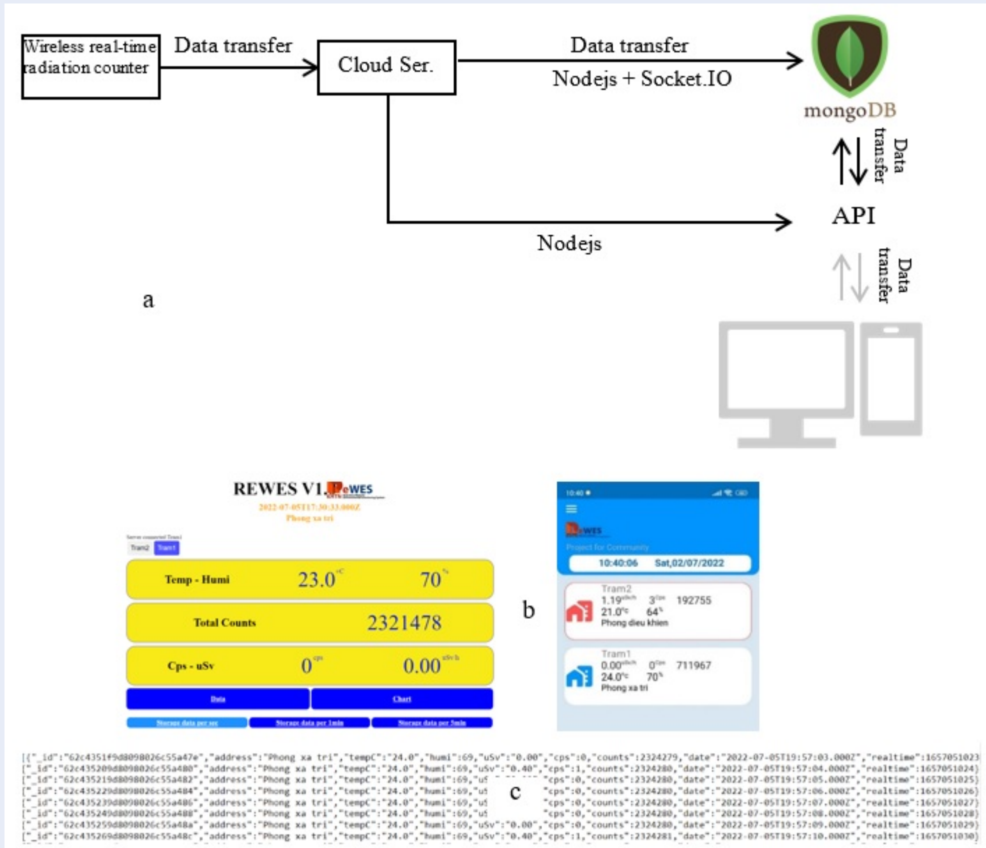

Figure 3: Data transmission and storage from the radiation detection system to the cloud server. (a) Data Flow: Schematic diagram. (b) Monitoring Interface: Web and Android App. (c) Cloud Storage: Stored Data Overview

Table 1: Summary of beam delivery metrics for 27-29 June.

	27 June	28 June	29 June	Average
Number of beam-on delivery/day	425	357	376	
Beam-on time delivery (sec)/day	3,112	2,647	2,818	
Number of beam-on during treatment time	363	348	365	359
Beam-on time delivery for treatment (sec)	2,668	2,507	2,679	2,618

CONCLUSIONS

In this study, we introduced a wireless real-time radiation monitoring system in a cancer treatment facility. Over a three-day evaluation, the system demonstrated high operational reliability with a data reception rate of 99.8%, ensuring continuous monitoring of radiation levels. This level of accuracy is critical for managing the use of medical linear accelerators (LINACs), allowing precise tracking of beam testing and patient treatment patterns.

The system's ability to differentiate between background radiation and active beam delivery underscores its utility in real-time safety monitoring and quality assurance processes. It enhances patient safety, optimizes treatment schedules, and improves operational efficiency within radiation therapy.

The deployment of this monitoring system represents an advancement in radiation therapy management. Its successful application not only enhances radiation safety and treatment efficiency but also opens possibilities for broader adoption in various healthcare settings. Future applications could extend to other medical fields and industries where real-time radiation monitoring is crucial, potentially increasing the standard of care and operational safety across the board.

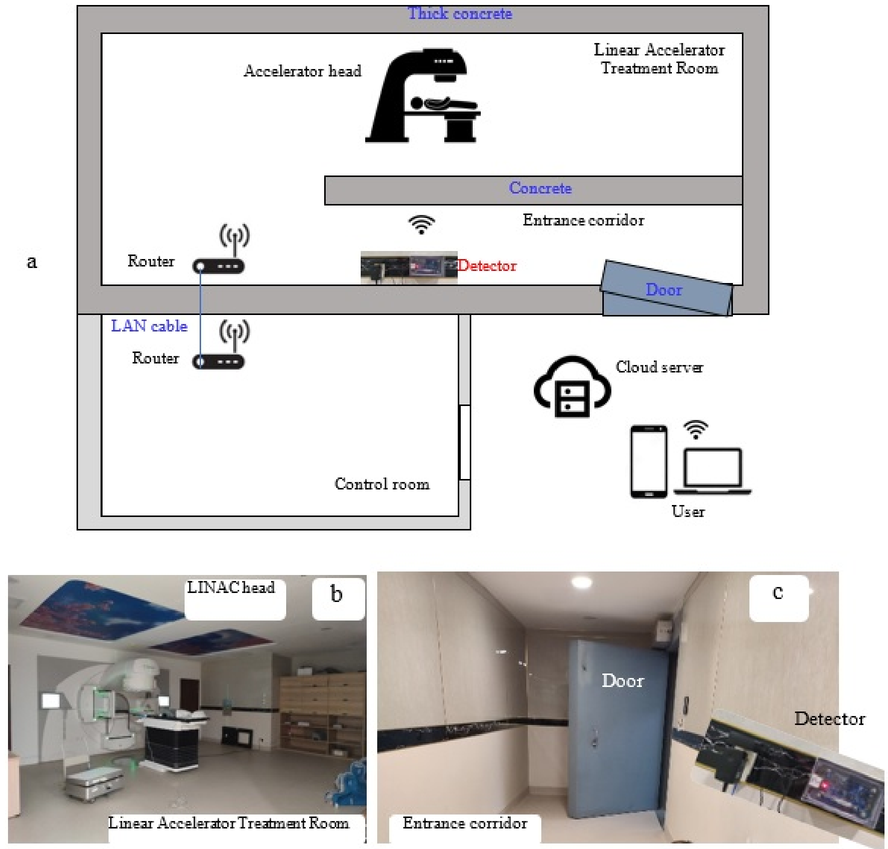

Figure 4: Experimental setup of a medical linear accelerator treatment room. (a) Overview: schematic diagram of the setup; (b) Treatment room: photograph of the linear accelerator; (c) Detector placement: mounted on the wall at the entrance corridor.

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AUTHOR CONTRIBUTIONS

Vo Hong Hai was responsible for designing and conducting the experiments, as well as for drafting and revising the manuscript. Nguyen Trung Hieu participated in conducting the experiments. Nguyen Tri Toan Phuc checked and revised the manuscript.

CONFLICT OF INTEREST

The authors declare that there are no conflicts of interest related to this study.

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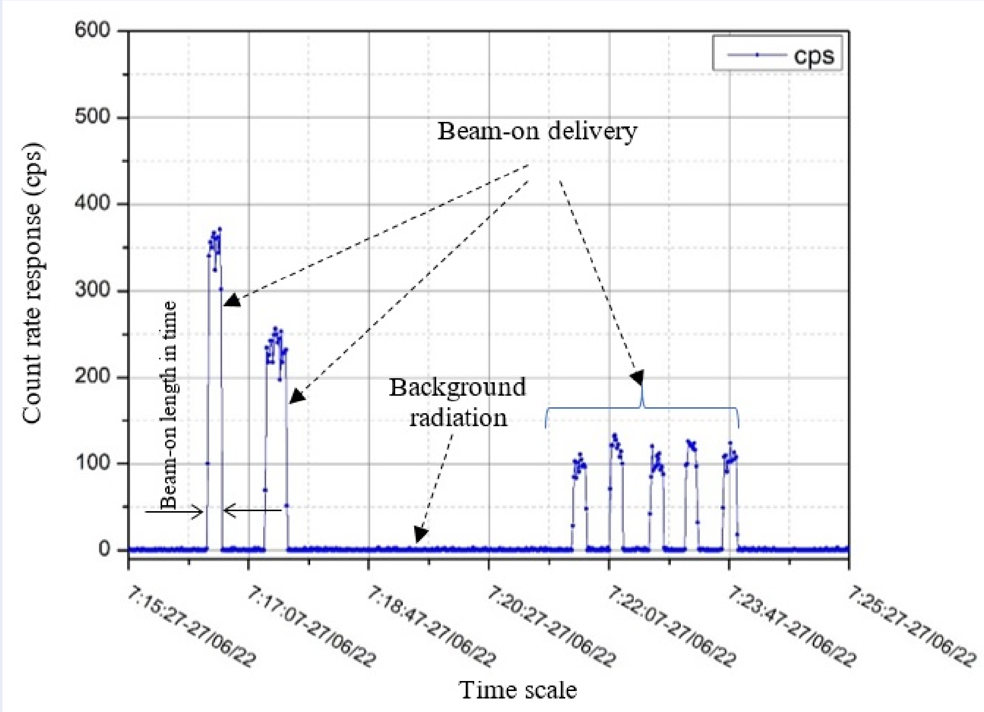

Figure 5: Dynamic response of the LINAC monitoring system to active beam events.

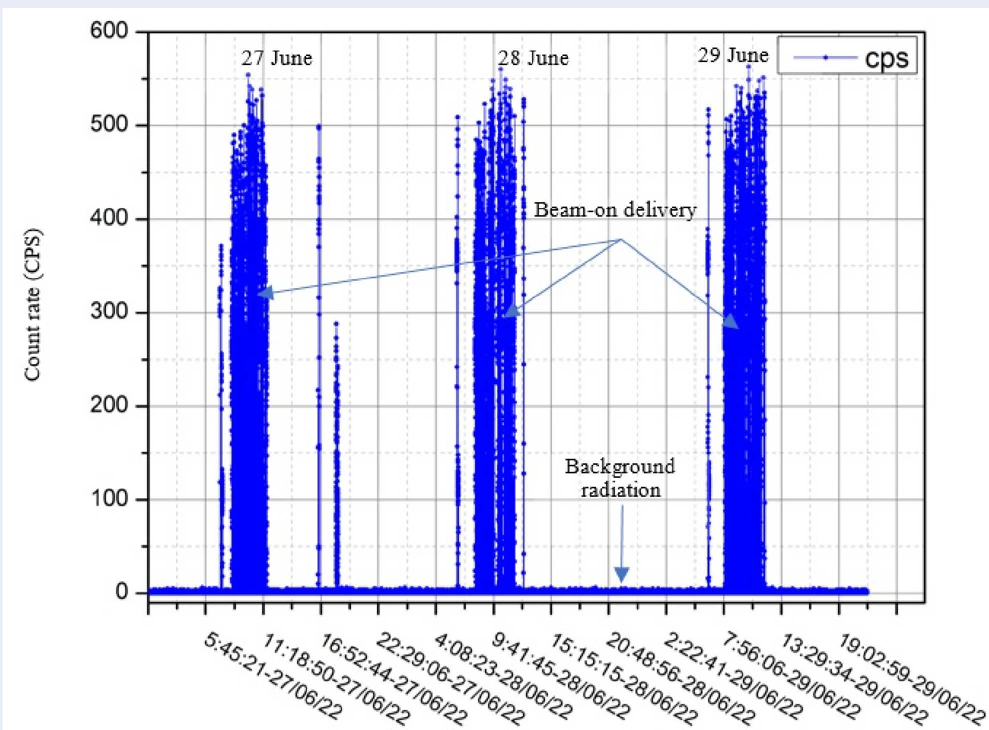

Figure 6: Three-day radiation count rate (cps) analysis for LINAC beam monitoring.

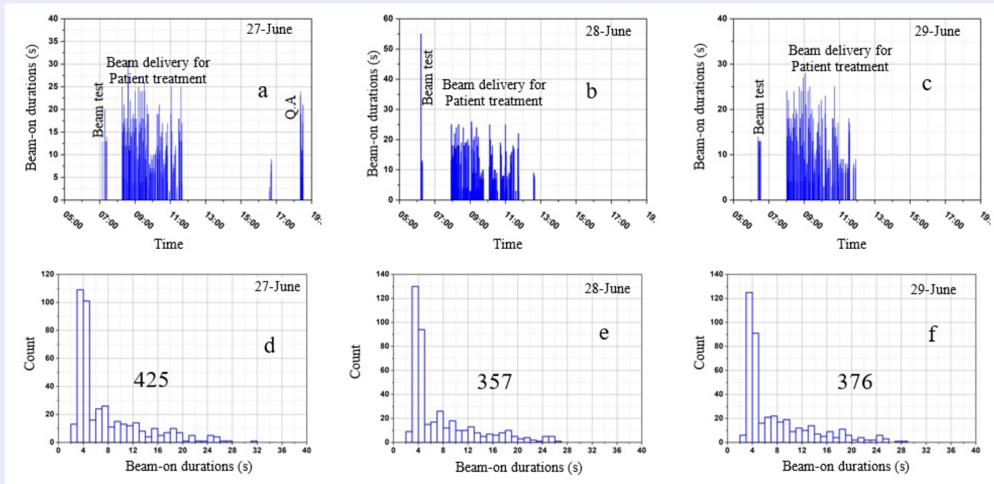

Figure 7: Analysis of LINAC beam-on delivery patterns. (a), (b), and (c) Time durations of beam-on events from 27 June to 29 June, respectively. (d), (e), and (f) Statistical overview of beam-on durations from 27 to 29 June, respectively.

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