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Development and Comparative Evaluation of a Webcam-based and Barcode Scanner-based Check-in/check-out System for Enhancing Thermoluminescent Dosimeter Management

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The management of thermoluminescent dosimeters (TLDs) is of paramount importance in diagnostic medical and nuclear medicine environments where X-ray radiation and magnetic fields are present. This study aimed to develop a check-in/check-out system based on a webcam and barcode scanner to prevent the loss of TLDs and enhance their management. TLD barcode scanning was performed using a webcam and barcode scanner with a Python-based PyQt5 graphical user interface. The main functions of the system include TLD registration, check-ins, and check-outs. The performance of the system was evaluated based on barcode recognition speed, barcode scan execution time, and recognition accuracy. Barcode recognition speed showed no significant difference during check-in (p = 0.169), in contrast to the significant difference found during check out (p = 0.007). However, scan execution time was significantly shorter for the barcode scanner-based system (check-in: 3.68 seconds vs. 20.93 seconds, check-out: 3.89 seconds vs. 18.53 seconds, $p < 0.01$). Additionally, the barcode scanner-based system achieved 100 % accuracy, whereas the webcam-based system had significantly lower accuracy (check-in, 32.12 %; check-out, 28.47 %; $p < 0.01$). Implementing a barcode scanner-based approach in the TLD check-in/check-out system provides a faster and more reliable solution for TLD management.

Keywords : radiation management, diagnostic medical and nuclear medicine environments, PET-MR safety, thermoluminescent dosimeter (TLD), barcode scanner

1. Introduction

Personal radiation dosimeters are key to measuring and managing the radiation exposure of employees in medical fields, and they exist in various forms. Representative types of personal dosimeters include the film badge, thermoluminescent dosimeter (TLD), optically stimulated luminescence dosimeter (OSLD), pocket dosimeter, and active electronic dosimeter [1-3]. Among these, film badges, TLD, and OSLD are classified as legally recognized dosimeters by radiation safety regulatory agencies and are used for the official assessment of radiation exposure levels [4].

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TLD is a representative personal radiation dosimeter that provides high accuracy and reproducibility. When exposed to radiation, energy is stored within the crystal structure, and the radiation dose is evaluated by measuring the amount of light emitted upon heating [5]. TLDs are widely used to monitor personal radiation doses in various environments, such as nuclear power plants, hospitals, and research institutes. According to the international commission of radiological protection, the annual dose limits are set at 1 mSv for the general public and 50 mSv for employees (with a five-year cumulative limit of 100 mSv), alongside specific equivalent limits of 150 mSv for the lens of the eye and 500 mSv for the skin and extremities [5-7].

A systematic and efficient management system is required for the effective use of TLDs. The reliance on manual user management often leads to logistical issues with TLDs, such as displacement, inconsistent usage, or overdue retrieval. The loss of a TLD renders the accurate measurement of an employee's radiation exposure impossible, thereby compromising the overall reliability of radiation safety management.

In particular, the management of personal dosimeters in high-magnetic-field environments, such as Magnetic Resonance Imaging (MRI) and Positron Emission Tomography (PET)-MR facilities, presents unique challenges. While TLDs are generally not worn inside the MRI scanner rooms due to ionizing radiation from radiopharmaceuticals coexist [8]. A reliable check-in/check-out system is critical to prevent the inadvertent introduction of dosimeters into restricted zones or their loss during garment changes.

Lost dosimeters must be handled according to radiation safety management procedures, and even after retrieval, measurement difficulties may arise if contamination or damage is detected. The TLD fading effect refers to the gradual reduction of the stored signals in the TLD over time after radiation exposure. This phenomenon occurs because of environmental factors, such as high temperature, humidity, and radiation dose, as well as the intrinsic properties of the TLD material [9, 10]. Long-terms loss or exposure to high temperatures (e.g., 65 °C) can lead to significant TLD measurement errors and up to 30 % signal lose due to fading [11].

Loss of a personal dosimeter can occur anytime and anywhere. The internal atomic energy agency has reported that the loss of personal dosimeters is a significant issue in terms of legal obligations and responsibilities. According to the Nuclear Safety Act and the Medical Law, employees are required to wear personal dosimeters, and in the event of a loss, the dosimeter may be registered as a reading-specific item, or the institution may be subject to a fine. Among the types of personal dosimeter losses occurring in hospitals, the most common cases involve loss during the process of changing work clothes. The prevention and management of dosimeter loss require continuous efforts at both the individual and institutional levels, along with the exploration of various methods. According to previous studies, methods such as using anti-loss rings, attaching contact stickers, and utilizing personal dosimeter storage boxes have been employed to prevent losses. However, no single method can completely eliminate the loss rate, making multifaceted approaches necessary. Therefore, in addition to effectively managing the distribution and related procedures of personal dosimeters, it is essential to strengthen management measures to prevent losses.

This study aimed to develop a check-in/check-out system based on a webcam and barcode scanner to prevent the loss of TLD and strengthen their management. Furthermore, the performances of the two systems were compared and evaluated.

Table 1. System development environment of thermoluminescent dosimeter (TLD) check-in/check-out system.

Category	Details
PC	Intel(R) Core(TM) i5-1038NG7 2.00 GHz 16GB 3733 MHz LPDDR4X Sequoia 15.2 macOS
Program language	Python 3.11
GUI framework	PyQt5
Barcode recognition	PyQt5 KeyPressEvent
Database	SQLite3
Web-camera	Microsoft LifeCam VX-800 Model 1407
Barcode scanner	Unique Vision Wired 1D Barcode Scanner UV-1400 (USB)

2. Materials and Methods

2.1. Development environment

We developed a check-in/check-out system based on a webcam and barcode scanner for the efficient management and operation of TLDs in this study. The system development environment and details are listed in Table 1. A graphical user interface (GUI) was created using Python, and the barcodes attached to the TLDs were identified using a webcam and barcode scanner.

2.2. TLD check-in/check-out system

2.2.1. User interface and system functionality

Fig. 1 shows the operational process of the TLD check-in/check-out system. The system consists of several stages, including database and log file initialization, TLD registration, deletion registration, reset, record, check-in, and check-out. A PyQt5-based GUI was designed to allow users to perform a TLD check-in/check-out intuitively. The GUI is structured into three panels: left, center, and right. The left panel contains buttons for the TLD registration, deletion, reset, record, check-in, and check-out functions. The center panel displays the list of currently registered TLDs and their respective statuses, whereas the right panel shows the list of checked-in TLDs along with user information (Fig. 2).

2.2.2. Database and management

An SQLite3 database was established to efficiently store and manage TLD information. To maintain data integrity, a 'tld_log' table was defined. This table stores the unique barcode identifier of each TLD, user information associated with each TLD, current usage status (unused or in use),

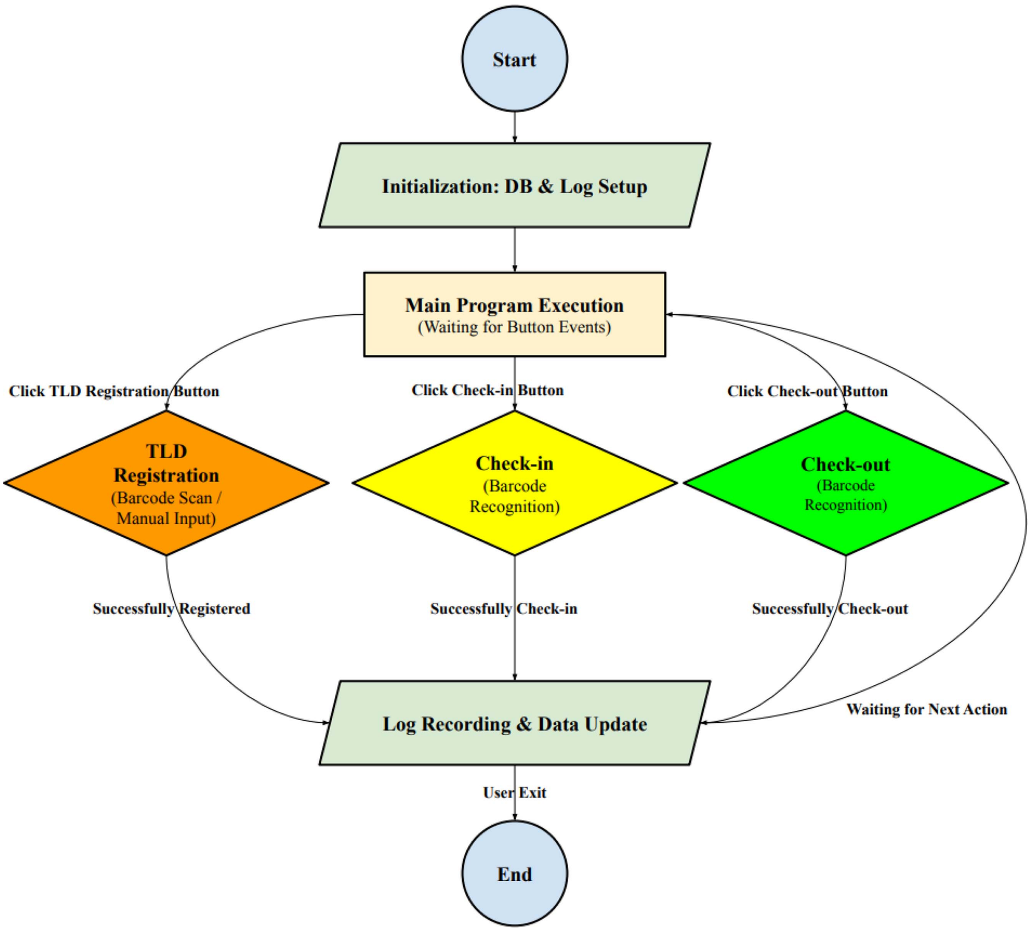

Fig. 1. (Color online) Flowchart of the operational process of the thermoluminescent dosimeter (TLD). This flowchart illustrates the operational process of the TLD check-in/check-out system, which manages TLD using barcode recognition. The system initializes the database and log files, then processes TLD registration, check-in, and check-out while continuously updating records until the user exits the application.

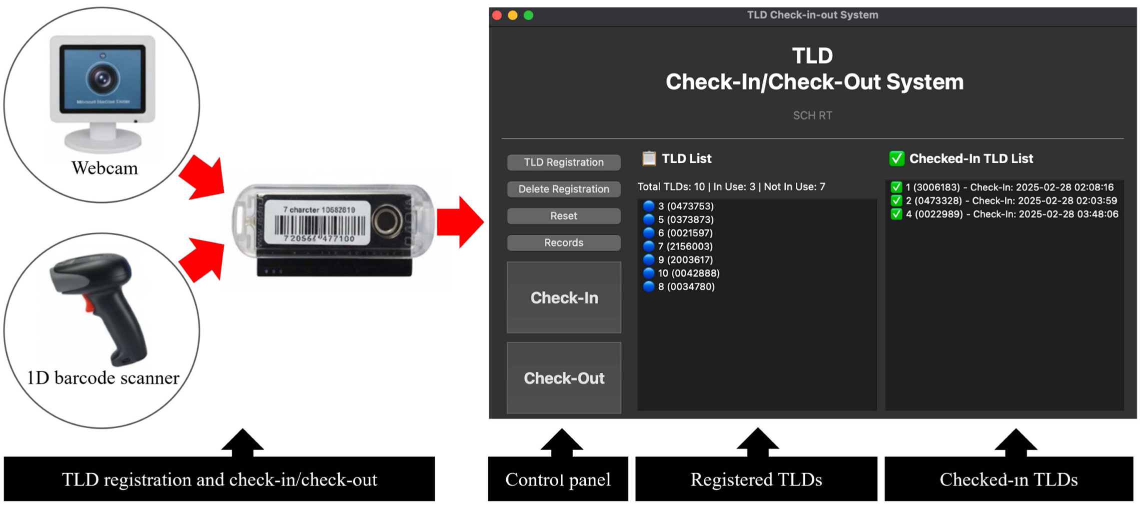

Fig. 2. (Color online) Thermoluminescent dosimeter (TLD) check-in/check-out system interface. The system allows users to register, check-in, and check-out TLDs while tracking their usage status. The left panel contains control buttons for registration, deletion, resetting, records, and performing check-in/check-out actions. The center panel displays the list of all registered TLDs, including available ones with blue icons. The right panel shows the checked-in TLDs with their unique IDs and timestamps.

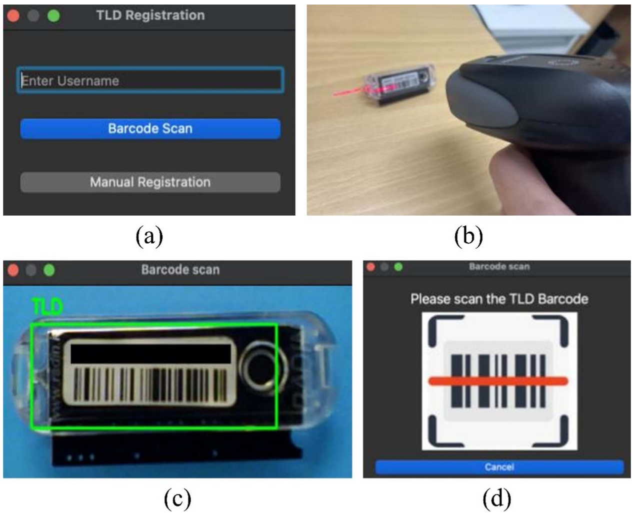

Fig. 3. (Color online) Overview of the thermoluminescent dosimeter (TLD) check-in/check-out system. (a) The TLD registration interface has a username input field, allowing users to select either barcode scanning or manual registration. (b) A barcode scanner is used to scan the barcode. The barcode scanning process using (c) a webcam or (d) a barcode scanner.

and check-in and check-out times. This design enables clear tracking of TLD usage history and facilitates its efficient management.

2.2.3. Check-in and check-out process

The check-in and check-out processes for the TLD were developed based on both a webcam and a barcode scanner. Fig. 3 shows the barcode scanning screen, which includes the TLD registration, using either a barcode scanner or a webcam. When a user requests a TLD, the barcode is scanned to query the corresponding records in the database. If the TLD is in an "unused" state, it is changed to "in use," and the check-out time is recorded. Conversely, when the user returns the TLD, the barcode is scanned to query the database, and the status is changed from "in use" to "unused," with the check-in time being recorded. All check-in and check-out records are stored in a {tld_log.txt} file to ensure traceability. Additionally, feedback was provided to the user via a GUI and voice prompts, confirming that the operation had been completed.

2.3. Performance evaluation

The performance of the webcam- and barcode scanner-based check-in/check-out system was evaluated using three main metrics: barcode recognition speed (scan speed), barcode scan execution time (scan execution time), and accuracy (scan recognition rate). A total of 6 evaluation parameters for each system were assessed. The evaluation involved 10 TLDs, with each metric measured 10 times, resulting in a total of 100 measurements.

Barcode recognition speed refers to the time taken for the system to complete the check-in or check-out process after the user scans the barcode using either the webcam or barcode scanner. In the webcam-based system, barcodes were recognized within a region of interest (ROI) set at the center of the video. The barcode scan execution time represents the total time from when the user clicks the check-in or check-out button to when the process is completed. This metric evaluates the responsiveness of the user interface and database processing speed. Finally, accuracy refers to the percentage of successful check-ins and check-outs performed correctly by the system and serves as a metric for comparing the reliability of the two systems. The average value for each evaluation metric was calculated by repeating each measurement ten times.

2.4. Data analysis

The performance evaluation analysis of the webcam-based and barcode scanner-based systems involved calculating the mean, median, standard deviation (SD), and minimum and maximum values. Statistical comparison between the two systems was performed using the Wilcoxon Signed-Rank test ($p < 0.05$), a non-parametric method suitable for paired samples with a small sample size. Statistical analyses were performed using the SPSS software version 27 (IBM, Armonk, NY, USA).

3. Results

3.1. TLD check-in/check-out system

A TLD check-in/check-out system was developed for use on both Windows and Mac operating systems. As shown in Fig. 1, the main functions included TLD registration, check-in, and check-out. The program layout was designed to be intuitive for users. The system allows users to view the list and count of registered TLDs. The checked-in TLDs are moved to the far-right panel. Conversely, when a TLD is checked out, it is moved from the check-in panel to the center panel. Additionally, the voice message set by the user can be delivered to the user along with the number of identified TLDs when the barcode is recognized.

The webcam and barcode scanner used for barcode scanning were connected to the PC via a USB, and they functioned properly without any issues during program execution. The necessary files for running the system included the main Python file (main.py), a database file for TLD registration and check-in/check-out management {tld_management.db}, and a text file for event logging {tld_log.txt}.

Table 2. Comparison of performance between webcam-based and barcode scanner-based systems.

Parameter	Webcam	Barcode scanner	Z	*p*-value
Barcode scan speed (s)				
Check-in	0.047 ± 0.002	0.046 ± 0.003	-1.376	0.169
Check-out	0.055 ± 0.011	0.046 ± 0.007	-2.701**	0.007**
Barcode execution time (s)				
Check-in	20.93 ± 6.94	3.68 ± 0.40	-2.803**	0.005**
Check-out	18.53 ± 5.67	3.89 ± 0.44	-2.803**	0.005**
Recognition rate (%)				
Check-in	32.12 ± 6.64	100	-2.803**	0.005**
Check-out	28.47 ± 5.56	100	-2.803**	0.005**

**, Indicates statistically significant difference - $p < 0.01$

3.2. Performance evaluation

Table 2 presents a comparison of performance between the webcam-based system and the barcode scanner-based system.

3.2.1. Scan speed

During check-in, the barcode recognition speed was 0.047 ± 0.002 seconds on average for the webcam-based system, and 0.046 ± 0.003 seconds for the barcode scanner-based system ($p = 0.169$, $p > 0.05$). The median for the webcam-based system was 0.045 seconds (range: 0.038–0.076 seconds), while the median for the barcode scanner-based system was 0.043 seconds (range: 0.035–0.066 seconds).

During check-out, the barcode recognition speed was 0.055 ± 0.011 seconds on average for the webcam-based system, and 0.046 ± 0.007 seconds for the barcode scanner-based system ($p = 0.007$, $p < 0.01$). The median for the webcam-based system was 0.049 seconds (range: 0.037–0.520 seconds), whereas that for the barcode scanner-based system was 0.043 seconds (range: 0.034–0.061 seconds).

3.2.2. Scan execution time

During check-in, the barcode scan execution time was 20.93 ± 6.94 seconds on average for the webcam-based system, and 3.68 ± 0.40 seconds for the barcode scanner-based system ($p = 0.005$, $p < 0.01$). The median for the webcam-based system was 15.23 seconds (range: 2.06–75.22 seconds), while the median for the barcode scanner-based system was 3.33 seconds (range: 2.06–7.40 seconds).

During check-out, the barcode scan execution time was 18.53 ± 5.67 seconds on average for the webcam-based system, and 3.89 ± 0.44 seconds for the barcode scanner-based system ($p = 0.005$, $p < 0.01$). The median for the webcam-based system was 13.94 seconds (range: 3.14–70.33 seconds), while the median for the barcode scanner-based system was 3.77 seconds (range: 2.04–6.82 seconds).

3.2.3. Scan recognition rate

During check-in, the barcode recognition rate (%) was 32.12 ± 6.64 % on average for the webcam-based system, and 100 % for the barcode scanner-based system ($p = 0.005$, $p < 0.01$). The median for the webcam-based system was 23.08 % (range 18.50 %–100 %). During checkout, the barcode recognition range (%) was 28.47 ± 5.56 % on average for the webcam-based system and 100 % for the barcode scanner-based system ($p = 0.005$, $p < 0.01$). The median for the webcam-based system was 20.00 % (range: 17.39 %–100 %).

4. Discussion

The loss of TLDs poses radiation protection and safety concerns for employees involved in the medical field. Administrative consequences, such as classification as reading-specific items or penalties, can cause disadvantages for individuals or institutions. However, the most crucial concern is that in the event of a radiation safety incident, the exposure dose due to the loss of a TLD cannot be determined. Measures to prevent TLD loss can be implemented at both individual and institutional levels. First, it is important to identify situations and causes of TLD loss. In medical institutions, TLDs may be lost when surgical gowns, work clothes, or lab coats are removed or washed [12]. Prevention methods include using anti-loss rings, attaching contact stickers for retrieval when a third party finds a lost dosimeter, using personal dosimeter storage boxes, wearing personal dosimeter necklaces, and implementing return checklists for retirees. Nevertheless, effective loss prevention requires both system improvements and reinforced individual management awareness.

In this study, a check-in/check-out system was developed to prevent TLD loss and enhance management. The performances of both the webcam-based and barcode scanner-based systems were compared and evaluated. A program was developed to recognize, identify, and check TLD barcodes using a webcam and 1D barcode scanner. The system was designed using a PyQt5 GUI to ensure that users could intuitively perceive the interface and functions, prioritizing practicality in line with the development objectives. Users can register, delete, reset, and record TLDs from the left panel, and perform check-in or check-out operations. The middle panel displays a list of registered TLDs, whereas the far-right check-in panel shows the list of checked-in TLDs, including check-in data and time (Fig. 2).

The computer vision technologies such as webcams, were expected to be suitable for TLD loss prevention systems. However, uncertainties were observed during the process of recognizing the 7-character TLD barcodes selected for this study. During the check-in/check-out test process, the barcode recognition speed was found to be very fast, approximately 0.05 seconds, but it was also confirmed that the barcode scan execution time was affected by several factors, such as the user, lighting, angle, and background. Researchers have considered alternative barcode recognition methods, such as Radio Frequency Identification (RFID) with electronic tags and barcode scanners, in addition to webcam-based systems. RFID was excluded from system development because it requires separate tags. The check-in/check-out system was designed to align with the research objectives, considering convenience, practicality, and sustainability, and a comparative evaluation was conducted between the webcam and barcode scanner systems. Barcode recognition speed showed no significant difference during check-in, in contrast to the significant difference found during check out; however, the barcode scanner-based system demonstrated superior performance in terms of barcode scan execution time compared with the webcam-based system ($p < 0.01$).

There was no statistically significant difference in barcode recognition speed between webcam- and barcode scanner-based systems. However, a significant difference was observed in barcode scan execution time. For the webcam-based system, the average time for check-in was 20.93 seconds, and for check-out was 18.53 seconds, whereas the barcode scanner-based system took an average of 3.68 seconds for check-in and 3.89 seconds for check-out, which was more than five times faster ($p < 0.01$). This suggests that the webcam-based system requires an image-processing step to improve barcode recognition, whereas the barcode scanner directly accesses the database.

The barcode scanner-based system demonstrated superior performance compared with the webcam-based system in terms of barcode recognition accuracy. During check-in (check-out), the average recognition rate for the webcam-based system was only 32.12 % (28.47 %), whereas the barcode scanner-based system achieved a 100 % recognition rate ($p < 0.01$). This suggests that webcam-based systems are more susceptible to factors such as user handling skills and environmental conditions (lighting, focus, angle, etc.), which can affect the clarity of barcode identification [13]. In contrast, the barcode scanner is not influenced by these external factors and can immediately read the barcode, resulting in a higher recognition rate.

This study is significant in that it developed a systematic approach for preventing TLD loss and strengthening management while experimentally comparing the performance of the two recognition methods. In particular, the practical performance differences between the webcam-based and barcode scanner-based systems were quantitatively evaluated, allowing for the identification of approaches to enhance convenience and safety management for radiation employees for whom TLD attachment is mandatory. However, this study has several limitations. First, the number of TLDs used in the experiment was limited to 10, highlighting the need for testing in more diverse environments. Second, the performance of the webcam-based system can be significantly influenced by hardware (camera resolution and frame rate) and software (image processing algorithms and threshold settings); therefore, future research should account for these factors. Third, for improved usability, various high-performance barcode scanner devices should also be considered.

Furthermore, the proposed system significantly enhances safety protocols for PET-MR operational workflows. Staff in these environments frequently transition between high-magnetic-field zones and radiation-controlled areas, making automated tracking essential for preventing dosimeter loss during mandatory screening and garment changes. Since the developed system utilizes electromagnetic principles for barcode scanning, it aligns with the technological infrastructure of magnetic-based medical environments. Future integration of this system could prevent dosimeter loss during the mandatory screening process required before entering high-magnetic-field areas.

Based on the experimental results of this study, future research may consider introducing deep-learning-based barcode recognition models to enhance the recognition accuracy of webcam-based systems or developing a system for centralized TLD management through cloud-based database integration [14, 15]. Additionally, the potential for developing a TLD check-in/check-out system using smartphone cameras with barcode-scanning capabilities is being considered. The key focus is to build a practical system that can be effectively used in real work environments for the intended purposes. Furthermore, fostering a radiation-safe culture is essential. Proper use of personal dosimeters is necessary to accurately assess radiation exposure doses, and careful adherence to regulations is required [16]. Most importantly, preventing the loss of dosimeters and strengthening management measures should be prioritized to ensure the long-term health and safety of employees.

5. Conclusion

This study confirmed that using a barcode scanner in the TLD check-in/check-out system is a faster and more reliable solution. The barcode scanner recorded a barcode recognition execution time that was more than five times faster than that of the webcam-based system ($p < 0.01$) and achieved 100 % accuracy in barcode recognition. Through further research and technological advancements, this system is expected to contribute to the development of a more effective TLD loss prevention and management system.

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