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The Usefulness of X-ray Output Management in General Radiography Systems Using Exposure Index

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Abstract

PURPOSE:

The periodic quality control of X-ray devices is important for obtaining optical medical images and determining the appropriate X-ray exposure dose. Additionally, the measurement of the X-ray output is constrained by time, technical aspects, and expenses. Therefore, we investigated the usefulness of a simple method for managing X-ray output using an Exposure Index (EI).

METHODS:

The entire surface of the flat panel detector was X-ray-irradiated every Friday at the time of end-of-work inspection under the condition that the recorded EI was approximately 1,000. The EI and exposure dose were measured, and the linearity and accuracy were evaluated.

RESULTS:

The output gradually decreased from the start of the measurements in Room 1 and stabilized after the output was adjusted. The relationship between exposure dose and EI showed high linearity, with $R^2 > 0.99$, and the CV of EI was less than 2.41%, indicating high reproducibility.

CONCLUSIONS:

We demonstrated that the results of constancy tests can be easily quantified using EI. The EI method can manage the X-ray output with good reproducibility.

Keywords

Constancy tests, exposure index (EI), exposure dose, flat panel detector (FPD), digital radiography (DR), X-ray output

1. Introduction

An essential condition for diagnostic X-ray equipment is the assurance of quality, including electrical, mechanical, and radiation safety [1]. Managing the accuracy of X-ray equipment is extremely useful for maintaining the equipment under optimal conditions, ensuring the best possible medical images, and determining an appropriate level of X-ray exposure [2]. According to notifications from the Health Policy Bureau in 1996 (No. 263) and the Medical Affairs Bureau in 2005 (No. 1222001), "the maintenance and inspection of medical equipment should be appropriately performed by medical institutions as part of their duties," and the management of equipment is the responsibility of medical institutions [3]. However, the maintenance contract rates of general radiography systems are low, and although acceptance tests are frequently conducted at the time of purchase, the implementation rate of constancy tests performed by users is low [2,4]. The low implementation rate of constancy tests is attributed to the need for specialized and expensive equipment such as dosimeters and luminance meters [1] and the complexity and time-consuming nature of the measurement procedures.

X-rays are generated when the thermal electrons emitted from the cathode are accelerated and focused by the potential distribution between the cathode and anode, striking the anode. The tube current is controlled by adjusting the heating current of the X-ray tube filament. The tube current represents the flow of thermal electrons emitted from the cathode of the X-ray tube, and the number of electrons is controlled by the heating value of the filament. The number of thermal electrons depends on the

temperature of the cathode; when the cathode cools, the number of thermal electrons emitted decreases, resulting in a lower X-ray output [5–6]. In addition, X-ray tube filaments gradually deteriorate when they are first used after being replaced with new filaments [7]. These technical factors emphasize the need for regular monitoring and adjustment of X-ray equipment to ensure consistent performance and output stability.

To address these challenges, a method utilizing the system sensitivity value (S value) was proposed [8]. The S value is a critical parameter in digital radiography, representing the response of the imaging system to the incident X-ray dose. It is inversely proportional to the logarithm of the dose, meaning that as the dose increases, the S value decreases. This relationship allows for the detection of changes in X-ray output, making the S value a useful tool in monitoring the performance of X-ray equipment.

However, while the S value is effective in detecting output changes, interpreting the magnitude of these changes can be challenging. Because the S value is inversely related to the dose logarithmically, changes in output may not be easily understood or quantified in a straightforward manner.

The Exposure Index (EI), proposed by the International Electrotechnical Commission in 2008, represents the dose incident on a detector. In 2010, a study group on "Appropriate Dose Considering Image Quality and Exposure of Digital Images" reported that EI is useful for dose optimization in digital radiography, as it serves as a unified dose index [9]. Unlike the S value, EI is directly proportional to the incident dose [9–11], making it easier to understand changes in X-ray

output. This characteristic makes EI more practical for routine quality control, as it simplifies the interpretation of dose variations.

Therefore, this study aims to evaluate the effectiveness of EI for routine inspection of X-ray output management in general radiography systems. By developing a straightforward and cost-effective method, we seek to enable users to conduct these inspections easily and efficiently, addressing the current barriers to regular constancy testing in clinical settings.

2. Methods

2-1 Equipment Configuration

There are three general radiography rooms in our hospital. Rooms 1 and 3 each have one X-ray tube, whereas Room 2 has two X-ray tubes. The X-ray generators used are RADspeed Pro DR pack (Shimadzu Corporation) in Rooms 1 and 2, and a KXO-50SS (Canon Medical Systems Corporation) in Room 3. The X-ray tubes in Room 1, 2, and 3 are 0.6/1.2P366D-150 (Shimadzu Corporation), 0.6/1.2P364DK-85 (Shimadzu Corporation), and DRX-3724HD (Canon Electron Tubes & Devices Co. Ltd.), respectively. During the process, the X-ray tube in Room 1 was replaced due to performance deterioration; the X-ray tube 0.6/1.2P366D-150 (Shimadzu Corporation) was replaced by a new X-ray tube of the same type on April 27, 2022 and November 25, 2022. Images were processed using Console Advance (Fujifilm Medical Co., Ltd.) and the flat panel detectors (FPD) used were CALNEO Smart G47, CALNEO Smart G77, and CALNEO Smart C77 (Fujifilm Medical Co., Ltd.). The

maximum effective image sizes for the G47 were 13.8×16.8 inches (image matrix size 2336×2836 pixels), and 16.8×16.8 inches (image matrix size 2836×2836 pixels) for the G77 and C77. The combinations of equipment used are listed in Table 1.

Table 1: Combination of devices used.

X-ray tube No.	X-ray generator	X-ray tube	FPD (CALNEO Smart)
1	RAD speed Pro DR pack	0.6/1.2P366D-150	G47
2-1	RAD speed Pro DR pack	0.6/1.2P364DK-85	G77
2-2	RAD speed Pro DR pack	0.6/1.2P364DK-85	G47
3	KXO-50SS	DRX-3724HD	G47 (-2022/12/22) C77 (2022/12/23-)

2-2 Measurement of EI, Dose Accuracy, and Linearity

The setup shown in Figure 1 was used with the imaging conditions set to 70 kV and 100 mA, and the imaging distance was set to 180 cm (174 cm in Room 1 owing to structural issues). The filters attached to the equipment were 0.2 mm Cu in Rooms 1 and 2, and 1.5 mm Al + 0.1 mm Cu in Room 3. The exposure time was varied from 0.006 s to 0.1 s, and the EI and dose were measured. Measurements were taken five times under each condition, and the coefficient of variation (CV) was calculated using the formula below to determine the accuracy. The measurements were conducted after changing the FPD in Room 3.

$$CV (\%) = (\text{standard deviation} / \text{mean}) \times 100 \cdot \cdot \cdot \cdot \cdot (1)$$

The dosimeter sensor was placed at the same position as the center of the FPD surface when measuring the dose. The dosimeter used was a RaySafe X2 (Unfors RaySafe). Simple linear regression analysis was performed to evaluate the linearity between the EI and dose. The statistical analysis software Eazy R (EZR, Saitama Medical Center, Jichi Medical University, Saitama, Japan) was used for this analysis [12].

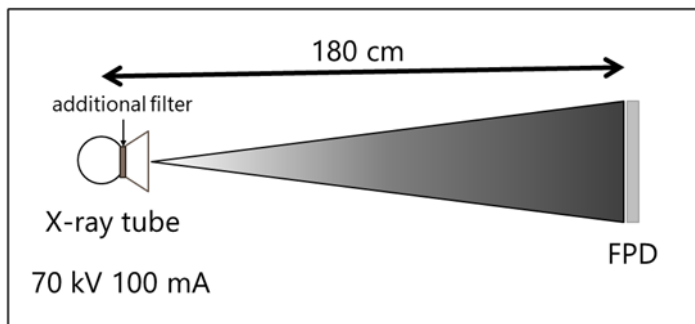


Fig. 1 The measurement setup.

2-3 Measurement Method

In this study, a routine inspection method that does not impose a burden on the operator and can be performed in a short time was adopted. The EI_T (Target EI) is the EI value at the time of equipment renewal or X-ray tube replacement. The reason for setting the EI to approximately 1,000 is that it is intuitively easy to understand the amount of output change when there is a change in EI, it is possible to check images without saturation of pixel values owing to overdose, and it is possible to evaluate uniformity and FPD damage simultaneously because the entire FPD surface is irradiated. The number of measurements was set to one because the EI did not vary even when measured multiple times under

the same conditions in a preliminary experiment conducted before the control. The control range was set to 20% because JIS Z 4752-2-11 states that X-ray output should be within 20% of the basic value. JIS Z 4752-2-11 is a standard procedure outlined in the Japanese Industrial Standards (JIS) document titled "Evaluation and routine testing in medical imaging departments - Part 2-11: Constancy tests - Equipment for general direct radiography." This standard provides guidelines for ensuring the stability and accuracy of X-ray equipment through regular constancy tests [13]. By adhering to this standard, our method ensures that the X-ray output remains within the recommended tolerance, thereby maintaining the quality and reliability of diagnostic imaging.

The image processing parameters used were those for quality control, with Semi Auto as the Exposure Data Recognizer (EDR) mode, GA=1, GT=a, GC=12, and GS=0, and the multifrequency processing parameters were MRB=B, MRT=F, and MRE=5. Other image-processing parameters were turned off.

The EI is calculated from the representative pixel values extracted from the EDR (Exposure Data Recognizer) histogram analysis results for the entire image area and is defined by equation (2).

$$EI = c_0 \cdot g(V) \cdot \dots \cdot (2)$$

Where, c_0 is a constant of $100 \mu\text{Gy}^{-1}$, and $g(V)$ is a function that derives the air kerma (K) incident on the detector front from the sensitivity index (V). EI is expressed by the calibration in Equation (3).

$$EI = c_0 \cdot K_{\text{cal}} \cdot \dots \cdot (3)$$

The relationship between K_{cal} and sensitivity index is expressed by Equation (4).

$$K_{cal} = g(V_{cal}) \cdot \cdot \cdot \cdot \cdot \cdot \cdot (4)$$

Therefore, the EI was obtained by calculating the air kerma incident on the front surface of the detector from the actual sensitivity index using the approximate formula obtained by calibration and multiplying by 100 [10].

3. Results

Figure 2 shows the relationship between the exposure dose and the EI, and Table 2 shows the results of the single regression analysis. The adjusted coefficient of determination R^2 was 0.998 for X-ray tubes 1, 2-1, and 2-2, and 0.993 for X-ray tube 3, with $p < 0.001$ for all P values.

Figure 3 shows the progression of the EI. The output gradually decreased from the beginning of the measurement in radiography Room 1 and stabilized after the output was adjusted on June 27, 2021; however, a gradual decrease in output was observed after the X-ray tubes were replaced with new ones on April 27 and November 25, 2022. After the output was adjusted on December 8, 2023, it stabilized.

Table 3 shows the measurement results for EI and exposure dose. The CV of EI ranged from 0 to 2.41%, and the exposure dose ranged from 0.09 to 2.44% for all the measured irradiation times.

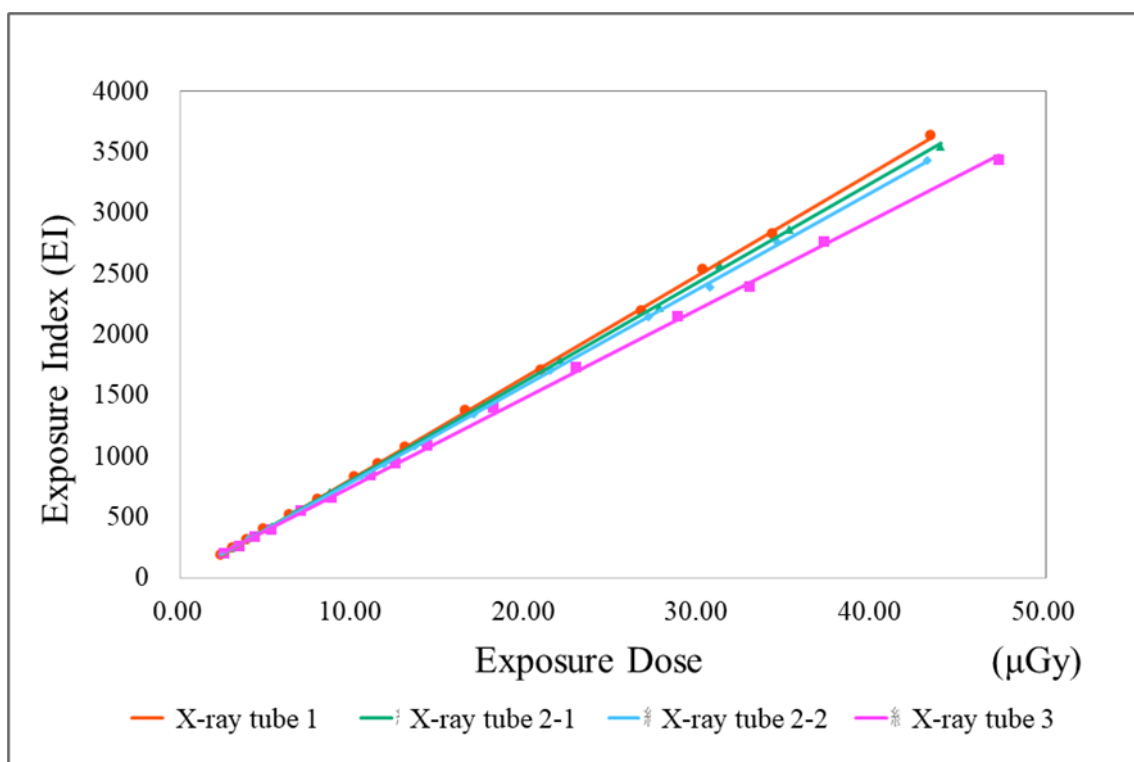


Fig. 2 Relationship between exposure dose and EI for the four X-ray tube used in the measurement.

Table 2 Results of single regression analysis.

	Estimate	Standard Err	95%CI	adjusted R ²	P-value
X-ray tube1	83.5726	0.3173	82.88722 - 84.25806	0.9998	p<0.001
X-ray tube2-1	81.489	0.3062	80.82741 - 82.1506	0.9998	p<0.001
X-ray tube2-2	79.3174	0.2767	78.71967 - 79.91519	0.9998	p<0.001
X-ray tube3	72.7935	0.5323	71.64344 - 73.94348	0.9993	p<0.001

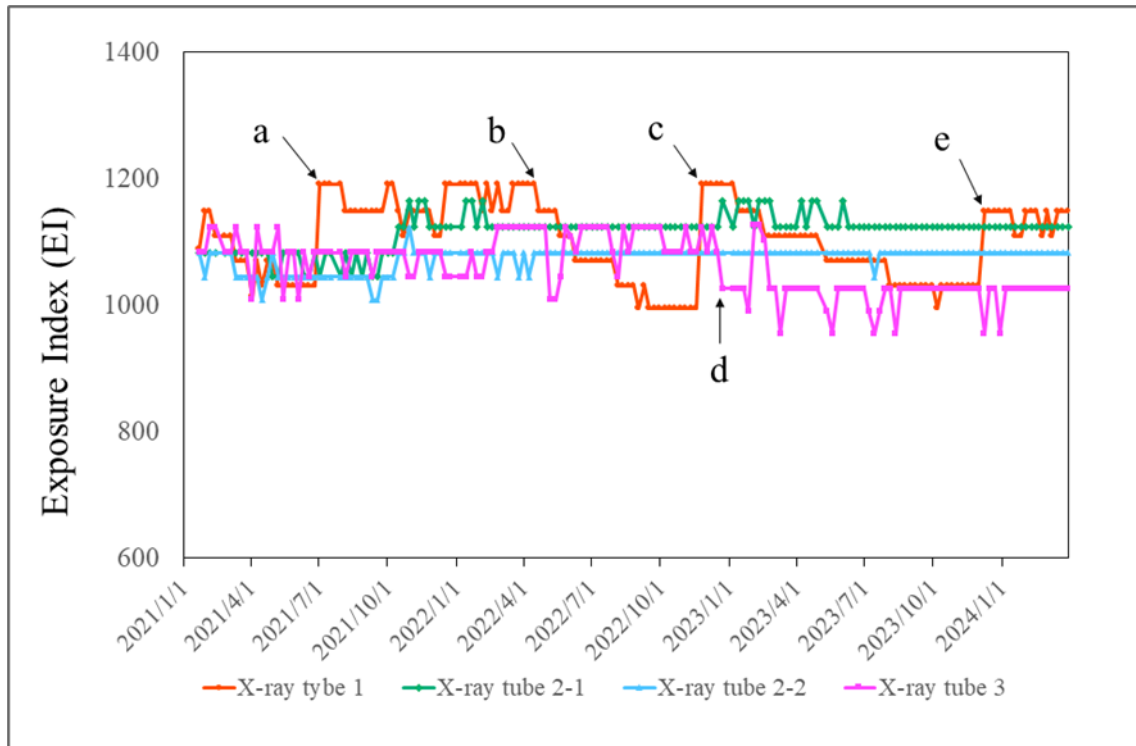


Fig. 3 The transition of the EI.

- (a) X-ray tube 1 output adjusted (2021/6/27).
- (b) Replaced X-ray tube 1 (2022/4/27).
- (c) Replaced X-ray tube 1 (2022/11/25).
- (d) Adjusted X-ray tube 3 output (2022/12/18) and changed FPD (2022/12/23).
- (e) Adjusted X-ray tube 1 output (2023/12/8).

Table 3: Accuracy of EI and exposure dose measurements.

Timer (s)	X-ray tube1				X-ray tube2-1				X-ray tube2-2				X-ray tube3			
	EI	CV(%)	μ Gy	CV(%)	EI	CV(%)	μ Gy	CV(%)	EI	CV(%)	μ Gy	CV(%)	EI	CV(%)	μ Gy	CV(%)
0.0063	192	1.65	2.36	0.63	200	0.00	2.52	0.79	193	0.00	2.39	0.60	193	2.41	2.54	2.44
0.008	249	1.79	3.05	0.58	257	0.00	3.29	0.45	248	0.00	3.13	0.47	257	1.63	3.42	1.70
0.01	314	0.00	3.86	0.24	331	0.00	4.16	0.78	319	0.00	4.02	0.90	331	1.66	4.31	1.21
0.012	399	1.73	4.83	1.29	425	0.00	5.30	0.64	396	0.00	5.06	0.60	396	2.16	5.26	1.70
0.016	520	0.00	6.31	1.12	547	0.00	6.86	0.37	528	0.00	6.57	0.56	547	1.38	7.00	1.29
0.02	646	0.00	7.94	0.53	704	0.00	8.63	0.43	655	0.00	8.31	0.49	655	1.74	8.77	0.98
0.025	831	0.00	10.07	0.78	873	0.00	10.85	0.43	842	0.00	10.50	0.30	842	0.00	11.03	1.03
0.028	935	1.64	11.39	0.42	973	0.00	12.19	0.19	938	0.00	11.80	0.09	938	0.00	12.44	1.22
0.032	1069	0.00	13.02	0.61	1123	0.00	13.96	0.15	1083	0.00	13.51	0.41	1083	0.00	14.32	1.00
0.04	1375	0.00	16.47	0.18	1420	1.80	17.49	0.28	1344	0.00	16.94	0.29	1394	1.78	18.09	1.47
0.05	1706	0.00	20.83	0.24	1793	0.00	21.94	0.23	1702	1.81	21.37	0.25	1730	1.57	22.85	1.18
0.063	2194	0.00	26.61	0.12	2225	0.00	27.67	0.19	2146	0.00	27.03	0.23	2146	1.76	28.74	0.97
0.071	2534	0.00	30.17	0.27	2569	0.00	31.15	0.24	2391	0.00	30.58	0.21	2391	1.71	32.90	0.91
0.08	2823	0.00	34.21	0.18	2862	0.00	35.17	0.20	2761	0.00	34.47	0.15	2761	1.72	37.19	1.39
0.1	3631	0.00	43.31	0.21	3552	0.00	43.92	0.13	3426	0.00	43.17	0.20	3426	0.00	47.29	0.50

4. Discussion

We investigated a cheap and fast method for performing X-ray output control that enables users to periodically check the constancy of their X-ray inspection systems. The present method, which does not use any special equipment or phantoms but simply exposes X-rays to the FPD, requires less than 5 min to test a radiographic room and can be performed without burdening the user. However, to reduce the burden on the user, we believe that it is possible to extend the interval to 1 month, as reported by Tanaka [8]. JISZ4752-2-11 states that "constancy tests shall be conducted daily for 1 week after installation, every 2 weeks for 6 months, and at least every 3 months thereafter" [13], so it is desirable to set an interval not exceeding the stated timeframe.

It has been documented in the literature that the EI is proportional to the exposure dose [9-11], and the results of this study demonstrate this relationship with high accuracy. Therefore, any changes in the

output can be easily quantified. Consequently, if immediate output adjustment is not feasible, modifying the default imaging conditions according to the change in the output can ensure that the delivered dose remains consistent before and after the change, thereby enabling the production of stable images.

Although equipment manufacturers verify whether the tube current and other parameters match the displayed values, they do not measure the final output dose. If the tube current is correctly displayed but the output is reduced because of X-ray tube deterioration, it is difficult to detect such issues during inspections. Therefore, our method of using EI for X-ray output management is useful for the prompt detection of equipment malfunctions.

In constancy tests, consistency in imaging conditions and test environment is essential for conducting tests with good reproducibility [8]. If the irradiation time is short, the error increases because the ratio of the variation to the irradiation time increases when the exposure time fluctuates. For example, if the exposure time is set to 0.01 s, a difference of 10% in the exposure dose occurs if the actual exposure time differs by 0.001 s from the time indicated on the device. In addition, if the distance is measured with a tape measure each time, errors owing to distance measurements are likely to occur. In this study, distance measurement was unnecessary because the distance at the position where the ceiling runs stopped was measured, and the irradiation time required to set the EI to approximately 1,000 was 0.032 s. This minimizes errors owing to differences in irradiation time between the X-ray generators and

errors in distance measurement by the measurer, thereby reducing the variation in the EI.

One of the significant advantages of the proposed EI-based quality control method is its efficiency compared to conventional dosimeter-based methods. In terms of time, the EI measurement process takes approximately 1 minute, while the measurement using a semiconductor dosimeter requires around 10 minutes. This makes the EI method more practical for routine use, particularly in busy clinical settings where time is critical. In addition to time efficiency, cost is another important factor.

Dosimeters typically range from several hundred thousand yen to several million yen, which may present a financial burden for medical institutions. In contrast, EI measurement utilizes the existing imaging system, eliminating the need for additional hardware and thus significantly reducing costs.

Regarding image quality, although this study does not provide specific data, it is generally recognized that a decrease in X-ray output often results in a reduced delivered dose, leading to increased image noise. This is typically observed as a reduction in the signal-to-noise ratio under insufficient exposure conditions. While image quality data were not collected in this study, maintaining stable X-ray output through regular monitoring with the EI method should help mitigate these potential effects by ensuring consistent output levels. In terms of accuracy, the coefficient of variation (CV) for EI measurements ranged from 0 to 2.41%, while for dosimeter measurements, it ranged from 0.09 to 2.44%. These results demonstrate that the EI method offers comparable accuracy to dosimeter-based measurements, making it a reliable alternative for managing

X-ray output. Furthermore, JIS Z 4752-2-11 specifies that X-ray output should be measured using a device with a reproducibility of 5% or less [13]. The EI method used in this study meets this requirement, as the maximum CV of EI was 2.41%, ensuring that the method is both accurate and compliant with the standards for reproducibility. By offering similar accuracy while reducing both time and cost, the EI method provides a practical solution for routine quality control in X-ray systems.

In our hospital, owing to the operation of the equipment, there is often a time interval between the last imaging and measurement in imaging Room 3, during which the cathode cools and the EI becomes low. In such cases, the cathode was aged and re-measured.

In addition, a gradual decrease in the output power after output adjustment was observed for approximately 1 year after the equipment was updated. In Figure 3, taking the case of Room 1 as an example, the output gradually decreased from the beginning of the measurement and stabilized after the output adjustment on June 27, 2021; however, it continued to decrease gradually after the X-ray tube was replaced with a new one on April 27, 2022, and November 25, 2022 and stabilized after the output adjustment on December 8, 2023, one year after the X-ray tube was replaced. The X-ray tube filaments gradually deteriorate when they are first used after being replaced with new filaments [7]. It is known that these degradations stabilize after 6 months to 1 year, depending on the frequency of use and other conditions, which is thought to be the reason for the phenomenon observed in this study. We believe that the stabilization observed after output adjustment was due to the settling of the filament

degradation. Therefore, it is desirable to carefully observe the output for approximately 1 year until it stabilizes when the equipment is newly installed or when the X-ray tube is replaced with a new one.

One limitation of this study is that only follow-up observations were made using the same equipment.

The uncertainty (error) of $g(V_{cal})$ is specified to be less than 20% using Equation (4) and following the measurement method in Section 2-3 [11], and the calibration of EI has a tolerance specified by the equipment manufacturer, so the same EI value is not obtainable for all detectors even if they are exposed to the same exposure dose. Therefore, although it is suitable for monitoring the progress of the same device, it is impossible to compare the large and small doses achieved using other devices.

In addition, it should be noted that when starting the management of an existing device, it is impossible to know that the output has decreased at the start of the management.

5. Conclusion

The routine inspection method for X-ray output management using the EI in general radiography systems was found to be a simple, quick, and effective method to ensure the stability of the X-ray output without burdening the user. This method can be widely adopted in clinical settings, contributing to the consistent production of high-quality medical images and the safe use of X-ray equipment.

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