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Location Analysis for Additional Permanent Radiation Detector in X-Ray Radiography Unit

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***Abstract*—We have developed a Digital Fluorescence X-Ray Radiography prototype at the Department of Physics, Gadjah Mada University (UGM). The prototype should comply with radiation protection rules. Using an additional permanent dose detector to measure dose radiation indirectly is necessary. We indirectly controlled the dose analysis through a dose control chart from a permanent detector. We consider the Heel Effect in determining the position of the detector at the edge of the screen while reducing the scattered radiation and minimizing the difference to the reference point. The position of the detector follows a grid 5x5. The dose measurement will show the dose distribution pattern. It shows that the radiation dose at the edge point close to the cathode side has the closest dose value to the center point. The dose value variation at 70 kVp and 80 kVp is less than 5%. The dose value equation for the prototype is μGy = |(0.3579* *kVp*) -16.27| * mAs. A control chart will control that equation from the permanent detector to ensure that the dose value obtained is always valid. The Warning Limit (WL) dose from the control chart is 68.75 μGy, 63.99 μGy, and the Action Limit (AL) is 69.94 μGy and 62.80 μGy. The dose radiation monitoring may use the dose value equation controlled by a control chart from the permanent detector. Continuous reports on the dose value and the limit dose value are essential to ensure the health of the RSFD prototype.**

***Keywords*— Radiography; x-ray machine; dose radiation; radiation protection; x-ray detector.**

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I. INTRODUCTION

X-rays are formally used in radiography systems to obtain an image of an organ in the human body. Doctors use that image to diagnose a patient illness. However, x-rays can cause radiation effects that can harm the patient. Therefore, the use of x-rays must be carried out following applicable regulations. The International Atomic Energy Agency (IAEA) published the latest Safety Standard Series No. GSR Part 3 in 2014 states that all radiation-related activities, both in the health sector, nuclear installation operations, production, transportation, and use of radioactive materials and waste, are the responsibility and regulation of the respective regulatory bodies in each country [1]. In this case, it is the Nuclear Energy Regulatory Agency (BAPETEN) in Indonesia. Diagnostic radiology must implement the optimization of Radiation Protection [2]. The dosage information in diagnostic radiology is essential to know. Radiologists should be familiar with the dose quantities to inform patients about radiation risks and benefit [3]. The patient dosage must be as low as possible without sacrificing the image quality. By utilizing the right type of detector, digital x-ray radiography can obtain an optimal image at a lower dose [4].

A significant development in radiology today is computer technology, known as Digital Radiography [5]. The Laboratory of Imaging Physics in Gadjah Mada University at Yogyakarta, Indonesia, has developed digital radiography. The developed Digital Fluorescent X-Ray Radiography prototype is a Direct Digital Radiography (DDR) based on a fluorescent screen coupled with a digital camera. DDR technology tends to be slightly higher than conventional technology movie screens [6]. However, the DDR dose value is much smaller than the Computerized Radiography (CR) technology [7]. The prototype must comply with applicable regulations to operate in Indonesia, specifically for radiation protection. Following radiation protection rules for radiation workers, the environment, and the general public, a series of radiation dosimeter systems based on a wireless sensor network may continuously monitor the radiation exposure around the room [8]. A series of dosimeters equipped with a

GUI can optimally determine gamma and x-ray radiation exposure very well [9]. While radiation protection for patients, an x-ray machine must provide dosage information that a conventional x-ray machine cannot do. A permanent addition of radiation detectors may be added to the x-ray machine to comply with these regulations. It is necessary to analyze the implementation of adding a permanent detector to apply for radiation protection.

In this study, several analyses have been carried out. The first is the analysis of detector placement. The detector must be placed at the right point to avoid artifacts from the detector itself. Determination of the permanent detector placement point must consider the heel effect. The heeling effect has been investigated in vertical and horizontal x-ray directions in the previous study. That study concludes that the heel effect in anode has more effect on x-ray in a vertical direction [10]. We will find out the characteristic heel effect of this prototype to determine the location detector placement.

The following analysis is to determine the patient dose value. The dose value analysis was carried out through calculations following the IAEA Publication TRS No. 457 (2007) standards to obtain a relation between the exposure factor and the incident air kerma (INAK) [11]. The previous study regarding patient dosage is an application containing calculations to obtain the Entrance Skin Dose (ESD) value by entering the x-ray exposure factor. The dose value was obtained from the indirect method [12]. The new approach in this research is controlling the dosage values from the indirect method by the control chart obtained from a permanent detector. This study will make a system so that quality control can be done quickly. Through a control chart obtained from a permanent detector, validation of the dose value equation can be carried out, and quality control of the prototype. This advanced practice does benefit the healthcare system, which is cost reduction and workload [13].

II. Material and Method

The first step of our study is instrument validation to ensure that the prototype used in the research can be trusted [14]. Instrument validation is also known as the acceptance test. We tested three parameters: voltage-compliant, linearity test on the radiation output, and stability test. Finally, three analyses were carried out after the prototype was declared valid: dose value analysis, dose distribution, and control chart analysis.

Dose value analysis was used to obtain the dose equation. The dose equation can be used to obtain the patient dose value from the exposure factor. The dose equation is obtained from an indirect method at a specific time, so we use the permanent detector to control the equation through a control chart so that the equation is always valid. Dose distribution was used to obtain the location detector placement. A control chart was made from the permanent detector at the point determined in the previous stage.

A. Acceptance Test

An acceptance test validates the x-ray machine condition [14]. We use an X-ray *Raysafe xi* detector that measures all three testing parameters. First, the voltage-compliant test checks the voltage difference of the actual voltage measured by the detector to the one set on the control panel. Equation 1 can be developed to obtain the error compared to the maximum acceptable error of 10%.

$$Error = \frac{kVp\ set - kVp\ actually}{kVp\ set} * 100\% \quad (1)$$

Second, the consistency test on the radiation output value (μGy/mAs) is related to the increasing exposure factor. The linearity coefficient (CL) can be calculated by Equation (2), and the acceptable CL is less than 0.1.

$$CL = \left| \frac{\left(\frac{\mu Gy}{mAs}\right)_{max} - \left(\frac{\mu Gy}{mAs}\right)_{min}}{\left(\frac{\mu Gy}{mAs}\right)_{max} + \left(\frac{\mu Gy}{mAs}\right)_{min}} \right| \quad (2)$$

The third is the consistency test on the radiation output following the voltage, time, and output dose. The acceptable coefficient of variation CVV for voltage, CVT for time, and CVOD for output dose are less than 0.05 based on the formula presented by Equation 3 to Equation 5. When those three parameters are below the acceptance requirement, the x-ray machine is considered valid and reliable.

$$CV_{OD} = \frac{SD}{\overline{\mu Gy}} \quad (3)$$

$$CV_T = \frac{SD}{\overline{ms}} \quad (4)$$

$$CV_V = \frac{SD}{\overline{kVp}} \quad (5)$$

B. Dose Value

The dose value is collected indirectly, where the method used follows IAEA Publication TRS No. 457 (2007). The dose calculation runs by using the exposure factor parameter and the output tube $Y(d)$. The measurement of dose data is at a distance between the tube and the detector of 100 cm. Then the measurement was carried out with irradiation conditions by varying the exposure factor between 60kVp to 85kVp with a 5kVp increase in voltage while the current of 15mAs is constant. The x-ray output $Y(d)$ calculation is using Equation 6.

$$Y(d) = \frac{K(d)}{P_{lt}} \quad (6)$$

Where $K(d)$ is the dose value read by the detector, and P_{lt} is the current (mAs). Then a graph is made by connecting the kVp on the x-axis and $Y(d)$ (μGy/mAs) on the y-axis. So that, it is expected a linear graph with $y = mx+c$ or Air Kerma at 1 meter ((μGy/mAs) = m*(kVp)+c. From that equation, we can find the dose from the exposure factor.

C. Dose Distribution

The dose distribution determines the suitable location of the detector. The dose value measurement runs on the screen detector area under the patient table, as shown in Figure 1. The screen detector has 40 cm x 40 cm, divided into 25 parts (points A1 to E5). The dose value at each point at a particular exposure factor will be measured.

The exposure factors used were 60, 70, and 80 kVp with 15 mAs. The *Matlab R2017a* software will create an associated 2D graph for each variation exposure factor used, which presents the relationship between the coordinate points and the dose values obtained. The graph will visualize the difference between each point relative to the center point (point C3), a reference point. The point with the closest dose

value to the reference point (C3) at each variation will be the place of the permanent detectors.

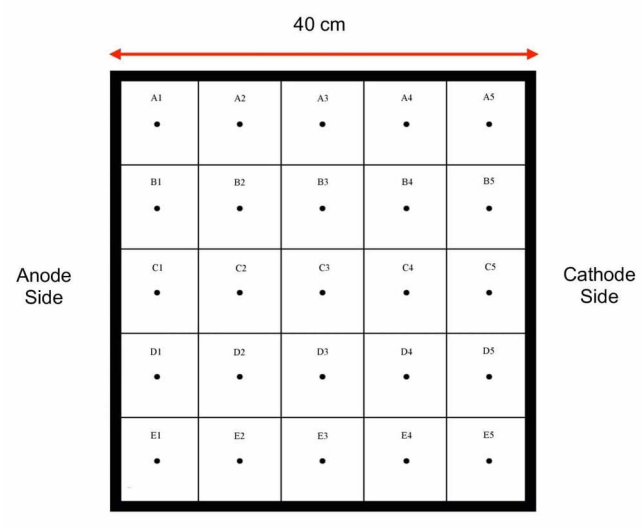

Fig. 1 Detector Screen area

D. Control Chart

When the detector location and the exposure factor are determined, the final step is to collect the data used as a control chart. The place of the detector is at the location determined according to the results of the previous step method. The exposure factor is at 70kVp, 100mA, and 0.15s. There are 50 data obtained and then entered into *Microsoft Excel*. Then the graph was created by setting the y-axis for the values obtained and the x-axis for the data collection time. The average of the data determines the Upper Warning Limit (UWL), Lower Warning Limit (LWL), Upper Action Limit (UAL), and Lower Action Limit (LAL) using Equations 7-10. Average values, UWL, UAL, LWL, and LAL, are put into the graph. [15]

$$UWL = mean + (2 * Standard\ Deviation) \quad (7)$$

$$LWL = mean - (2 * Standard\ Deviation) \quad (8)$$

$$UAL = mean + (3 * Standard\ Deviation) \quad (9)$$

$$LAL = mean - (3 * Standard\ Deviation) \quad (10)$$

A control chart is a tool for quality control. The quality control may run weekly or monthly. Medical physicists can perform quality control by doing exposures without objects with an exposure factor of 70kVp, 100mA, and 0.15s. The obtained new data is put into a graph and then compared with the data set at the old control chart via *F*-test and *T*-test, through Equation 11 and Equation 12.

$$F_{value} = \frac{s^2_{old}}{s^2_{new}} \quad (11)$$

$$t_{value} = \frac{\bar{x}_{old} - \bar{x}_{new}}{\sqrt{\frac{s^2_{old}}{n_{old}} + \frac{s^2_{new}}{n_{new}}}} \quad (12)$$

Measurement or equipment can be said to be out of control if it meets the following requirements:

F value > F v-old,v-new,α if s2 old > s2 new

F value < F v-old,v-new,α if s2 old < s2 new and

|t value| > t critical

If these measurements meet the requirements, it is necessary to verify procedures, radiation workers, or x-ray equipment whether the x-ray machine needs further Acceptance Tests or Recalibration.

III. Result and Discussion

A. Result

1) Acceptance Test: The acceptance test is essential to ensure that the prototype used in the research is reliable [16]. In this study, there were three types of tests carried out. The first test finds an error between the setup voltage on the x-ray control panel and the actual voltage through Equation 1. The exposure factor used is 100mA, 0.15s, and voltage variations between 60kVp to 85kVp. The allowed error limit of below 10%. The slightest error at voltage setting 60kVp is 1%, while the most significant error at 85kVp is 3.6%. Those errors show a slight difference between 1% to 3.6% on the actual voltage and the voltage set on the table control. Those errors are still reasonable and acceptable because the error is less than 10%. The next test is the Linearity Coefficient or consistency of the increase in the radiation output value (μGy/mAs) on the increase in the exposure factor used. The Linearity Coefficient (CL) is obtained by Equation 2. The linearity coefficient (CL) is 0.02. The maximum CL value allowed is 0.1. It means that the increase in the exposure factor will increase the radiation output linearly. The last test is to find the stability of the x-ray machine. The parameters tested were tube voltage, exposure time, and dose. The exposure factors used in the consistency test were 60kVp, 100mA, and 0.15s. The Coefficient Variation (CV) obtained from Equations 3 to 5 is 0.002 at that voltage, 0.003 at that time, and 0.034 at that dose. The maximum CV that can be accepted is 0.05, which means that the tools used are consistent.

2) Dose Value: Dose value was collected at a distance of 100 cm from the tube and detector (SDD) by varying the exposure factor between 60kVp to 85kVp with a 5kVp increase, while the current setting remains at 15 mAs. Measurement is done three times for each exposure. The graph is made by connecting the kVp on the x-axis with Y(d) (Equation 6) on the y-axis, as shown in Figure 2.

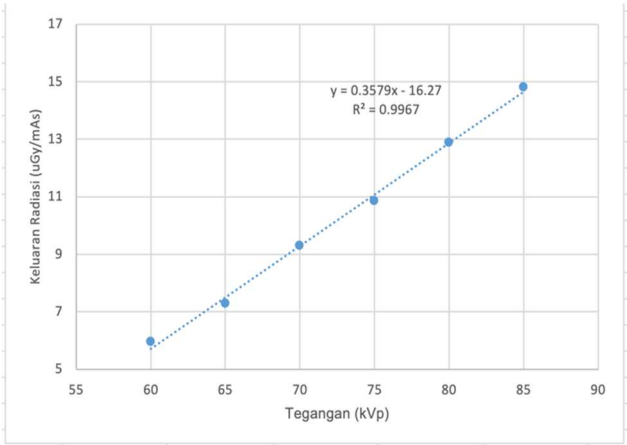

Fig. 2 Tube Output Chart

From Figure 2, we obtained the linear equation $y = 0.3579x - 16.27$. This equation found that a dose at a one-meter distance from the focal point is independent of the exposure factor, according to Equation 13.

$$y = 0.3579x - 16.27$$

$$\frac{\mu Gy}{mAs} = 0.3579(kVp) - 16.27$$

$$\mu Gy = \lfloor(0{,}3579 * kVp) - 16.27\rfloor * mAs \qquad (13)$$

Table 1 shows the validation of Equation 13. The dose value obtained from the calculation by Equation 13 compares with the dose value obtained from measurement.

TABLE I
COMPARISON DOSE VALUE

Exposure Factor	Dose (µGy)	Uncertainty (µGy)	Calculated Dose (µGy)
60 kVp 10 mAs	53	3	52
65 kVp 15 mAs	102	6	105
60 kVp 20 mAs	105	5	104

Table 1 shows that three-dose values obtained through the calculation are within the boundary of uncertainty, which means that Equation 13 is valid.

3) Dose Distribution

Dose distribution data is the dose value taken on a screen detector located under the patient's table. The location used to place the permanent detector is under the patient's table, precisely above the screen or image receptor. The next prototype may use a permanent detector in which the detector is under the table to get the value of the exit dose and the value of the receptor dose. These values may determine the characteristics of the prototype for both dosimetry and image quality purposes.

The *Matlab R2017a* software plots the dose distribution data into 2D graphics color mode to visually the value of the dose distribution so that it is easier to observe. The 2D graphics color mode shown in Figure 2 follows the detector position shown in Figure 3.

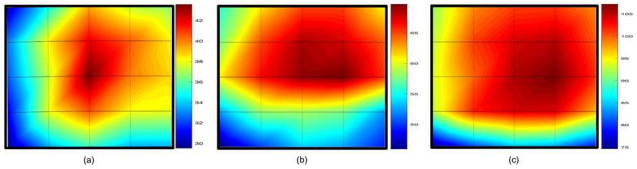

Fig. 3 Dose Distribution Data (µGy) at (a) 60 kVp, (b) 70 kVp, (c) 80 kVp, (in 2D Color Mode)

The position for placing the detector is the point at the edge of the screen. So that there is no image of the detector disturbs the radiography image. The dose value at that point must be the closest to the reference point because the dosage is closely related to safety. Figures 3 shows a similar radiation distribution pattern in every variation, where the center point (C3) is the reference point. The outermost point closest to the center point dose value is at point C5. At 60kVp, the reference point C3 is 44 µGy, and C5 is 39 µGy. While at a voltage of 70kVp, the reference point C3 is 68 µGy, and C5 is 65 µGy. At 80kVp, the reference point C3 is 106 µGy, and C5 is 101 µGy.

The deviation at point C5 is the smallest deviation value compared to other points located on the edge of the screen. The deviation values of point C5 at a voltage of 60kVp, 70kVp, and 80kVp are 9.8%, 4.1%, and 5%. The data conclude that point C5 is the optimal point for placing a permanent detector.

4) Control Chart

The next step is to collect data 50 times at that point to obtain a control chart. The detector placement is at point C5. The exposure factors used were 70kVp and 15mAs. Through Equation 7-10 are obtained Upper Warning Limit (UWL), Lower Warning Limit (LWL), Upper Action Limit (UAL), and Lower Action Limit (LAL) values. That values will be put into a graph, as shown in Figure 4.

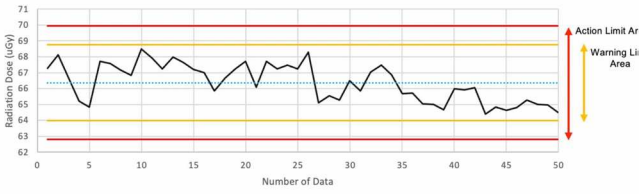

Fig. 4 Control Chart

Figure 4 shows a Control Chart where the y-axis is the dose value in µGy units. This control chart can be a quality control tool for the dose value obtained from the calculation in Equation 13. The value of the Warning Limit Area is 63.99 µGy to 68.75 µGy, and the value of the Action Limit Area is 62.80 µGy to 69.94 µGy. The dose value read by the detector at an exposure factor of 70kVp and 15mAs must be at the Warning Limit Area (63.99 to 68.75 µGy). Further investigation is necessary if the dose value read is outside of that limit. Whereas, if the dose value read exceeds the Action Limit Area, which is less than 62.80 µGy or more than 69.94 µGy, the prototype needs further investigation and is temporarily out of order. Statistical calculations may use *F*-test and *T*-test by comparing the two old data sets (control chart) and the new data.

B. Discussion

Based on the three parts of the instrument validation tests, the x-ray voltage error is 3.6%, which is still below the maximum error of 10%. The linearity coefficient is at 0.02, below the maximum acceptable linearity coefficient of 0.1. Moreover, the consistency test by measuring the coefficient of variation of the voltage, time, and dose parameters is 0.002, 0.003, and 0.034, respectively, below the maximum acceptable coefficient of variation of 0.05. Those parameters indicate that the x-ray machine is in healthy condition.

Through indirect method, dose value equation obtained is $\mu Gy = \lfloor(0{,}3579 * kVp) - 16.27\rfloor * mAs$. This equation only applies to the prototype used in the study. Dose value can be obtained from the exposure factor used. This equation is obtained at a particular time, but there is no guarantee that the x-ray machine is always in good condition. We need a system to ensure that the dose value obtained from the equation is always valid. A control chart of dose from a permanent detector can be a tool to control that equation.

The place of the permanent detector is at the outermost point of the receptor to avoid artifacts from the detector itself.

The dose value should be closest to the dose value at the center point, which is the point closest to the cathode axis (point C5). The deviation value at point C5 is smaller than the other outer side points.

A control chart is made by exposing fifty times at point C5. The dose value obtained is then put into a control chart graph. The Warning Limit Level and The Action Level is 63.99 μGy to 68.75 μGy and 62.80 μGy to 69.94 μGy. Medical Physics can do quality control before an x-ray machine is used. They expose the x-ray machine with a specified exposure factor. The dose value from the permanent detector is then compared with the control chart. If the value is within the warning limit, it means that the dose value equation is still valid, and the x-ray machine is in healthy condition and ready to use. If the dose value exceeds the warning limit, that will get the investigation started because there is an indication of a decrease in the ability of the x-ray machine. However, if the dose value exceeds the action limit level, the x-ray machine is not in good condition and the dose value equation is not valid.

The place of the permanent detector is at the outermost point of the receptor to avoid artifacts from the detector itself. The dose value should be closest to the dose value at the center point which is the point closest to the cathode axis (point C5). The deviation value at point C5 is smallest than other points on the outermost side.

IV. Conclusion

The permanent detector is best on the cathode axis as the dose value is close to the dose value at the center point with the smallest deviation. The deviation value at 60kVp, 70kVp, and 80kVp are 9.8%, 4.1%, and 5%, respectively. Hence, the optimal point for placing a permanent detector is at the point close to the cathode. The dose control chart obtained from the permanent detector is necessary to validate the dose equation. This method makes a medical physicist easily identify errors in equations or equipment. The control chart found that the UWL, LWL, UAL, and LAL values are 68.75 μGy, 63.99 μGy, 69.94 μGy, and 62.80 μGy, respectively. Quality control aims to maintain the dose value at Warning Limit Area. If the dose exceeds that warning limit level, an investigation must be done immediately.

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