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# Kilovolt peak meter design as a calibrator of X-ray machine

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**ABSTRACT**

This research aimed to design the KvP meter for checking the error of output voltage from X-Ray machine with the range of 50-70 KvP. It used Arduino Gelatino microcontroller programmed with Arduino IDE software as data processor of detector result. The detector was designed based on the physics principle using material attenuation coefficient namely aluminum whose good effect in reducing the energy level of X-ray photons. Thus, the photodiode sensor only read the effective energy of the X-ray energy. Based on the radiation intensity ratio through the aluminum filter with 0.25 mm and 0.5 mm thickness, it is better to measure X-ray tube voltage non-invasively The KvP Meter was tested by setting duration of X-ray exposure that was 0.3 second, tube current was 10 mA, and KvP Meter distance from collimator was 90 cm. A prototype unit was made, and the performance was tested in terms of error and precision. After testing and analyzing the data, the error result was less than 5.1% with the highest measurement precision of ± 1.50. It is generally concluded that this equipment can be used to measure the voltage of the X-ray tube.



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## 1. INTRODUCTION

Radiodiagnostics is a medical treatment utilizing ionizer radiation (X-ray) for performing a diagnostic without surgery treatment. X-ray will be emitted to object and the beam which penetrate the object is projected onto rontgen film (processed digitally) so that condition in the object can be observed visually [1]. Therefore, it enables diagnostic process. In spite of offering advantage in diagnostic treatment, on the one hand, dosage error of X-ray usage highly disadvantages patient, operator, technician, and the generator of X-ray (rontgen) [2-3]. When control panel is adjusted in lower dose, it will beget image result different and hard to diagnose. Therefore, it should conduct emission repetition. Conversely, if the dose is too high, patient will receive unnecessary radiation and the image result will be dark particularly for conventional X-ray machine. Despite it, over X-ray radiation dosage (ionizer) can cause ionization process in soft tissue, organ and liquid in human body resulting cell damage, mutant gent, free radical, cancer cells, etc [4-6].

One of dosage error causations of X-Ray usage is that there is incompatibility between tube voltage adjusted to control panel of X-ray instrument and X-ray intensity resulted. To investigate the incompatibility of the tube, it should perform a goodness of fit test on X-ray machine. This test performs callibration test on several parameters in X-ray machine, such as radiation duration (s), tube current (mA), and tube voltage [7]. Conducting tube voltage measurement, it needs Kilovolt Peak Meter (kVp Meter) as a measurer. There are still a few hospitals having kVp Meter, thus, a goodness of fit test of tube voltage of X-ray machine is unable to be performed internally [8]. Consequently, X-ray dosage error exists due to dissonant tube voltage output that is late detected. Hence, this research creates a design of kVp meter by applying non-invasive data collecting method to measure compatibility between tube voltage output of X-ray machine and another which is adjusted in control panel.

During this time, the testing and calibration services conducted by Balai Pengamanan Kesehatan Kesehatan (BPFK) and Loka Pengamanan Fasilitas Kesehatan (LPFK). In fact, currently there are only 4 BPFK and 2 LPFK in Indonesia, namely BPFK Jakarta, BPFK Surabaya, BPFK Medan, BPFK Makassar, LPFK Surakarta and LPFK Banjarbaru. With only 4 BPFK plus 2 LPFK, it is certainly not worth the amount of Health Service Facilities that must be served. Such a great responsibility has resulted in poor service, testing and calibration impacts, for example too many and too long queues to get service at BPFK and LPFK. Latest fact-update data from the Indonesian Ministry of Health, states that the number of hospitals currently reaches 2,309 units, the total of 9655 units of Puskesmas, with 3,152 Community Health Centers across Indonesia and among them are hospitals with accreditation status. All hospitals demand Testing and Calibration services that is timely, coupled with the existence of health facilities such as laboratory clinics [9]. This responsibility certainly cannot be overcome by BPFK and LPFK only, it would be necessary role of other institutions (private institutions) to support the development in the field of Health as mandated in the Regulation on Medical Device Examiners Institution. But it is not easy because of the high price of calibration tools, including KVP meter tools as an X-ray machine calibrator. For that, required KVP meter with low cost price, but have good quality. The measurement of tube voltage output of X-ray machine is conducted by turning X-ray effective energy emitted by rontgen instrument into electric quantity by using photodiode detector. This voltage is reinforced by IC log101 in order that electric quantity of photodiode is able to be processed well by microcontroller, therefore, tube voltage can be determined [10].

This research refers to some previous researches. The first was conducted by [11], the method used for measuring tube voltage was non-invasive that turned X-ray into visual light with intensifier screen and was caught by solar cell so that it became electricity voltage and processed by microcontroller AT89951 with external ADC 0884. The measurement result had been not linear and precision. It was due to effects of solar cell detector and after glow of intensifier screen abilities becoming causal factors. The second study reference was conducted by [10], the method used was non-invasive measurement of tube voltage of X-ray machine by turning X-ray into electric quantity using semiconductor. Measurement result accuracy was 1% with the highest error of 3%. The disadvantage of this study is the measument was only performed on tube voltage over 60 kVp by using three detectors which two of them was to measure X-ray quantity and the rest was as a voltage switch to start measurement. The third study reference was conducted by [12], this study explained physics theory fundamental principle of non-invasive measurement method of tube voltage of X-ray machine and also compared these two methods conducted commonly by applying KVp test cassette Wiscousin model 105 and RMI digital kVp Meter.

There are some disadvantages in the studies above that will be improved in this research of kVp Meter design production. Non-invasive measurement of tube voltage of X-ray machine has not been conducted using neither intensifier screen nor detector whose function as voltage switch to start X-ray energy reading. It aims to prevent measurement result from after glow effect of intensifier screen. Hence, X-ray energy can be read directly by the detector without being turned into visual light [13-14]. The measurement is conducted without using detector as voltage switch to start X-ray energy reading. It has purpose that all energy exposure of X-ray can be detected without pause (should not wait another detector instruction in order that the machine starts to perform reading process) [15-16]. X-ray filter used was aluminum (Al) whose thickness 0.25 and 0.5 mm so that it could conduct measurement of tube voltage at range 50 to 70 kVp by using photodiode sensor. In addition, X-ray effective energy after passing through aluminum (Al) filter was read by photodiode and it was turned into electric quantity and then reinforced by logarithmic reinforcement. Its result was processed by Microcontroller Arduino Gelatino programmed by applying software Arduino IDE so that the score of tube voltage of X-ray machine (kVp) would be able to be measured non-invasively.

## 2. RESEARCH METHOD

### 2.1. Component used

In making this kVp meter, there are several circuits that will be made, namely detector, amplifier algorithm, minimum system and display circuit using simple and easy to get components, so as to reduce the amount of cost used. List of components can be seen in Table 1.

### 2.2. Hardware execution

In Figure 1 is Display of KVp Meter. There are processes for executing hardware such as:

a. The first step of making the hardware is to prepare the microcontroller circuit, electronic components, and design.
b. Next, make the detector holder and position the aluminum filter on each detector.

c. Connecting detector module, logarithmic amplifier module, microcontroller module, comparator and LCD.
d. After all components have been assembled, then made coding for microcontroller.

Table 1. Component list

| No | Component List | Number of Components |
|---|---|---|
| 1 | Detector circuit | |
| | Thermal copper | 2 |
| | Photodioda | 4 |
| 2 | Log amplifier circuit | |
| | IC Logaritma | 1 |
| | Capacitor | 4 |
| | Resistor | 3 |
| 3 | Minimum system circuit | |
| | Microcontroller ATMEGA 16 | 1 |
| | Resistor | 5 |
| | Kapasitor | 2 |
| | Cristal 12 mhz | 1 |
| | Regulator 7805 | 1 |
| | Switch | 1 |
| | Jack DC | 1 |
| | Multiturn | 1 |
| | FCP | Pair |
| | Push button | 1 |
| | Push on/off | 1 |
| 4 | Display Circuit | |
| | Resistor | 1 |
| | LCD 2 X 16 | 1 |

Figure 1. Display of KVp Meter

### 2.3. Software execution

Arduino IDE software is used to code minimum systems of Atmega 16, so that data from logarithmic amplifier can be converted into voltage so that the value shown is equal to tube voltage value. From the flowchart in Figure 2, it can be seen that first it will appear initialization in LCD that tool ready to do tube voltage measurement. When the process of exposure, X-rays will be captured by the detector and convert X-rays into electrical voltage. Furthermore, the value of the voltage is converted into kVp to be displayed on LCD 2x16 and LED 1 turns on as an indicator of X-ray radiation.

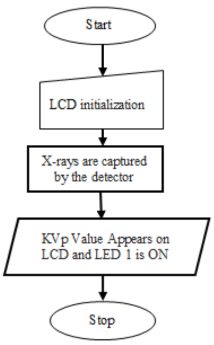


Figure 2. Flowchart of processes

### 2.4. Calculating attenuation coefficient (μ)

Non-invasive measurement of tube voltage of X-ray machine was performed by measuring X-ray effective energy of X-ray intensity produced by rontgen machine. It was obtained by calculating the score of material attenuation coefficient ($\mu$) in this study that was Aluminum (Al). The μ value obtained would be equal with tube voltage of X-ray machine [10]. Attenuation coefficient ($\mu$) was able to determine by applying Beer-Lambert law as follows [17].

$$I=I_0.e^{-\mu t} \quad (1)$$

I was continued X-ray energy intensity (photon), I0 was arisen photon intensity, μ was attenuation coefficient of the material used as filter here that was aluminum. The attenuation coefficient in this study was material absorbent coefficient toward X-ray energy, t was the thickness of the material. All variables above were able to be determined except μ. Figure 3 shows the coefficient graphics between μ aluminum and X-ray energy.

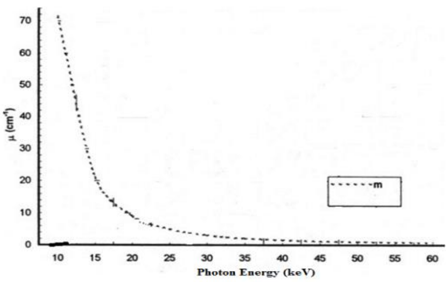


Figure 1. Attentuation coefficient (μ) Aluminium Vs X-Ray Energy [18]

Attentuation coefficient (μ) could be obtained by calculating ratio of two measurements using the following (2).

$$I_1=I_0.e^{-\mu} \text{ and } I_2=I_0.e^{-\mu t} \quad (2)$$

According to the equation above, $I_0$ was eliminated, thus, it gained a formula (3).

$$\mu_{\mathrm{Al}} = \ln \frac{(I1/\,I2)}{t1-t2}. \quad (3)$$

Based on the formula (3), we can see that for obtaining the μ value, it needed two detectors. Each detector was filtered by aluminum with varied thickness so that it obtained $I_1$ and $I_2$. Next, each detector's value was calculated by ratio logarithm formula, and at the same time, it conducted reinforcement by applying IC LOG101 with the formula as follows (4) [18].

$$\text{Vout} = 1 \text{ Volt. } \log\,(I_1/I_2) \quad (4)$$

After conducting the calculation based on the formula (4), electric quantity of reinforcement results as well as the calculation would be processed by Microcontroller Arduino Gelatino for gaining μ value. The value of μ was in the quantity electric whose values would be equal with tube voltage of X-ray machine.

### 2.5. System

In Figure 4 is mechanism of block diagram. When it conducted tube voltage measurement of X-ray machine, detector D1 and D2 would be exposed by X-ray with varied intensity caused by X-ray filtered by two aluminum filters whose different thickness. Subsequently, the detectors produced two electric quantity characteristics. Then, they were reinforced by a Log amplifier circuit, hence, they produced stabil voltage with comparative formula (2-4). From the process result of Log amplifier above, it obtained an electric quantity representing μ value of aluminum filter on X-ray intensity, which the intensity produced depends on tube voltage score. Measuring the electric quantity, it was later inputted into pin ADC Arduino Gelatino with IC Atmega 16 [19]. Subsequently, the electric quantity representing μ value was converted into voltage in millivolt (mV).

Figure 5 showed result of the detector output in electric quantity (mV) influenced by the tube voltage score in Kilo Volt Peak (kVp). From the data above, it indicated that the detector output score generated was non-linear, or in other words, the increase of detector voltage was different with every increase of tube voltage of X-ray machine. Hence, conducting the detector data process in order to be equal with tube voltage displayed on comparator kVp meter (Gold Standard), it applied non-linear transfer function, i.e. logarithmic function formula (5) [20].

$$\mu = \ln I_1/I_2 \quad (5)$$

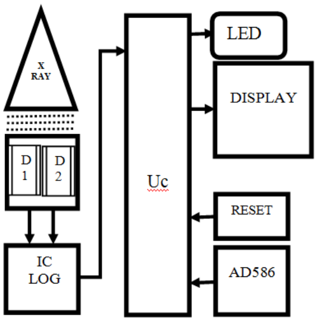


Figure 2. Block diagram system

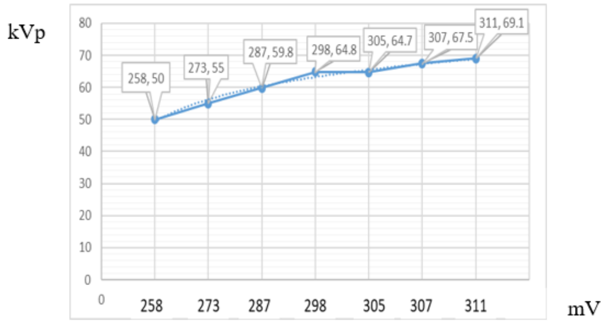


Figure 3. A correlation graphics between detector voltage (mv) and tube voltage (kVp)

In this stage, the formula usage was in the step of result calculating the ratio of first and second detector outputs ($I_1$ / $I_2$). The following is non-linear transfer function (6).

$$Y = a + b \ln X \quad (6)$$

In Figure 4, IC AD586 had function as a reference voltage stabilizer of Arduino Gelatino. When the detector was emitted by X-ray, LED would emmit automatically. It could be a sign whether there was X-ray radiation or not generated by X-ray machine. Reset button had fuction to remove the scores have been read, therefore, measurement could be conducted again.

### 2.6. Detector characterization

The detector used in this research was a handmade. Hence, to find out characteristics or X-ray intensity (kVp) effect on detector output in electric quantity (mV), it performed a single characterization on the detector by finding the detector transfer function. Characterization would be performed after obtaining attenuation coefficient value of aluminum filter (μ) in the form of electric signal in millivolt. The following is the detector characterization on tube voltage from 50 to 55 kVp.

The transfer function in Figure 6 was y=88.476 ln (x)-441.31. It informed that every transformation of tube voltage 1 kVp, it existed detector output voltage transformation totalled ± ln 88.5 mV. X-ray detector sensitivity was ±ln 88.5 mV/kVp and the offset ln 441.31. The transfer function (y=88.476 ln(x)-441.31) was inputted into microcontroller formula as the data processor. Afterwards, it created a look up table for data collecting and re-testing. This re-testing was perfomed by applying Gold Standard (Radcal kVp meter).

### 2.7. Data testing and collecting

Data testing and collecting kVp meter had been conducted on five test points of X-ray machine tube voltage setting that were 50, 55, 60, 65 and 70 kVp, with exposure duration setting that were 0.3 second, tube current setting 10 mA and measurement distance 90 cm from collimator/100 cm from cathode anode of X-ray machine. Each test point was tested 7 to 8 X-ray exposes, with Gold Standard, Radcal kVp meter widely used and good for measuring tube voltage of X-ray machine. We can see the schema of data collecting kVp meter in Figure 7.

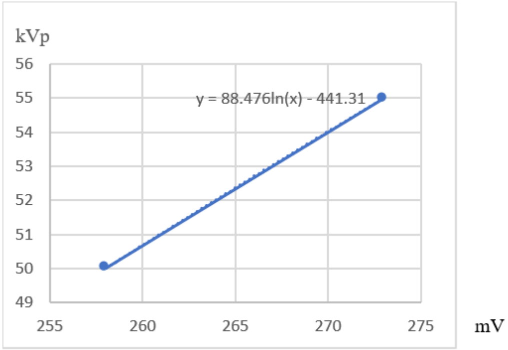


Figure 4. The correlation between kVp gold standard and in (natural algorithm) voltage detector

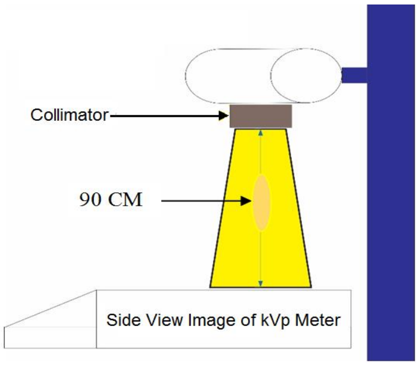


Figure 5. The schema of kVp meter testing

## 3. RESULTS AND DISCUSSION

After completing system of Kilovolt Peak (kVp) as a calibrator of X-ray machine, it conducted several tests on photodiode sensor, filter, as well as kVp meter after uniting all circuits. These tests had to be conducted to obtain characteristics of sensor, filter, and error level of the tool for measuring tube voltage intensity on the range of 50 to 70 kVp. The followings are the tests results.

### 3.1. Photodiode sensitivity testing

This test aims to obtain the type photodiode that is sensitive to X-ray. The photodiodes tested were BV10NF1 and BPW34. This test was conducted in the distance of 90 cm from X-ray machine collimator, with varied tube voltage adjustment such as 50, 60, and 70 kVp, constant time 0.3 second and the voltage generated by photodiode measured by Arduino Gelatino. It indicated tube voltage effect of X-ray machine on electric quantity generated by photodiode. Table 2 illustrates the test result.

Table 2. Photodiode sensivity of BV10NF1 vs BPW34

| No | kVp | BPV10NF (mV) | BPW34 (mV) |
|---|---|---|---|
| 1 | 50 | 0 | 0.07 |
| 2 | 60 | 0 | 0.09 |
| 3 | 70 | 0 | 0.14 |

From the result, it indicated that BPW34 was better than BPV10NF to be used for X-ray energy detector sensor. It can be proved by the increase of result voltage of photodiode BPW34 as a response of tube voltage increase of X-ray machine.

### 3.2. Filter Testing

This test has purpose to obtain the suitable filter type and characteristics, from the aspects of filter material type and thickness. Thus, it will be able to attain X-ray effective energy on the tube voltage from 50 to 70 kVp. The filter tested was Copper whose thickness 0.5 mm and 1 mm and also Aluminum whose thickness 0.25 mm and 0.5 mm. Table 3 and Table 4 show the test results.

Table 3. The test of copper filter vs tube voltage on X-ray

| No | Tube Voltage (kVp) | Copper's Filter Thickness (mm) | | Read Detector Voltage (mV) |
|---|---|---|---|---|
| | | Detector 1 | Detector 2 | 4.2.1 |
| 1 | 50 | 0.5 | 1 | 0 |
| 2 | 60 | | | 0 |
| 3 | 66.2 | | | 368 |
| 4 | 72.1 | | | 384 |
| 5 | 89.1 | | | 394 |

Table 4. The test of aluminum filter vs tube voltage on X-ray

| No | Tube Voltage (kVp) | Alumunium's Filter Thickness (mm) | | Read Detector Voltage (mV) |
|---|---|---|---|---|
| | | Detector 1 | Detector 2 | 4.2.2 |
| 1 | 50 | 0.25 | 0.5 | 270 |
| 2 | 60 | | | 279 |
| 3 | 63.2 | | | 297 |
| 4 | 68 | | | 308 |
| 5 | 69.1 | | | 311 |

According to the trial test result in Table 3 and Table 4, it could be concluded that the aluminum filter application was better to be used. This was because measurement could not be conducted while applying copper filter on tube voltage under 60 kVp.

### 3.3. kVp Meter testing

After gaining filter characteristics photodiode and making sure that all circuits had run well, conducted re-testing and data collecting. The test results were analyzed or calculated its error and precision level on Gold Standard reading. From the measurement result which was on tube voltage value of 50 kVp, it obtained measurement precision score ±1.18 with error level 5%. Next, on tube voltage 55 kVp measurement it obtained ±1.26 with error level 3%. Later, on tube voltage 60 kVp measurement, it obtained ±0.36 with error level 3%. On the one hand, in the group of 65 kVp measurement, it gained tool precision error ±1.15 with error level 1%. The last but not the least, it obtained measurement precision ±0.8 on tube voltage 70 kVp measurement with error level 1%. This kVp meter design worked effectively on tube voltage of 50-70 kVp. Tabel 5 illustrates result of non-invasive tube voltage measurement of X-ray machine using this tool compared with Gold Standard (Radcal kVp meter).

Table 5 shows the test result of kVp meter tool after being compared with Gold Standard (Radcal kVp meter) with varied tube voltage settings that were 50, 55, 60, 65, and 70 kVp. Furthermore, tube current scored 10 mA, X-ray exposure duration was 0.3 second, and the distance between the tool and X-ray machine collimator was 90 cm. from the results can be seen that there is a small error score after kVp meter compared with gold standard to measure voltage input from X-Ray Machine.

Table 5. Measurement result data of tube voltage of 50-70 kVp
using gold standard radcal kVp Meter, duration setting 0.3 s and tube current 10 mA

| Set. kVp | Reading Average | | Precision | Error |
|---|---|---|---|---|
| | Gold Standard | kVp Meter | | |
| 50 | 52.6 | 50 | ±1.18 | 5% |
| 55 | 56.77 | 55 | ±1.26 | 3% |
| 60 | 63.27 | 61.47 | ±0.36 | 3% |
| 65 | 62.8 | 64.21 | ±1.15 | 2% |
| 70 | 69.71 | 68.9 | ±0.82 | 1% |

## 4. CONCLUSION

From the test results, it can be concluded that BPW34 as the photodiode utilized had good sensitivity for detecting X-ray, therefore, it is able to apply as a sensor to measure X-ray intensity. Inasmuch as aluminum is the material whose good characteristics, it is better to be used it as filter on X-ray. Obtaining X-ray effective energy, it should calculate attenuation coefficient (μ) of aluminum filter on tube voltage of 50-70 kVp.

Based on the analysis results of kVp meter reading error on Gold Standard (Radcal kVp Meter) and precision level calculation, the following is the conclusion. Kilovolt Peak Meter (kVp) design can be applied for performing non-invasive tube voltage measurement with the highest error level that was 5% and the precision level that was less than ±1.2 on the tube voltage measurement range of 50-70 kVp. This non-invasive tube voltage measurement of X-ray machine using photodiode sensor and aluminum (Al) filter whose thickness 0.25 mm and 0.5 mm is suitable to be applied for conducting tube voltage measurement that is enough stable as well as on the range of 50-70 kVp.

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