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Disposable Condenser Dosimeter Using a Skin-Insulated Mini-Substrate with a Silicon X-Ray Diode in Image-Guided Radiation Therapy

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Abstract

To measure integral doses in image-guided radiation therapy, we developed a disposable mini-substrate with a 1.0-μF condenser and a silicon X-ray diode (Si-XD). The Si-XD is a high-sensitivity photodiode selected for detecting X-rays. In the substrate with dimensions of 15 × 15 mm^2, the initial charging voltage is 3.30 V, and the charging voltage is decreased by photocurrents flowing through the Si-XD during X-ray exposing. The condenser in the substrate is charged by a microcomputer dock, and the charging voltage is also measured using an analog to digital converter in the dock after exposing X-rays. The dock is connected to a personal computer through a USB cable, and integral doses are shown on the PC monitor. The doses were proportional to decreases in the charging voltage, and the calibrated doses corresponded well to those obtained using a readily available ionization chamber.

Keywords

Condenser Dosimeter, Disposable Mini-Substrate, Surface Mounting, Si X-Ray Diode, X-Ray Tube, Image-Guided Radiation Therapy

1. Introduction

Currently, ionization chambers are used to measure X-ray integral doses and dose rates, and various chambers [1] [2] have been developed corresponding to objectives. In this regard, a condenser-discharge ionization chamber [3] is used to measure integral doses in various fields; the integral dose is measured by the decrease in the condenser-charging voltage.

Silicon X-ray diode (Si-XD) is a high-sensitivity photodiode selected for detecting X-rays, and the diode has been applied to a direct-conversion detector in a high-sensitivity X-ray computed tomography (CT) scanner [4]. Subsequently, we have developed a dual-energy (DE) X-ray diode to perform DE-CT [5] for energy subtraction.

Lately, we are interested in an integral dosimeter using the Si-XD for measuring patient-skin doses in radiation therapy. Since various X-ray tubes are used clinically to improve the accuracy of dose delivery in radiation therapy [6] [7]. Instead of the chambers, a Si-XD is useful for discharging electric charges in the condenser, and the substrate dimensions can be reduced below 10 × 10 × 10 mm^3 to stick on a patient without cables. Next, the electric circuit should be insulated from the skin of the patient by surface mounting, and the substrate may be disposable corresponding to each cancer patient in radiation therapy [8] [9] [10].

It is well known that standard deviations (SDs) of fluorescent-glass and thermoluminescence dosimeters are larger than those of chambers. However, it is easy to measure integral doses using small elements of the two dosimeters. In this regard, a small-SD mini-dosimeter is useful for measuring integral doses with high accuracies.

In our research, major objectives are as follows: to develop an integral dosimeter using a mini-substrate with a Si-XD, to measure integral doses with small SDs, to realize a low-priced dosimeter, to design a skin-insulated disposable substrate, and to construct a microcomputer dock for charging a condenser and for measuring discharging voltages corresponding to doses. Therefore, we constructed a condenser dosimeter using a surface-mounting mini-substrate and a dock. We also measured integral X-ray doses with changes in the exposure time and in the tube voltage.

2. Experimental Methods

2.1. Integral Dosimeter

Figure 1 shows the block diagram for measuring the integral dose using a dosimeter substrate. A condenser in a substrate is charged using a microcomputer dock (mbed LPC11U24, NXP), and the substrate is separated from the dock and set 0.3 m from an X-ray source (RXG-1052, R-tec). When the substrate with the charged condenser is exposed by the X-ray generator, the condenser discharges. After exposing X-rays, the substrate is connected to the dock again, and the condenser charging voltage is measured using the dock. The dock with a mini-USB port is connected to a personal computer (PC) through a USB cable.

The dosimeter substrate and its electric circuit are shown in **Figure 2**. The substrate is of a surface-mounting type to insulate skins from the circuit and consists of a 1.0 μF condenser, a Si-XD (S1087-01, Hamamatsu) packaged by ceramic with photosensitive dimensions of 1.3 × 1.3 mm^2, and a 10-kΩ resistor. In the Si-XD, X-ray photons are detected directly by a Si substrate, and scattered

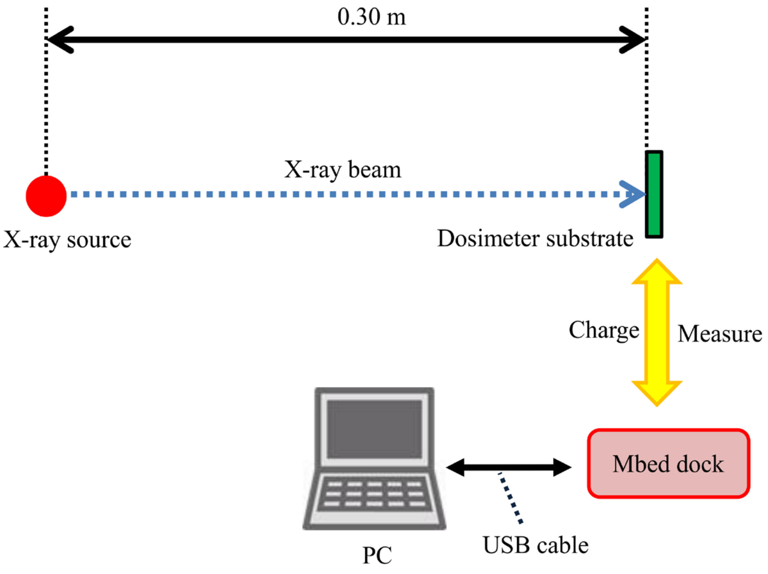


Figure 1. Block diagram for measuring the integral dose using a mini-substrate, an mbed dock, and a PC. The condenser in the substrate is charged to 3.30 V by the dock, and the condenser charging voltage is also measured using the dock after exposing X-rays.

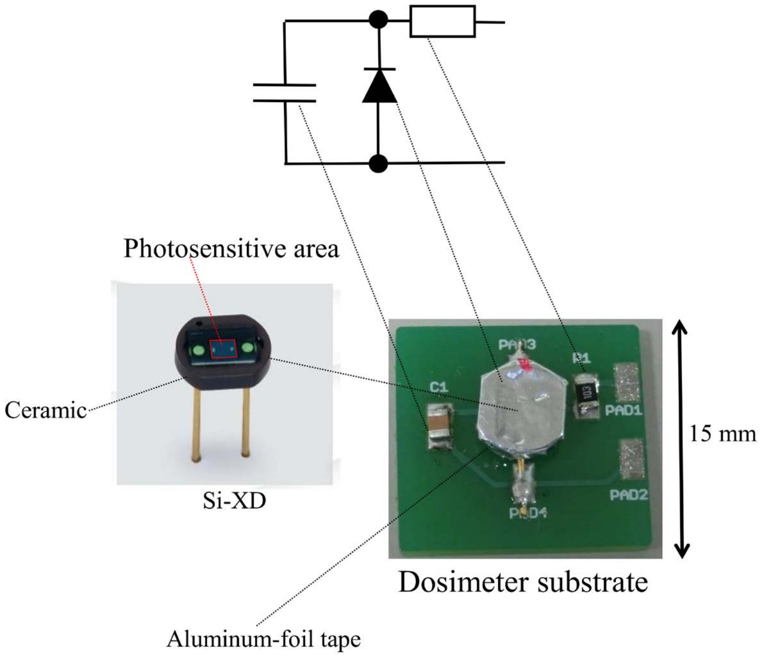


Figure 2. Dosimeter substrate and its electric circuit.

photons including fluorescence from the ceramic are also detected by the Si substrate [11]. The Si-XD is shaded using a 25-μm-thick aluminum tape, and penetrating X-ray photons are detected using the Si-XD.

Figure 3 shows the measurement principle of the integral dosimeter. First, the condenser is charged to 3.30 V through the resistor after closing a switch (SW1) connecting to a pin 40 in the mbed dock [**Figure 3(a)**]. Second, the Si-XD in the

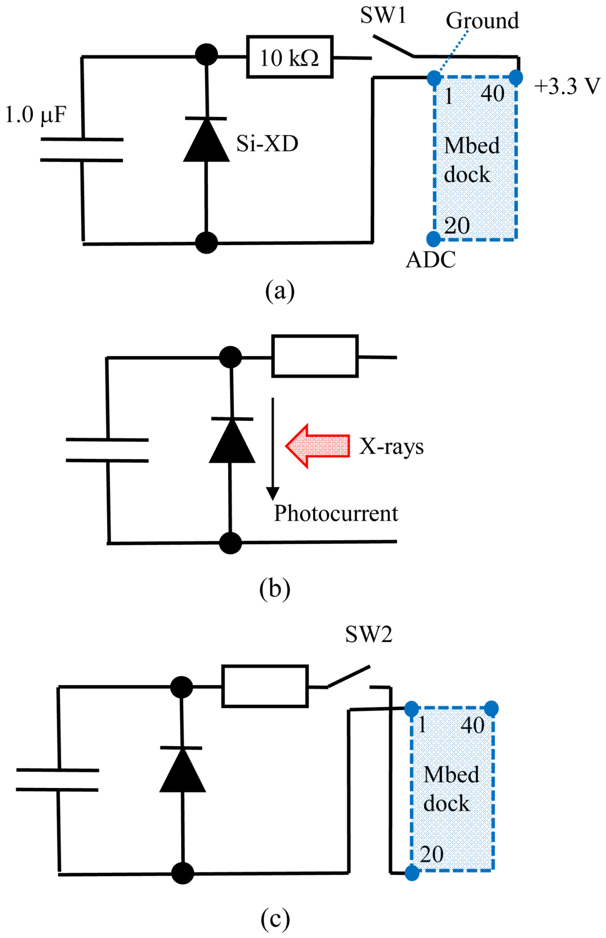


Figure 3. Principle of the integral-dose measurement using the mini-substrate and the mbed dock. (a) The condenser is charged to 3.30 V using a pin 40 in the dock after closing SW1; (b) The condenser charging voltage decreases during X-ray exposing; and (c) The charging voltage is measured using an ADC (pin 20) in the dock after closing SW2.

substrate is exposed, and the charging voltage decreases by photocurrents flowing through the Si-XD [Figure 3(b)]. Finally, the condenser charging voltage is measured using an analog to digital converter (ADC, pin 20) in the mbed dock when the switch SW2 is closed.

During X-ray exposing, the photocurrent flows, and the condenser charging voltage V_c (V) decreases. Therefore, the integral dose D (Gy) is written by:

$$D = k\left(V_i - V_c\right), \quad (1)$$

where V_i (=3.30 V) is the initial charging voltage before exposing and k (=0.70) is a constant.

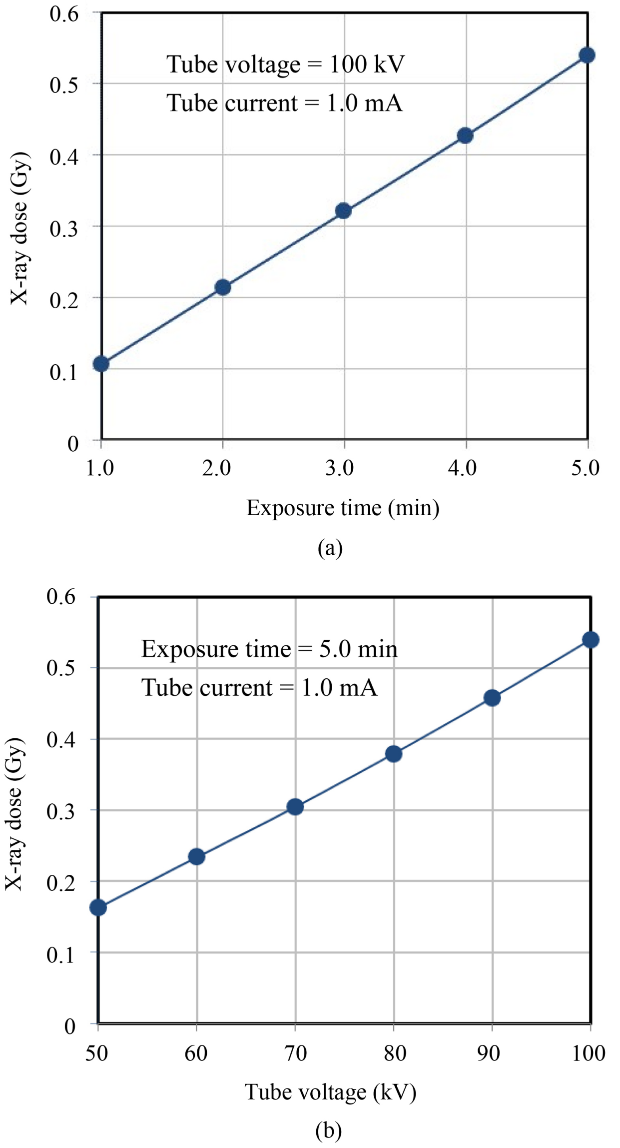
2.2. Standard Dose Measurement

Measurement of integral X-ray dose using a readily available ionization chamber is important to convert discharging voltages into doses. The integral X-ray dose from the X-ray generator was measured using an ionization chamber (RAMTEC 1000 plus, Toyo Medic) at a tube current of 1.0 mA without filtration. The chamber was placed 0.30 m from the X-ray source, and we measured the integral dose with changes in the exposure time from 1.0 to 5.0 min and in the tube voltage from 50 to 100 kV.

3. Results

3.1. Standard Integral Dose

Figure 4 shows the standard integral doses measured at a constant tube current



(a)

(b)

Figure 4. Integral doses measured using an ionization chamber placed 0.30 m from the X-ray source at a tube current of 1.0 mA. (a) Exposure time dependence of the integral dose at a tube voltage of 100 kV; and (b) Tube voltage dependence of the dose at an exposure time of 5.0 min.

of 1.0 mA. At a constant tube voltage of 100 kV, the integral dose was proportional to the exposure time [**Figure 4(a)**]. Next, the integral dose increased with increases in the tube voltage at an exposure time of 5.0 min [**Figure 4(b)**]. The maximum dose was 0.54 Gy at a tube voltage of 100 kV and an exposure time of 5.0 min.

3.2. Condenser Charging Voltage

Table 1 shows average values of the condenser charging voltages and their standard deviations (SDs) at the indicated conditions. The dose measurements were performed five times, and the maximum SD was 1.2×10^{-2} V at an average voltage of 2.75 V. Therefore, the condenser discharging voltages corresponding to the integral doses were quite stable, and the integral-dose measurement could be carried out.

The condenser charging voltages at a tube current of 1.0 mA are shown in **Figure 5**. The SD bars are extended and shown by the secondary axis label of standard deviation (0.005 V/div.). At a tube voltage of 100 kV, the condenser charging voltage decreased with increasing exposure time [**Figure 5(a)**]. Next, at an exposure time of 5.0 min, the charging voltage decreased with increasing tube voltage [**Figure 5(b)**].

3.3. Dose Calibration

Figure 6 shows the coefficient data for dose calibration. The one-point calibration using a maximum value of 0.54 Gy at an exposure time of 5.0 min and a tube voltage of 100 kV is shown in **Figure 6(a)**. And the two-point calibration

Table 1. Average values and their SDs of the condenser charging voltage at the indicated conditions. (a) Variations with the exposure time, Tube voltage = 100 kV, Tube current = 1.0 mA and (b) Variations with the tube voltage, Exposure time = 5.0 min, Tube current = 1.0 mA.

(a)

		Charging voltage Vc (V)	
Exposure time (min)	Measurement times	Average	SD
1	5	3.19	0.006
2	5	3.01	0.003
3	5	2.84	0.004
4	5	2.71	0.002
5	5	2.53	0.003

(b)

		Charging voltage Vc (V)	
Tube voltage (kV)	Measurement times	Average	SD
50	5	3.07	0.007
60	5	2.92	0.006
70	5	2.84	0.005
80	5	2.75	0.012
90	5	2.63	0.004
100	5	2.53	0.003

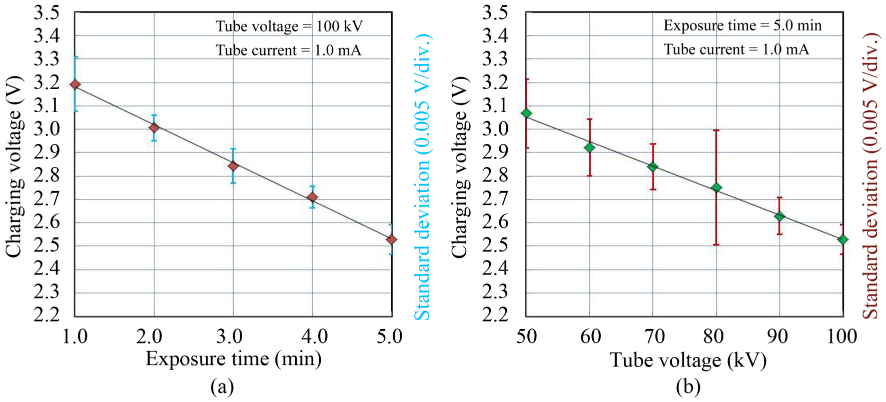


Figure 5. Condenser charging voltages after exposing X-rays at the indicated conditions. The charging voltage decreased by exposing X-rays. (a) Variations with the exposure time and (b) Variations with the tube voltage.

for exposure-time and tube-voltage dependences using both the maximum and minimum doses are shown in **Figure 6(b)** and **Figure 6(c)**, respectively.

3.4. Integral Dose

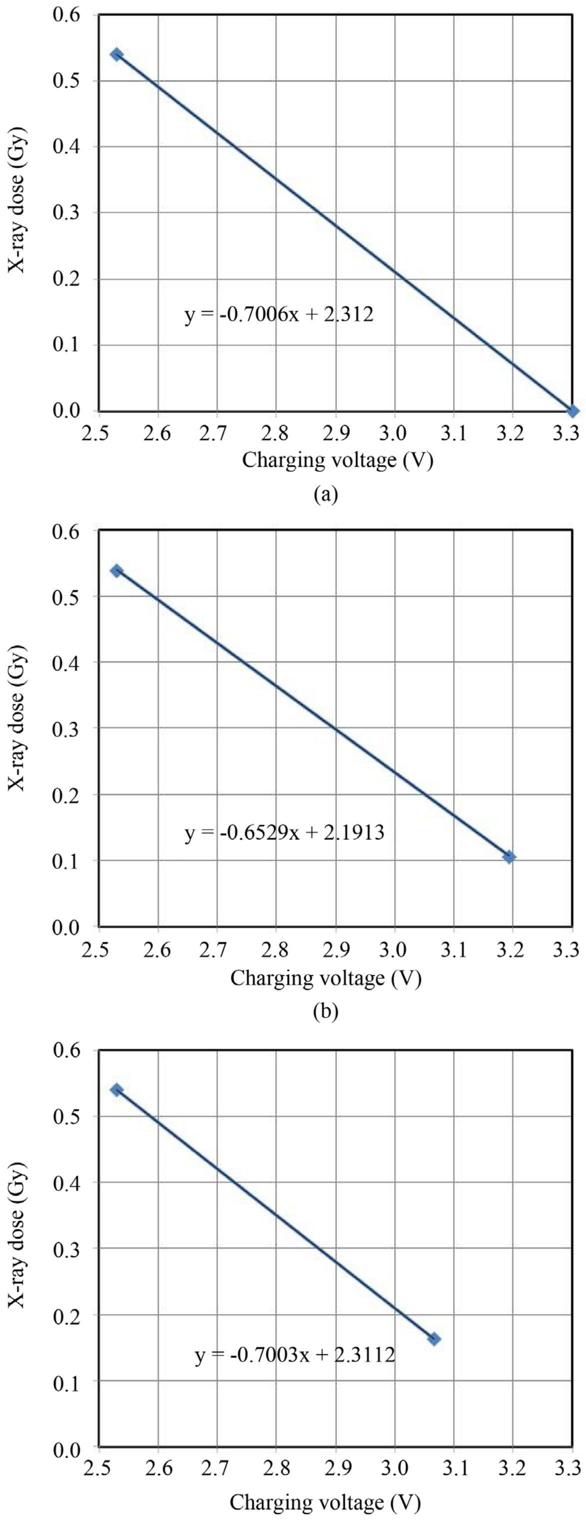
Figure 7 shows the integral X-ray doses measured using the substrate with changes in the exposure time and in the tube voltage. The absolute value of the integral dose was calculated by one-point calibration using a maximum value of 0.54 Gy at an exposure time of 5.0 min and a tube voltage of 100 kV. The integral dose was in proportion to the exposure time [**Figure 7(a)**], and the dose increased with increasing tube voltage [**Figure 7(b)**].

The integral doses determined by two-point calibration using both the maximum and minimum doses are shown in **Figure 8**. Using a minimum dose of 0.11 Gy at a tube voltage of 100 kV and an exposure time of 1.0 min, the integral doses were almost equal to those in **Figure 4(a)** [**Figure 8(a)**]. When the minimum dose of 0.16 Gy was used at a tube voltage of 50 kV and an exposure time of 5.0 min, the integral doses were almost equal to those in **Figure 4(b)** [**Figure 8(b)**].

4. Discussion

The direct-reading condenser-discharge chamber is commercially available [12]. However, the mini-substrate using a Si-XD is not available, and the dimensions can be reduced below 10 × 10 mm^2. Utilizing one-point calibration at a constant tube voltage of 100 kV, the integral dose was proportional to the X-ray exposure time. However, in the dose measurement with changes in the tube voltage, the doses were slightly different from those obtained using the ionization chamber owing to the energy dependence of the Si-XD. Therefore, the two-point calibration is desired to determine the doses with changes in the tube voltage with high accuracies.

The integral dose is proportional to the exposure time, and the linear approximation was used in **Figures 7(a)** and **Figures 8(a)**. Subsequently, although



(a)

(b)

(c)

Figure 6. Coefficient data for the dose calibration. (a) One-point calibration using a maximum value of 0.54 Gy at an exposure time of 5.0 min and a tube voltage of 100 kV. Two-point calibration using the maximum and minimum doses for (b) exposure-time and (c) tube-voltage dependences.

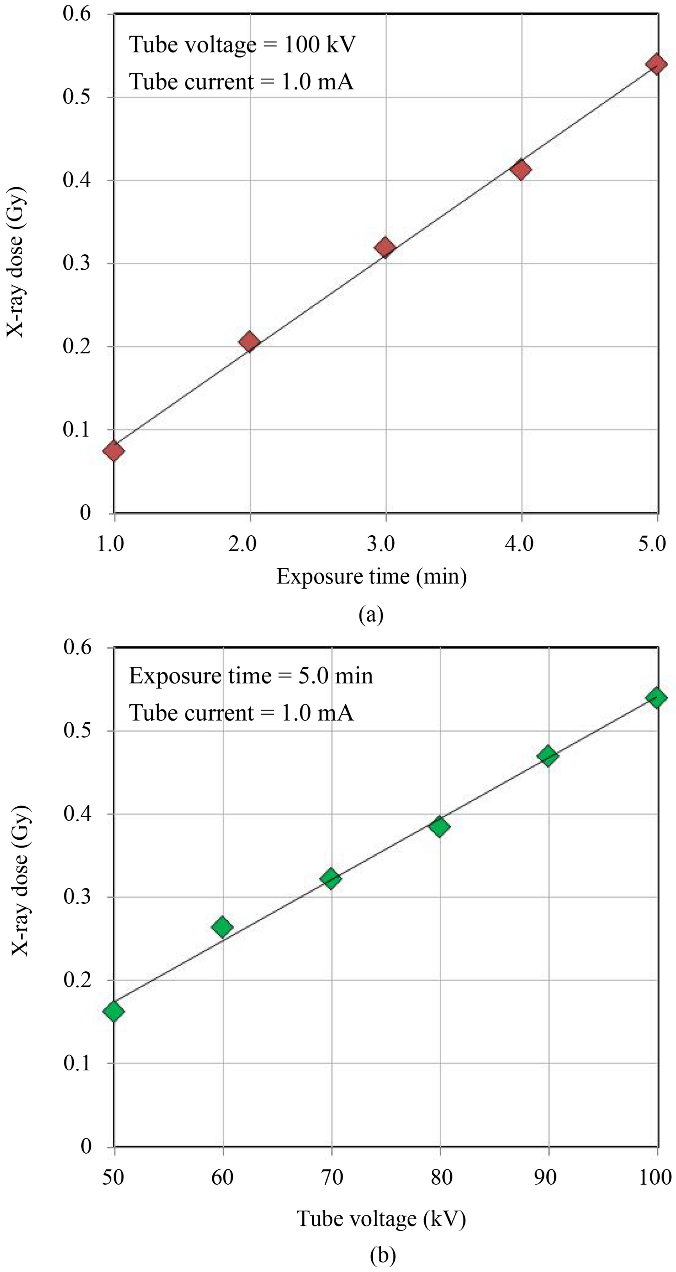
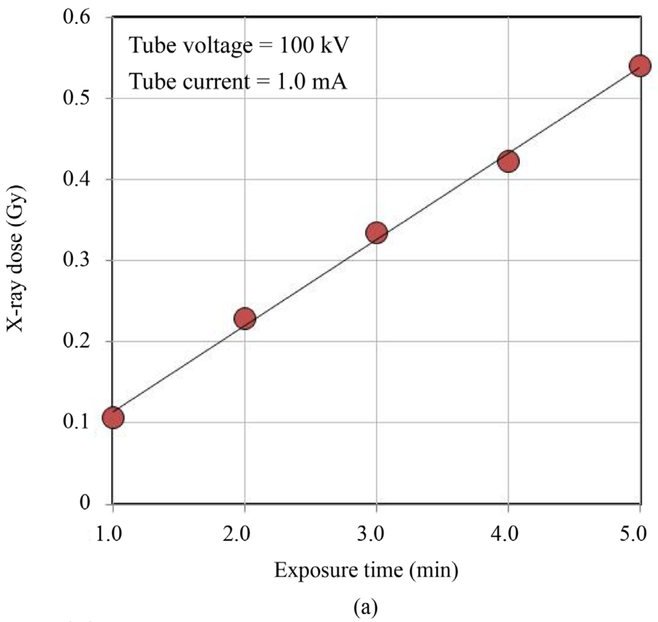


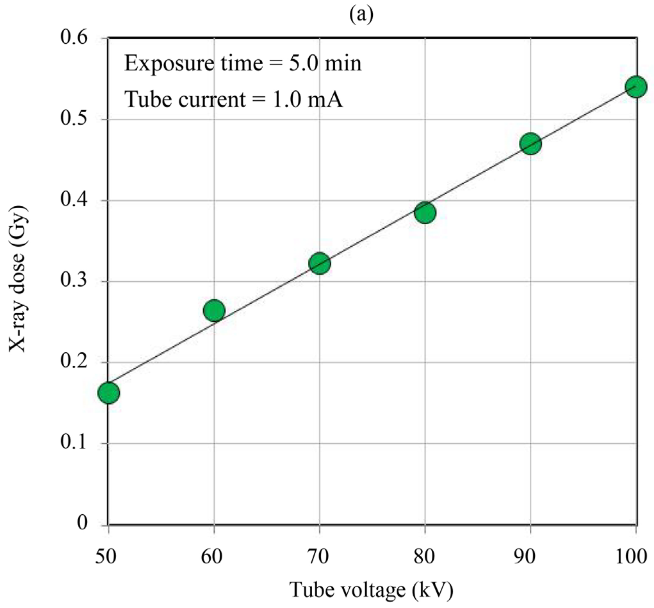
Figure 7. Integral doses calculated from the charging voltages. Absolute values of these doses are determined by one point calibration using the maximum value of 0.54 Gy at an exposure time of 5.0 min and a tube voltage of 100 kV. (a) With changes in the exposure time and (b) with changes in the tube voltage.

the integral dose at a constant exposure time increases in proportion to the second power of the tube voltage, the standard dose measured using the chamber was roughly proportional to the tube voltage at a tube-voltage range of 50 - 100 kV. Therefore, we also used the linear approximation in **Figure 7(b)** and **Figure 8(b)**.

The X-ray dose rate is proportional to the tube current and to approximately



(a)



(b)

Figure 8. Integral doses determined by two-point calibration using the maximum and minimum vales. (a) Exposure time dependence and (b) tube voltage dependence.

the second power of the tube voltage. Currently, the X-ray fluctuation increases with decreasing the dose rate, and the dose rates are quite stable at the measurement conditions. Particularly, the dose rates were integrated at exposure times ranging from 1.0 to 5.0 min, and the SDs were low in the integral-dose measurement.

Using the mini-substrate, the SDs of the charging voltage measured were quite low. However, the condenser capacity should be minimized to measure low integral doses at a tube voltage of 50 kV and an exposure time of 5.0 min. In addition, we are improving the electric circuits for charging the condenser and for measuring the voltages, and the integral doses would be measured at high accuracies.

The sensitivity of the integral dosimeter increases with decreases in the condenser capacity and to increases in the photoelectric area of the Si-XD. In addition, a Darlington transistor for the Si-XD will be useful to amplify the photocurrent and to improve the detector sensitivity.

In this experiment, we used an mbed dock to charge the condenser and to measure the charging voltage after exposing X-rays. Thus, it is not difficult to realize a low-priced dosimeter system in conjunction with a PC, and the mini-substrate is useful for measuring the integral dose using X-ray tubes in radiation therapy.

5. Conclusion

We developed a condenser-discharge integral dosimeter using a disposable mini-substrate with a Si-XD. The substrate is a surface-mounting type, and the patient's skin is insulated from the circuit. Using an mbed dock, the condenser was charged, and the charging voltage was also measured by the dock after exposing X-rays. The maximum error for measuring the voltage was below 0.5%, and it was easy to measure the integral doses accurately with changes in the exposure time utilizing one-point calibration. However, two-point calibration is desired to measure the dose variations with the tube voltage at high accuracies.

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