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# Product development of a condenser dosimeter using a skin-insulated USB-A-substrate with a silicon X-ray diode

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## Abstract

To measure integral doses in image-guided radiation therapy, we developed an integral condenser dosimeter comprising a disposable USB-A mini-substrate with a 0.1-μF condenser and a silicon X-ray diode (Si-XD), a microcomputer (mbed) dock, and a personal computer (PC). The Si-XD is a high-sensitivity photodiode selected for detecting X-rays. The USB-A substrate with dimensions of $24 \times 14$ mm$^2$ is inserted into the microcomputer dock, and the condenser is charged to 3.23 V through a 10-kΩ resistor. The condenser charging voltage is subsequently measured directly using an analog–digital converter (ADC) in mbed. When the condenser is fully charged, the microcomputer dock is switched to high impedance, and the substrate is removed. Subsequently, the substrate is exposed to an X-ray source, and the condenser is discharged via the photocurrent flowing through the Si-XD. The substrate is inserted into the dock again, and the charging voltage is measured. The dock is connected to a PC through a mini-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 typically available ionization chamber.


**Keywords** Condenser dosimeter · Disposable USB-A-substrate · Integral-dosimeter product · Si X-ray diode · Microcomputer dock · X-ray dose

## 1 Introduction

Currently, both the X-ray dose rate and the integral dose are measured using ionization chambers, and a wide variety of chambers [1–3] have been developed corresponding to the radiographic objectives. However, reducing the dimensions, response time, and price of the chamber's dosimeter system is challenging.

A silicon X-ray diode (Si-XD) is a high-sensitivity photodiode selected for detecting X-rays. Therefore, an Si-XD was applied to a direct-conversion detector in a high-sensitivity first-generation X-ray computed tomography (CT) scanner [4, 5]. Subsequently, the Si-XD can be used to disperse X-ray photons; hence, we constructed a photon-counting CT scanner [6].

Recently, we have developed a semiconductor dosimeter using an Si-XD, an amplifier, and a personal computer (PC). Using the dosimeter, we measured both the X-ray dose rate and integral dose with high accuracies; the dose values are observed on the PC monitor. In addition, the output waveforms of the X-ray pulses were measured by reducing the time constant of the amplifier. Therefore, we are interested in using an integral dosimeter comprising the Si-XD for measuring patient-skin doses in radiation therapy [7–9] because various X-ray tubes are used clinically to improve the accuracy of dose delivery [10, 11].

Instead of the chambers, the Si-XD is useful for discharging electric charges in the condenser, and the substrate dimensions can be reduced under $20 \times 20$ mm$^2$ to adhere on to a patient without a cable. Next, the electric circuit should be insulated from the patient's skin by surface mounting, and the substrate can be disposable.

Measuring the integral doses using small elements of the fluorescent-glass and thermoluminescence dosimeters is easy. However, the standard deviations (SDs) of the integral

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doses measured using the two dosimeters are relatively larger than those of the chambers.

To measure the integral dose using the condenser dosimeter with the Si-XD, an optimal dock for charging the condenser and for measuring the charging voltage is desired. Hence, a small high-performance microcomputer is useful for constructing the dock, and both the dimensions and the price can be reduced.

The principal objectives of our current study are as follows: to develop an integral dosimeter using a mini-substrate with a condenser and an 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 the condensers and for measuring the discharging voltages corresponding to the dosage. Therefore, we constructed a condenser dosimeter using a surface-mounted USB-A substrate and a dock. We also measured the integral X-ray doses for different exposure times and tube voltages.

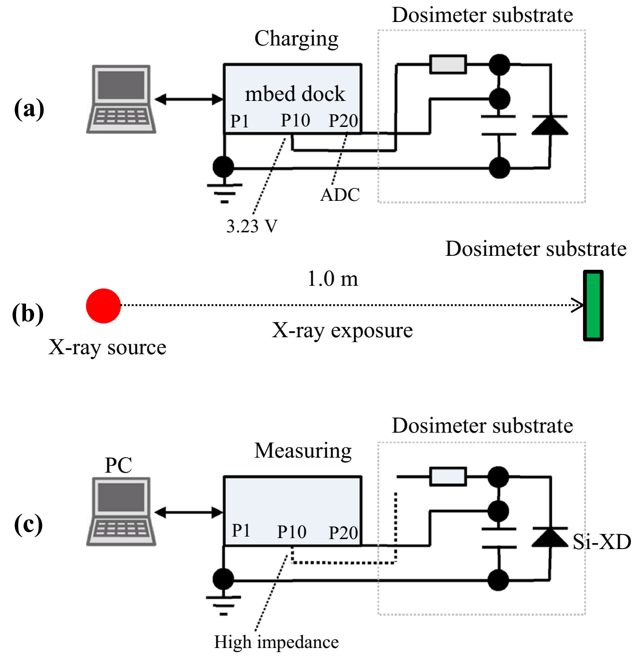


**Fig. 1** Methods for measuring the integral dose using a mini-substrate, an mbed dock, and a PC. The equivalent circuits of the substrate are also shown. **a** The condenser in the substrate is charged to 3.23 V via P10 in the dock, and the condenser charging voltage is measured using an ADC at P20. **b** The substrate is set at a distance of 1.00 m from the X-ray source and exposed to radiation. **c** The substrate is inserted into the dock, and the condenser charging voltage is measured using P20. Subsequently, the integral dose is calculated using the PC program

## 2 Methods

### 2.1 Integral dosimeter

Figure 1 shows the block diagram for measuring the integral dose using a dosimeter substrate, a microcomputer dock (mbed LPC11U24, NXP), and a personal computer (PC). When the substrate is inserted into the mbed dock, a condenser in the substrate is charged up to 3.23 V using pin 10 (P10) in the mbed. The condenser charging voltage is measured using an analog–digital converter (ADC) of pin 20 (P20) (Fig. 1a), and P10 is switched to high impedance after 5.0 s. Next, the substrate is removed from the dock and is set 1.00 m from an X-ray source (RXG-1052, R-tec) (Fig. 1b). The irradiation field was approximately 0.2 m in diameter, and the intensities in the irradiated-field plane were quite uniform. When the substrate with the charged condenser is exposed to the X-ray source, the condenser discharges owing to the photocurrent flowing through the Si-XD. After exposure to X-rays, the substrate is inserted into the dock again, and the condenser charging voltage is measured using P20 (Fig. 1c). The dock with a mini-USB port is connected to a PC through a USB cable, and both the condenser charging and the measuring voltage are controlled by the PC.

The dosimeter comprises the USB-A-substrate, the mbed dock, and the PC (Fig. 2). The substrate is of a surface-mounted type to insulate the skin from the circuit and comprises a 0.1-μF condenser, an Si-XD (S1087-01, Hamamatsu) with photosensitive dimensions of $1.3 \times 1.3$ mm$^2$, and a 10-kΩ resistor. In the Si-XD, X-ray photons are detected directly by a Si substrate, and scattered photons including fluorescence from the ceramic are also detected by the Si substrate. The Si-XD is shaded using a 25-μm-thick aluminum tape, and penetrating X-ray photons through the tape are detected using the Si-XD.

During X-ray exposure, the photocurrent flows and the condenser charging voltage $V_c$ (V) decreases. Therefore, the integral dose $D$ (Gy) is expressed as

$$D = k(V_i - V_c),$$

where $V_i$ (= 3.23 V) is the initial charging voltage before the exposure, and $k$ is a constant.

### 2.2 Standard dose measurement

The measurement of the integral X-ray dose using a typically available ionization chamber is important to convert the discharging voltages into doses. The integral X-ray dose from the X-ray generator was measured using an ionization chamber (DC300, Scanditronix Wellhofer) and an electrometer (RAMTEC 1000 plus, Toyo Medic) using a tube current of 1.0 mA without filtration. The absolute doses were calculated as air-kerma (Gy). The chamber was placed 1.00 m from the X-ray source, and we measured the integral dose

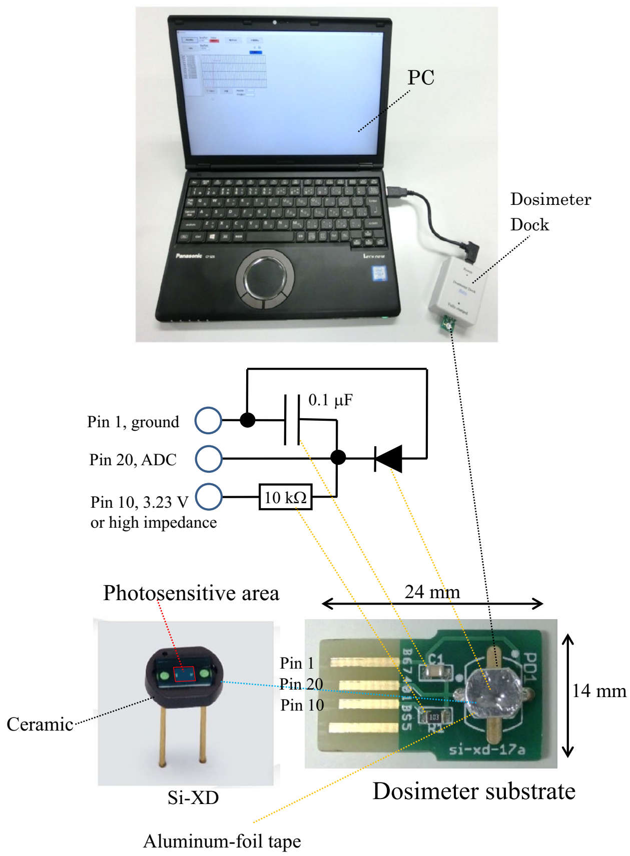


**Fig. 2** General view of the condenser dosimeter, the substrate, and its electrical circuit

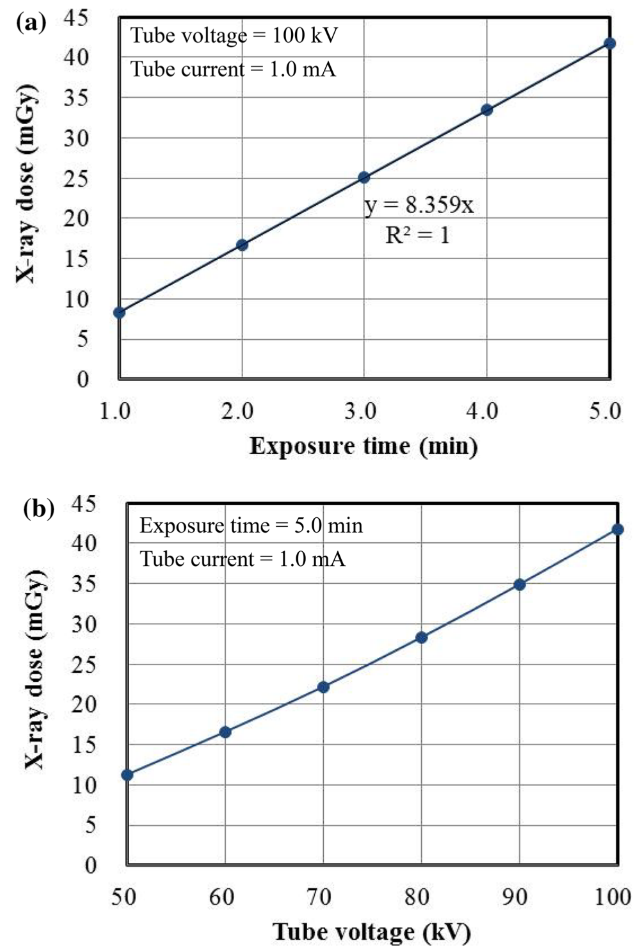


**Fig. 3** Integral doses measured using an ionization chamber placed 1.00 m from the X-ray source at a tube current of 1.0 mA: **a** exposure-time dependence of the integral dose at a tube voltage of 100 kV and **b** tube-voltage dependence of the dose at an exposure time of 5.0 min

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 3 shows the standard integral doses measured at a distance of 1.00 m from the X-ray source and a constant tube current of 1.0 mA. At a constant tube voltage of 100 kV, the integral dose was proportional to the exposure time (Fig. 3a). Next, the integral dose increased with increases in the tube voltage at an exposure time of 5.0 min (Fig. 3b). The maximum dose was 41.8 mGy at a tube voltage of 100 kV and an exposure time of 5.0 min.

### 3.2 Condenser charging voltage

Table 1 shows the average values of the condenser charging voltages and their SDs at the indicated conditions. The voltage measurements were performed five times, and the maximum SDs were $3 \times 10^{-3}$ V. Therefore, the condenser discharging voltages corresponding to the integral doses were relatively stable, and the integral-dose measurement could be performed.

The condenser charging voltages at a tube current of 1.0 mA are shown in Fig. 4. At a tube voltage of 100 kV, the condenser charging voltage decreased with increase in exposure time (Fig. 4a). Next, at an exposure time of 5.0 min, the charging voltage decreased with increase in tube voltage (Fig. 4b).

### 3.3 Dose calibration

Figure 5 shows the coefficient data for the dose calibration. One-point calibration using a maximum value of 41.8 mGy at an exposure time of 5.0 min and a tube voltage of 100 kV is shown in Fig. 5a. Further, Two-point calibration for

**Table 1** Average values and their SDs of the condenser charging voltage at the indicated conditions: (a) variations in the exposure time and (b) variations in the tube voltage

| Exposure time (min) | Measurement times | Charging voltage $V_c$ (V) | |
|---|---|---|---|
| | | Average | SD |
| (a) Tube voltage = 100 kV, tube current = 1.0 mA | | | |
| 1 | 5 | 3.09 | 0.003 |
| 2 | 5 | 2.97 | 0.003 |
| 3 | 5 | 2.83 | 0.003 |
| 4 | 5 | 2.69 | 0.003 |
| 5 | 5 | 2.56 | 0.001 |
| Tube voltage (kV) | Measurement times | Charging voltage $V_c$ (V) | |
| | | Average | SD |
| (b) Exposure time = 5.0 min, tube current = 1.0 mA | | | |
| 50 | 5 | 3.04 | 0.003 |
| 60 | 5 | 2.94 | 0.003 |
| 70 | 5 | 2.84 | 0.001 |
| 80 | 5 | 2.75 | 0.003 |
| 90 | 5 | 2.66 | 0.003 |
| 100 | 5 | 2.56 | 0.001 |

exposure-time and tube-voltage dependencies using both the maximum and minimum doses are shown in Fig. 5b, c, respectively.

### 3.4 Integral dose

Figure 6 shows the integral X-ray doses measured using the substrate at a tube current of 1.0 mA with changes in the exposure time and the tube voltage. The absolute value of the integral dose was determined by one-point calibration using a maximum value of 41.8 mGy at an exposure time of 5.0 min, and a tube voltage of 100 kV. The integral dose was proportional to the exposure time at a tube voltage of 100 kV (Fig. 6a), and the dose increased with an increase in the tube voltage at an exposure time of 5.0 min (Fig. 6b).

The integral doses determined by two-point calibration using both the maximum and minimum doses are shown in Fig. 7. For calibration, we used only the maximum and minimum doses. Using a minimum dose of 8.4 mGy at a tube voltage of 100 kV and an exposure time of 1.0 min, the integral doses were almost equal to those in Fig. 3a (Fig. 7a). When the minimum dose of 11.3 mGy was used at a tube voltage of 50 kV and an exposure time of 5.0 min, the integral dose roughly increased with an increase in the tube voltage owing to the energy dependence of the detector (Fig. 7b).

## 4 Discussion

Direct-reading condenser-discharge chambers [12, 13] have been used since the beginning of ionization-chamber developments. However, the condenser-substrate with an Si-XD is unavailable, and its dimensions can be reduced under $20 \times 20$ mm$^2$.

For dose measurement, determining the initial charging voltage $V_i$ correctly before the condenser discharges by the X-ray exposure is important because the $V_i$ decreases slightly owing to the input impedance of the ADC after the substrate is removed. Therefore, we used the charging-voltage variations with the exposure time in Fig. 4a, and the $V_i$ at an exposure time of 0 min is calculated as 3.23 V.

By one-point calibration using the maximum dose of 41.8 mGy at a constant tube voltage of 100 kV, the integral dose was almost proportional to the X-ray exposure time, and the minimum dose was slightly higher than that in Fig. 3a measured using the ionization chamber. Subsequently, for dose measurement with changes in the tube voltage, the minimum dose was almost equal to that in Fig. 3b. In principle, the integral dose is proportional to the exposure time at a constant tube voltage, and the dose is approximately proportional to the second power of the

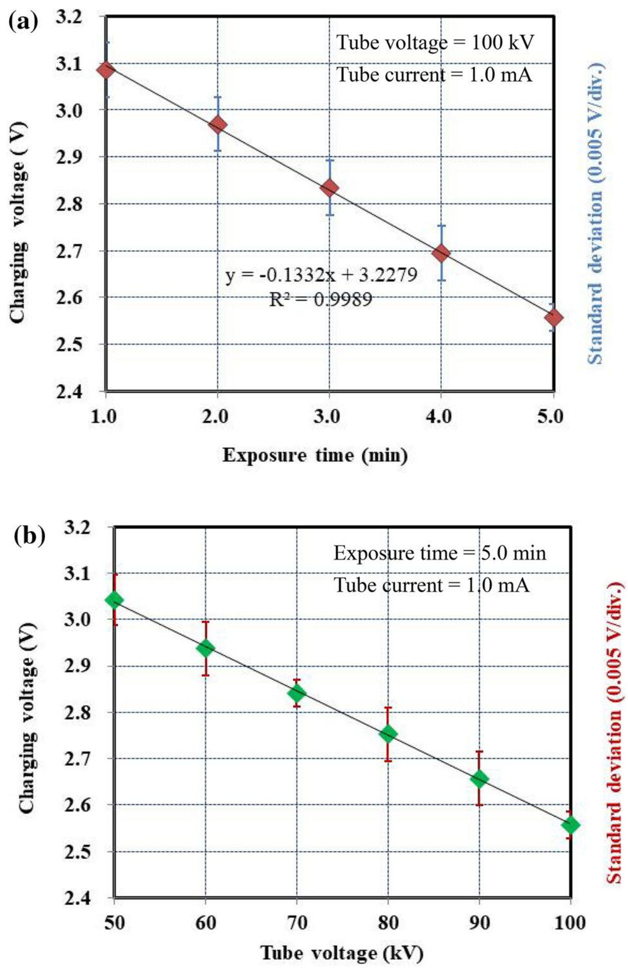


**Fig. 4** Condenser charging voltages after exposure to X-rays at the indicated conditions; the charging voltage decreased due to exposure to X-rays. **a** Variations in the exposure time and **b** variations in the tube voltage

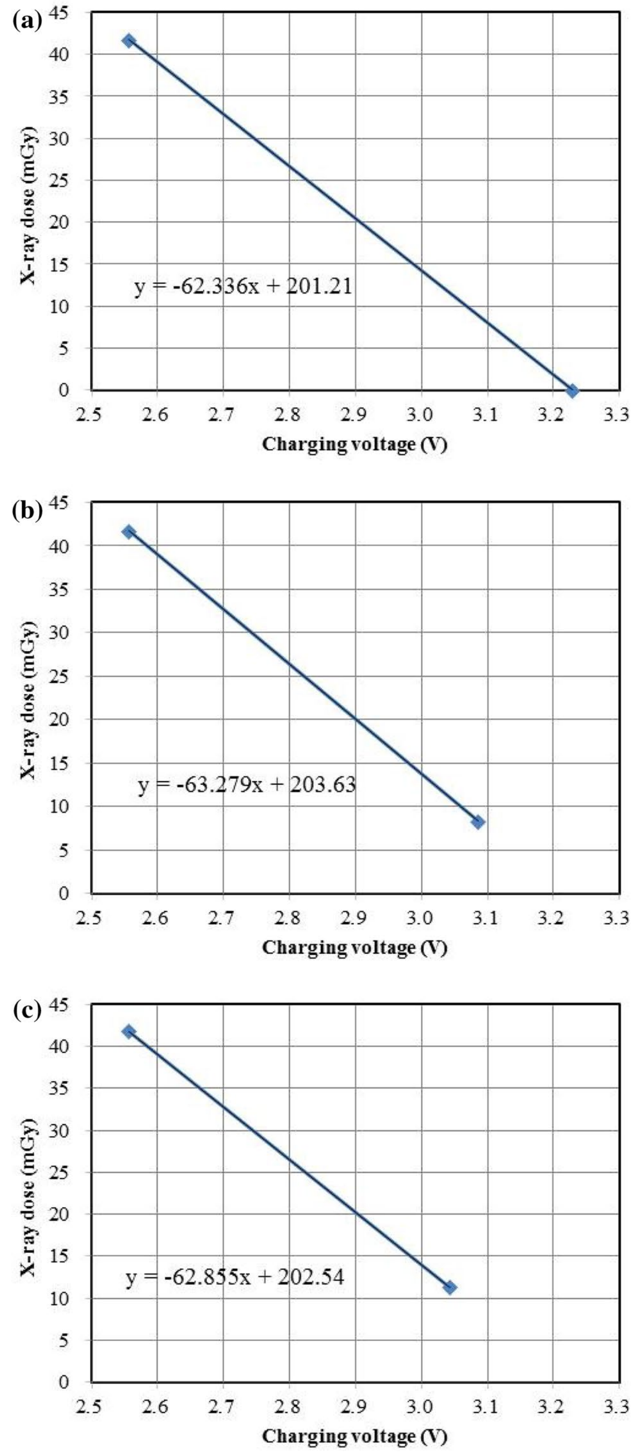


**Fig. 5** Coefficient data for dose calibration: **a** one-point calibration using a maximum value of 41.8 mGy at an exposure time of 5.0 min and a tube voltage of 100 kV. Two-point calibration using the maximum and minimum doses for **b** exposure-time and **c** tube-voltage dependencies

tube voltage at a constant exposure time. In the present study, the dose increased with an increase in the tube voltage owing to the energy dependence of the Si-XD. Therefore, two-point calibration is desired to determine the doses with high accuracies.

The sensitivity of the integral dosimeter increases with decreasing condenser capacity and increases the photoelectric area of the Si-XD. In addition, a Darlington transistor for the Si-XD might be useful for amplifying the photocurrent and for increasing detector sensitivity.

Using a USB-A connector, we have developed an mbed dock to charge the condenser and to measure the charging voltage after X-ray exposure; the mbed is connected to the PC using a mini-USB connector. Thus, we have realized a low-priced dosimeter system in conjunction with a PC, and the mini-substrate is useful for measuring the integral dose.

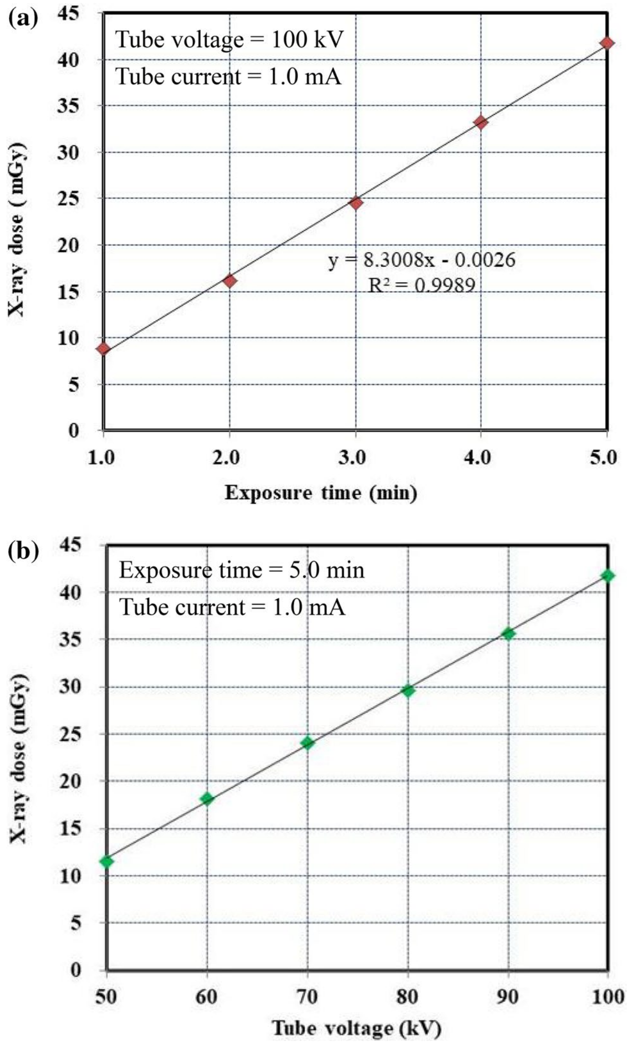


**Fig. 6** Integral doses determined by one-point calibration using the maximum value of 41.8 mGy at a tube current of 1.0 mA: **a** with changes in the exposure time at a tube voltage of 100 kV and **b** with changes in the tube voltage at an exposure time of 5.0 min

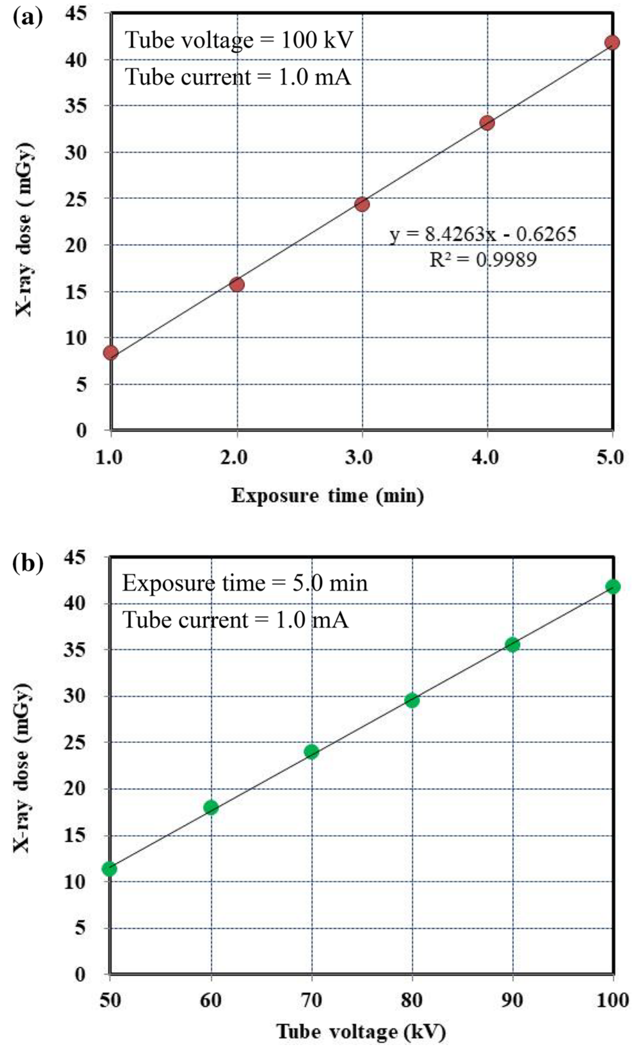


**Fig. 7** Integral doses determined by two-point calibration using the maximum and minimum values at a tube current of 1.0 mA: **a** exposure-time dependence and **b** tube-voltage dependence

## 5 Conclusions

We developed a condenser-discharge integral dosimeter comprising a surface-mounted USB-A substrate with an Si-XD, an mbed dock, and a PC. Using an mbed dock, the condenser was charged, and the charging voltage was measured by the dock after X-ray exposure. Although the maximum error for measuring the voltage was below 0.1%, both the maximum and minimum doses were almost equal to those obtained using an ionization chamber using one-point calibration. To measure the dose variations at high accuracies, two-point calibration using both the maximum and minimum doses is desired.

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## Compliance with ethical standards

**Conflict of interest** The authors declare that they have no conflict of interest.

**Ethical approval** This article does not contain any studies on animals or human participants.

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