学 術
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原 著

Long Term Characteristics Change of n-type Semiconductor Rectal Dosimeter

n型半導体直腸線量計の長期特性変化

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【Abstract】

Semiconductor rectal dosimeters are useful for patient monitoring during brachytherapy. Many authors have reported a variety of characteristics such as a decrease in sensitivity with irradiation history. Additional characteristics such as the dose rate dependence, dose per pulse dependence, sensitivity variation with temperature, dose linearity, and directional dependence have also been reported. However, the trend of these characteristics with irradiation history has not been well investigated. Approximately three years have passed since we introduced a new n-type silicon semiconductor rectal dosimeter in our hospital. Therefore, the purpose of this study is to investigate sensitivity, dark current noise, dose rate dependence, sensitivity variation with temperature of the semiconductor rectal dosimeter, and changes in the characteristics with brachytherapy irradiation history.

An n-type silicon semiconductor rectal dosimeter system (Intracavitary Detector IDF-5 channels) was used in this study. Measurements were performed with a High Dose Rate (HDR) Iridium-192 brachytherapy source. The radiation source was placed between the semiconductor detector and the Farmer-type ion chamber in a water phantom system. The ratio of the reading by the semiconductor dosimeter to the absorbed dose by the Farmer chamber as a reference was defined as the sensitivity index value of the semiconductor. Several characteristics were investigated by evaluating their sensitivity index.

For all the channels, the relative sensitivity decreased to approximately 0.92–0.95, with an irradiation history of approximately 200 Gy. Dark current noise values tended to converge towards zero according to the irradiation history. Dose rate dependence for HDR source strength was not observed, and it was not related to the irradiation history. Although there was sensitivity variation with temperature, it was small after irradiation history.

The identified characteristics may affect the actual measurement results. However, when sensitivity calibration is performed under appropriate conditions, they can be effectively used for rectal dose monitoring during brachytherapy.

【要 旨】

n型シリコン半導体線量計の相対感度，暗電流，線量率依存性，温度依存性，および照射歴によるそれらの特性の変化を調べた．Ir-192線源を，半導体線量計とFarmer形線量計（リファレンス）の間に置き照射した．Farmer形線量計による吸収線量と半導体線量計の読み値の比を半導体線量計の感度指標値とした．この指標値を評価して上記の特性を調べた．相対感度は約200Gyの照射歴で0.92-0.95に減少した．暗電流はゼロに向かって収束した．線量率依存性はなく，照射歴にも関係なかった．温度依存性があり，それは照射歴を経て小さくなった．これらの特性が実際の測定結果に影響を与える可能性があるが，適正条件下で感度校正することにより直腸線量モニタリングに十分使用できる．

1. Introduction

Real-time monitoring of rectal dose is essential for intracavitary brachytherapy in the treatment of gynecological malignancies [1)]. Monitoring is used to ensure that the treatment is accurately performed with the intended dose distribution. In addition, if administration differs from the intended dose and an unexpected dose increase to risk organs is identified, it is possible to respond promptly [2), 3)].

In our hospital, an n-type silicon semiconductor rectal dosimeter is used for real-time monitoring. Semiconductor dosimeters provide real-time readout, high sensitivity, small dimensions, simple instrumentation and the absence of bias voltages. As such, they are

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well-suited for in-vivo measurements during treatment [4].

However, as a physical phenomenon, when radiation is incident on the detector, excessive electron-hole pairs are created throughout the semiconductor. Minority carriers (holes in n-type) are swept across the junction by built-in potential and are measured by an electrometer. The minority lifetime of the carriers affects the sensitivity of semiconductors with irradiation history integrated dose, although this is dependent on the electrical properties of the semiconductor crystal and adversely affects the minority carrier lifetime [5)-7)]. These phenomena in semiconductor dosimeters cause various characteristics.

Previous studies on semiconductors [4), 8)-13)] have revealed that they exhibit a variety of characteristics such as a decrease in sensitivity, dose rate dependence, dose per pulse dependence, sensitivity variation with temperature, dose linearity and directional dependence. However, there is limited research on the dependence of the characteristics on the irradiation history with the exception of sensitivity decrease [14].

Therefore, in this study, we investigated characteristics that could be observed over the long term, such as the sensitivity change and the change in the dark current noise with irradiation history. In addition, the dose rate dependence and its change, and sensitivity variation with temperature and its change were investigated for a semiconductor rectal dosimeter.

2. Materials and Methods

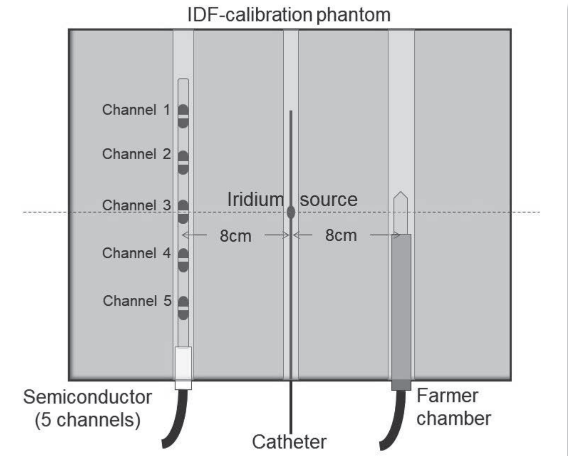
2-1 Experiment setup

The measurements were performed with a High Dose Rate (HDR) Iridium-192 (denoted hereafter as Ir-192) brachytherapy source (microSelectron-v2 HDR Ir-192; Nucletron B.V., Veenendaal, The Netherlands). The unit was equipped with an Ir-192 source with an average apparent activity of 370 GBq. The source was replaced approximately every six months.

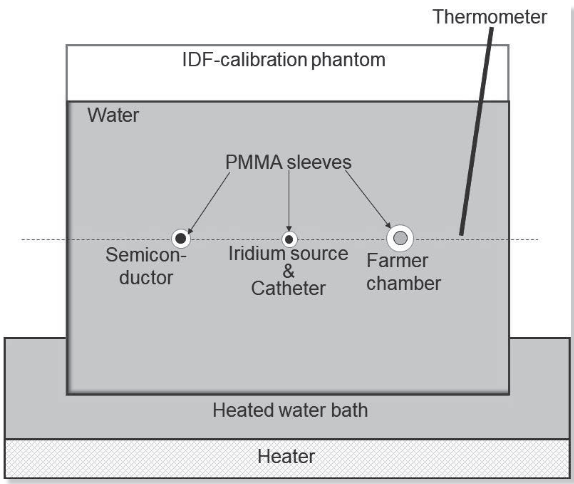
A 5-channel n-type silicon semiconductor dosimeter system (denoted hereafter as semiconductor dosimeter) is the subject of this study. The semiconductor dosimeter was an Intracavitary Detector IDF-5 (IBA Dosimetry, Schwarzenbruck, Germany) and was connected to a DPD12pc electrometer (IBA) to measure the dose. It consists of a flexible probe structure and rectal interstitial type with five semiconductors channels placed 20 mm apart. The probes were connected to a computerized control system. A computerized control system is a combination of an adapter, personal computer, and software. The reading value was output in units of 16 bits ADU. ADU is an analog-to-digital conversion unit that facilitates the monitoring of ionization output using a personal computer.

Fig.1 (a) shows the schematic of the experimental setup in a modification of the so-called sandwich method [15]. A water phantom system (IDF-Calibration Phantom, IBA) consisting of water cubes of $20 \times 20 \times 20$ cm^3 in size was used. The Ir-192 source was sandwiched using the semiconductor detector and Farmer-type ionization chamber (PTW-30013, Freiburg, Germany). As shown in Fig.1 (b), both detectors were fixed using a poly-methyl methacrylate (PMMA) sleeve. Both sleeves were located in a phantom system with a separation of 8 cm each from the Ir-192 source. The phantom was immersed in a water bath heated by a heater. This allowed the preset temperature to be maintained with an accuracy of ±0.2°C. For all measurements, a current was applied 1 hour before the start of the measurement and pre-irradiation was performed for 15 minutes immediately before the measurement.

All measurements were read simultaneously by the semiconductor and the farmer as a reference. The ratio of the reading by the semiconductor dosimeter to the absorbed dose by the Farmer chamber as a reference was defined



(a)



(b)

Fig.1 A schematic diagram of the experimental setup, (a) coronal plane and (b) axial plane. The two detectors were positioned in a water phantom with sleeves at a distance of 8 cm on either side of the Ir-192 source. The water phantom temperature was maintained using heated water.

as the sensitivity index value. This is the same principle of diode sensitivity calibration [16].

2-2 Sensitivity index and Ir-192 dosimetry

Both detectors were irradiated for 15 min with an Ir-192 radiation source, as shown in Fig.1. To minimize the influence of the transition time, the preset time was 15 minutes (maximum time). The measurements were repeated three times and the background was measured as dark current noise without a radiation source.

Referring to equation [14], for diode sensitivity calibration, the sensitivity index (denoted hereafter as *SI*) is expressed as:

$$SI = \frac{R_{actual}[ADU]}{D_{water}^{Ir-192}[cGy]} \quad (1)$$

D_{water}^{Ir-192} is determined from Farmers absorbed dose to water with the Ir-192 source:

$$D_{water}^{Ir-192} = MN_{D,w}^{Co-60}k_{Ir} \quad (2)$$

M is the chamber readings measured with the Ir-192 source, which is corrected for temperature and pressure, ion recombination, and polarity [17]. k_{Ir} is the beam quality conversion factor for Co-60 to Ir-192 sources, as indicated in the work by Araki et al [15].

R_{actual} is the actual reading from the semiconductor dosimeter with the background subtracted.

$$R_{actual} = R_{raw} - R_{background} \quad (3)$$

R_{raw} is the original raw reading and $R_{background}$ is the background noise. $R_{background}$ was measured as dark current noise without a radiation source. It was measured for 15 minutes in the same manner as the radiation source.

2-3 Evaluated characteristics

The following four characteristics were examined in this study.

2-3-1 Sensitivity change with the irradiation history

Sensitivity change with irradiation history was examined using *SI* over a three-year period and assessed as a relative value with the first *SI* value at the introduction of the semiconductor dosimeter set to 1.00. *SI* was measured at the time of introduction and thereafter periodically approximately every six weeks. The irradiation history recorded all irradiated doses in clinical use and experiments.

2-3-2 Change of dark current noise with the irradiation history

The background was measured as dark current noise without a radiation source. As shown in equations (1) and (3), dark current noise was measured each time *SI* was measured. Similar to the sensitivity change, dark current noise changes were observed with radiation history over a 3-year period.

In addition, $R_{background}/R_{raw}$ at each source strength was evaluated as a ratio of the dark current to determine the effect of the dark current noise on the source strength. This is the ratio of the dark current to the total reading of the semiconductor dosimeter including the dark current noise, which indicates the degree of uncertainty if this value is not accurately quantified. The maximum source strength for the three years holding the radiation source was defined as 1.0 and compared.

2-3-3 Dose rate dependence and its change

The dose rate dependence for the sensitivity of the semiconductor dosimeter was evaluated. The *SI* investigated in the 2-3-1 study was evaluated for each dose rate. Furthermore, the first year of the evaluated three years was classified as "Initial" and the third year as "Irradiated". The dose rate at the time of maximum source strength for the three years holding the radiation source was defined as 1.0.

2-3-4 Sensitivity variation with temperature and its change

To investigate the sensitivity of the semiconductor dosimeter dependence on temperature, *SI* was measured while changing the water temperature. Using the geometry shown in Fig.1, the temperature was set to 40, 38.5, 37, 35.5, 34°C with the body temperature set to 37°C [18]. Temperature and pressure correction was only performed for the farmer chamber reading. The sensitivity at a temperature of 37°C was normalized to 1.00 and the correlation with the sensitivity to temperature was observed. The temperature coefficient, defined as (dSI/dT) where *SI* is the sensitivity index and *T* is the temperature, was then determined via linear regression of the data. The temperature coefficient is expressed as 1%/°C as an *SI* increase per unit temperature.

This experiment was performed at the time of the new introduction. This is defined as "Initial". In addition, approximately 2 years after the irradiation history, the experimental procedure was repeated at almost the same dose rate. This is defined as "Irradiated". The two results were compared.

3. Results

3-1 Sensitivity change with irradiation history

[Fig.2 (a)–(e)] shows that sensitivity change for the irradiation history for each semiconductor detector channel. The x-axis represents all the irradiation history doses over a three-year term. The y-axis represents the relative *SI*.

The scale of the x-axis varies from channel to channel for clinical use, and the geometry is shown in Fig.1. The *SI* decreased to approximately 0.92−0.95 with an irradiation history of 200 Gy. Notably, an initial exponential reduction was observed.

3-2 Change of dark current noise with the irradiation history

The change of the dark current noise of the semiconductor dosimeter is shown in Fig.3. The y-axis represents the dark current noise at a given time. With respect to the dark current noise, individual differences among channels of the semiconductor detector were observed. Channel 3 had the highest dark current value. Negative currents were observed in channels 2 and 4. The dark current noise for channel 5 only from the time of introduction was almost zero. For the channels 1−4, the dark current noise converged to 0 from the introduction time.

Fig.4 shows the scatter plots of $R_{background}/R_{raw}$ versus the relative source strength. When the source strength was approximately 0.2, the percentage of dark current noise was approximately 6%. When the source strength is

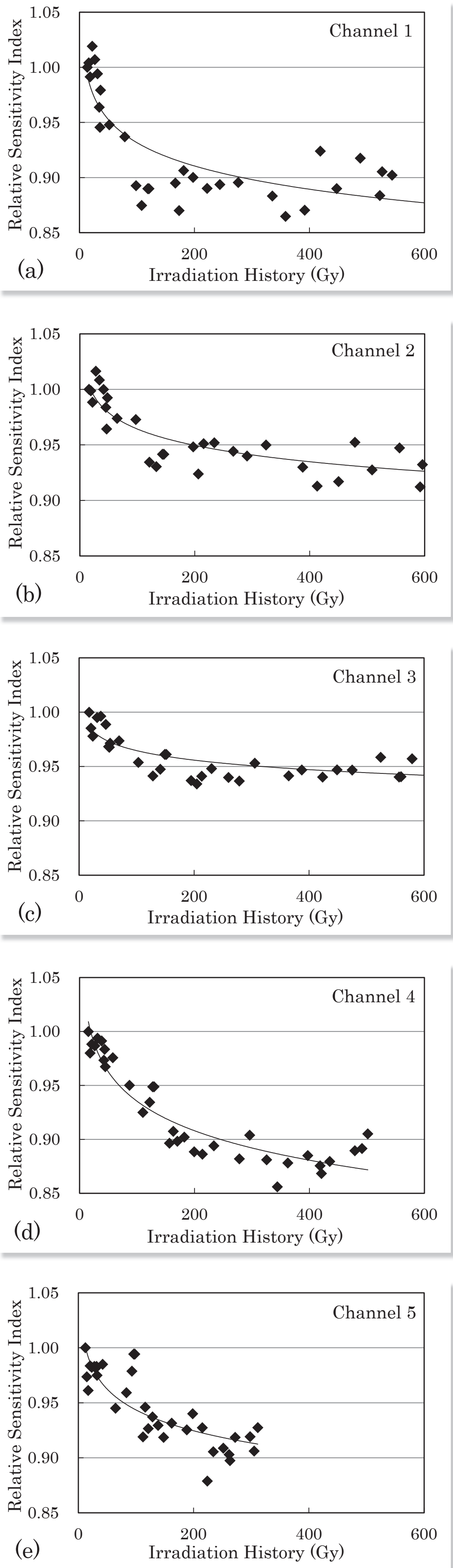


Fig.2 (a)–(e) Sensitivity change with the irradiation history

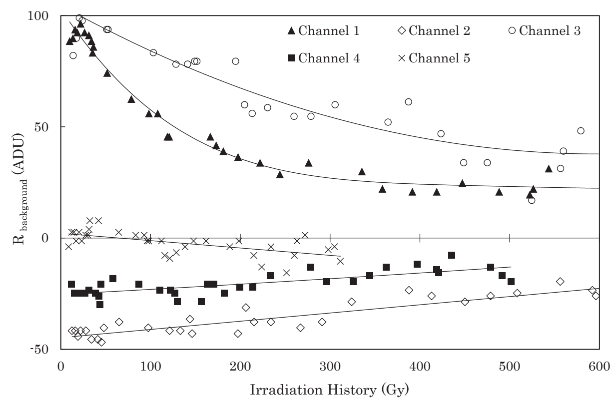


Fig.3 Change of dark current noise with the irradiation history

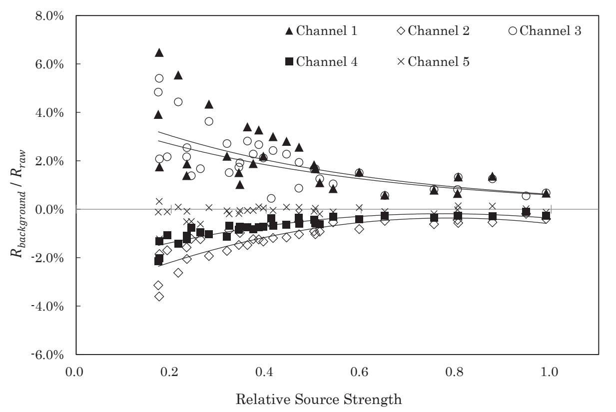


Fig.4 Ratio of dark current noise to source strength

approximately 0.7 or more, it is 1% or less.

3-3 Dose rate dependence and its change

[Fig.5 (a)–(e)] shows the result for the dose rate dependence. The y-axis represents the relative *SI* and the x-axis represents the relative dose rate. The white dots represent “Initial”, and the black dots represent “Irradiated”. As a rough estimate, the dose rate 1.0 corresponds to approximately 6.85 Gy/h and the dose rate 0.2 corresponds to approximately 1.45 Gy/h. At dose rates in the range of 1.45 Gy/h to 6.85 Gy/h, there is no correlation between the dose rate and *SI* both during the “Initial” and “Irradiated” term. Moreover, even when the term and the term are compared, there was no clear result that was common to all semiconductor detectors channels.

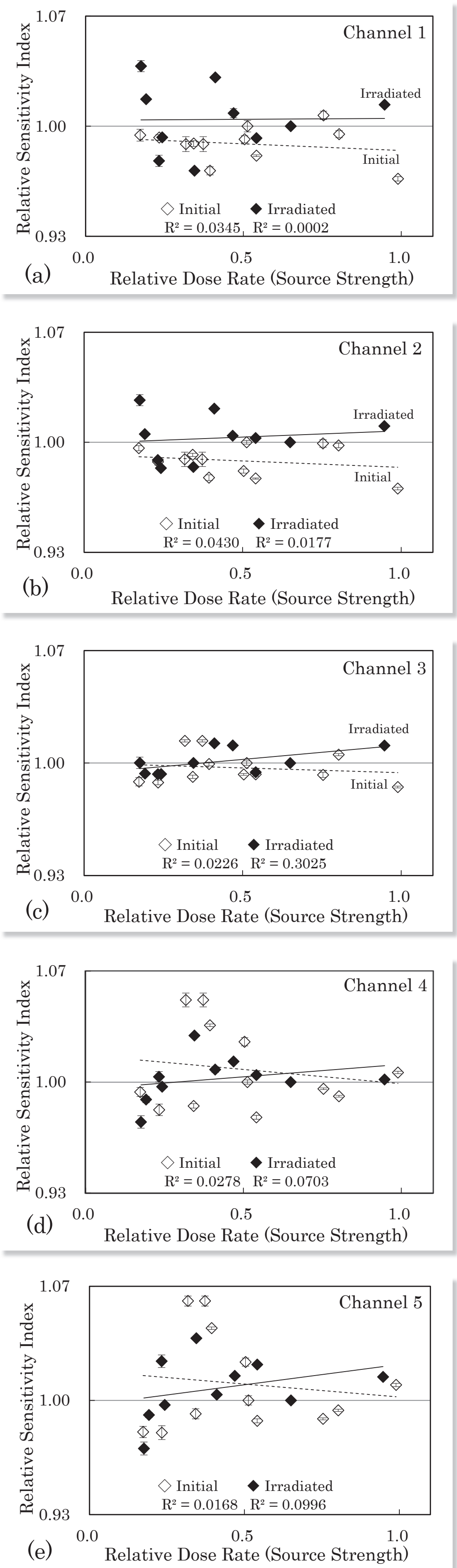


Fig.5 (a)–(e)　Dose rate dependence and its change

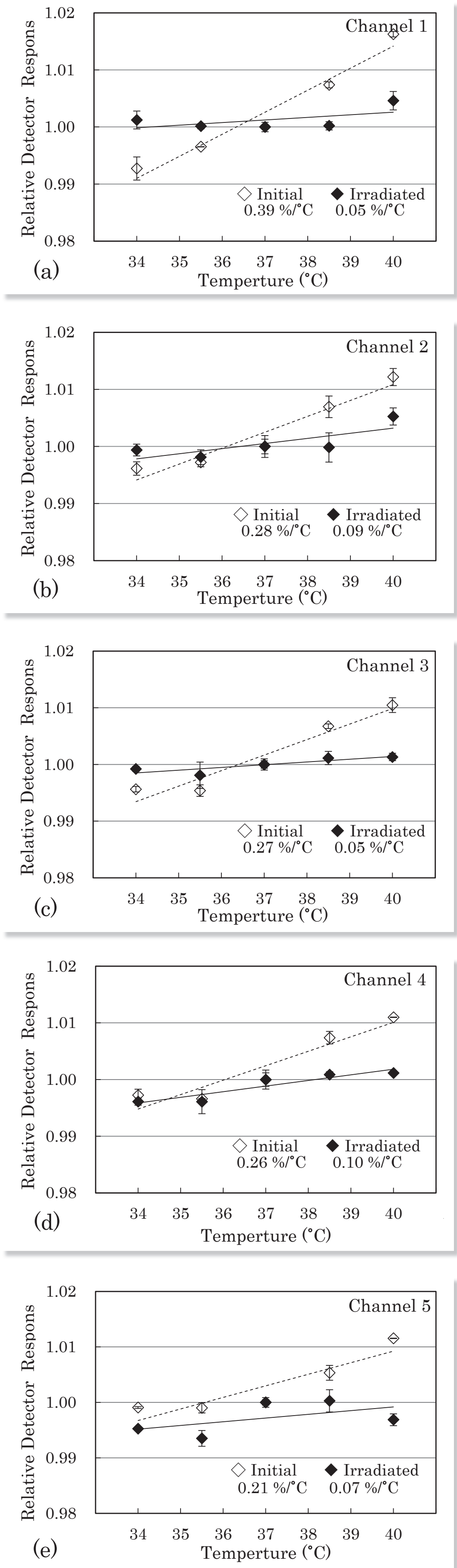


Fig.6 (a)–(e)　Sensitivity variation with temperature and its change

3-4 Sensitivity variation with temperature and its change

As shown in [Fig.6 (a)–(e)], the results are plotted as the *SI* versus temperature. The white dots represent the “Initial” whereas the black dots represent “Irradiated”. For all semiconductor detectors channels, the temperature coefficient was 0.2−0.4%/°C at the initial stage of introduction. However, it was 0.1%/°C or less after the irradiation history.

4. Discussion

Semiconductor dosimeters must be quantified under any clinical conditions for intracavitary brachytherapy to maximize their accuracy and clinical utility. Without accurate sensitivity calibration, it is not possible to determine if a reading is due to abnormal dose values or other errors. In this study, we focused on the sensitivity and dark current noise, dose rate, and temperature of the detector.

Regarding the decrease in the sensitivity associated with the irradiation, the result was in agreement with previously reported findings [4)-7), 13)], indicating an initial exponential reduction, which subsequently slowed down. From the experiments, it was determined that there was the sensitivity decreased to approximately 0.92−0.95 with irradiation. According to the guidelines of the American Association of Physicists in Medicine (AAPM) task group No.138, 3.4% of the total dose calculation uncertainty of high-energy HDR is recommended, and a 5−8% decrease is not negligible because it is higher than [19)]. Therefore, sensitivity calibration is required before use. Then, it is necessary to record the change in sensitivity over time and observe that the sensitivity gradually becomes moderate. To accomplish this, the historical irradiated dose delivered to the detector must be recorded if possible.

There are limited publications on dark current noise. In addition to the aforementioned phenomenon that the sensitivity with the Ir-192 source decreases with the irradiation history, the response to dark current noise also decreases. It has been determined that some semiconductor channels have a negative dark current noise. In addition, when the source strength was low, (i.e. before source replacement), the ratio of the dark current noise exceeded 6%, and it was not negligible, given that it exceeded the uncertainty 3.4% set by the AAPM as in the aforementioned sensitivity decrease. Depending on the treatment plan, the rectum may be far away from the iridium source and there may be channels that receive little or no radiation. Therefore, it is necessary to quantify the zero signal as exactly zero.

Investigations at high dose rates of 60 Gy/h[12)] were not feasible in this study. The dose rate dependence at rates from 1.8 Gy/h to 2.4 Gy/h has been reported as negligible [13)]. In addition, a dose rate dependence was not observed at dose rates of 1.4 Gy/h to 6.8 Gy/h in this study. The results were the same for “Initial” and “Irradiated”. As such, the decrease in the source strength due to the decay of the Ir-192 source with an average apparent activity of 370 GBq can be interpreted as not affecting the accuracy of sensitivity calibration. In other words, there was no dose rate dependence and no change due to irradiation history.

In terms of the sensitivity variation with temperature, for the case of “Initial”, the result was in agreement with reference [8)-11)]. Furthermore, it was determined in this study that the tendency becomes moderate with irradiation. Thus, it was considered that temperature dependence reduced with irradiation. However, it was challenging to determine whether the temperature of the element was owing to the temperature dependence of the electronic circuit system, and it can only be considered to affect the final reading. In actual clinical dose monitoring, the detector is inserted into the rectum. Therefore, it is desirable to perform sensitivity calibration while accurately maintaining the phantom temperature at 37°C, especially when irradiation is initially low.

For all the characteristics of the semiconductor dosimeter, the results show that there are no large individual differences among the 5 channels. In actual clinical practice, there are cases in which treatment is performed over multiple fractions and the insertion position of each fraction into the rectum may be evaluated based on the ratio of the measurement values of the 5 channels. Therefore, the absence of individual differences is a very important characteristic.

5. Conclusion

In this study, we examined characteristics that were evaluated using a semiconductor rectal dosimeter over a three-year period. The sensitivity changed with irradiation history and it was determined that there is a sensitivity variation with temperature, which changed with irradiation history.

It should be noted these characteristics may affect the actual measurement results. However, when sensitivity calibration is performed under appropriate conditions, it can be effectively used for rectal dose monitoring during brachytherapy.

Acknowledgments

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Conflict of interest

We have nothing to declare for this study.

図の説明

Fig.1　実験配置図．全てこの配置で検討した．（a）が平面図で，（b）が立面図である．
イリジウムを中心に8センチ離して両側に半導体線量計ファーマー形線量計を配置した．温度は水ファントムを加熱水で温めて維持した．

Fig.2　照射歴による感度変化

Fig.3　照射歴による暗電流の変化

Fig.4　線源強度に対する暗電流の割合

Fig.5　線量率依存性とその変化

Fig.6　温度依存性とその変化

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