Development and Evaluation of Monoxide Based Flexible Skin Dosimeter for Radiotherapy at Photon Energies

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Abstract

Radiation therapy uses high-energy radiation that can cause various side effects depending on the patient's exposure. In particular, side effects occur in the skin due to its radiation exposure to reach the target volume. Therefore, side effects are reduced by clinical trials using various skin dosimeters such as films and glass detectors to determine the dose exposed to the skin. However, accurately measuring the doses using these dosimeters is challenging due to human curvature. In this study, a flexible skin dosimeter was produced using the photoconductor materials mercury oxide (HgO) and lead oxide (PbO). The performance of the proposed dosimeter was evaluated by measuring reproducibility, linearity, dose rate independency according to dose, and percent depth dose (PDD) at photon energy beam. The results showed that the flexible skin dosimeter using HgO material has high applicability as a skin dosimeter due to its stability compared to PbO. The results provide useful insights for the radiation therapy field, particularly in areas where radiation measurement is difficult, depending on the human curvature. The proposed flexible skin dosimeter could serve in various radiation detection areas as a flexible, functional material

Introduction

Radiation therapy uses high-energy radiation to treat cancer patients. However, high-energy radiation used in radiation therapy affects not only tumor tissues but also normal tissues, causing side effects. Among other things, the skin is directly exposed to radiation because it must pass through the skin to reach the target volume during treatment. In addition, the side effects of hair loss, erythema, and blisters occur most frequently in radiation treatment because of their high sensitivity to radiation^{1,2}. Therefore, skin side effects due to radiation therapy should be minimized by accurately measuring the radiation dose exposed to the skin. Current skin doses are calculated using a treatment planning system; however, the accuracy of dermal doses has an uncertainty of $\pm 20\%$ ³⁻⁶. Therefore, in clinical patient treatment, dosimeters are used to verify the skin dose, such as film, glass dosimeter (GD), optically stimulated luminescent dosimeter (OSLD), and thermo luminescent dosimeter (TLD). Nevertheless, with these skin dosimeters, accurate dose measurements are challenging due to the curvature of the human body surface⁷⁻⁹. Thus, clinical patient treatments require digital dosimeters relying on flexible materials with no function loss when bent, depending on the human curve.

However, thus far, flexible dosimeter studies are insufficient, even though various materials have been studied in the field of radiation detectors. Among them, lead oxide (PbO) and mercury oxide (HgO) have high atomic numbers (Z_{Hg} : 80, Z_{Pb} : 82, Z_{O} : 8) and density (11.14 g/cm³, 9.53 g/cm³). Therefore, they have been actively used in direct conversion studies¹⁰⁻¹³. These materials can be used to produce flexible materials through the particle in binder (PIB) method, which is made by mixing them with silicone binder in polycrystalline form. Because the PIB method is simple for large-scale manufacturing, and it is simpler than the single crystal manufacturing method, this method can lower the manufacturing unit

price¹¹⁻¹⁵. This study focused on the performance evaluation of unit cell dosimeters based on HgO and PbO to lay the foundations for developing flexible large-area dosimeters.

For this purpose, a flexible skin dosimeter using the PIB method was developed. Moreover, its applicability is demonstrated by evaluating reproducibility, linearity, dose rate independence, and percentage depth dose (PDD), according to the assessment items of the quality assurance for radiation treatment.

Method

In this study, a flexible skin dosimeter was produced using the PIB method, which is simple to apply to photometric substances and silicone binders. The performance of the skin dosimeter was evaluated.

Fabrication of flexible skin dosimeter

For the lower electrode, a heat-resistant film was applied with indium tin oxide (ITO). The radiation absorption layer was manufactured by mixing 99.99% purity HgO, PbO (Kojundo Chemical Laboratory Inc., Japan) material, and silicone binder at a ratio of 4:1 and applying a screen printing technique to frames of $1 \times 1 \text{ cm}^2$ and $150 \text{ }\mu\text{m}$ thickness. Subsequently, the radiation absorption material was dried for 12 hours at a fixed temperature of $40 \text{ }^\circ\text{C}$. The vector placement method was used to create an upper electrode on the top of the radiation absorption material. The upper electrode used gold (Sigma Aldrich Inc. U.S.A.) with 99.999% purity to collect charges. Moreover, the size of the upper electrode was $0.8 \times 0.8 \text{ cm}^2$.

Figure 6 shows the experimental set-up. The performance of the flexible skin dosimeter was evaluated considering the reproducibility, linearity, dose rate independence, and PDD of the HgO and PbO flexible skin dosimeter at 6 MV and 10 MV. A LINAC system (Infinity; Elekta AB, Stockholm, Sweden) was used for measurements. Considering the 6 MV and 10 MV D_{max} photon energy, the build-up materials were set at 1.5 cm and 2.1 cm, respectively. The build-up material used a Slab phantom of equivalent tissue thickness (PTW, RW3, Germany). The source-to-surface distance (SSD) was set to 100 cm. Waveforms were acquired by the oscilloscope to collect signal values from radiation. The charge was calculated from the collected waveforms using ACQ software (Biopac, AcqKnowledge 4.2, CANADA). At this time, a drive voltage of $1 \text{ V}/\mu\text{m}$ was applied to the circuit using electrometers (Keithley, 6517A, USA).

Table 1 shows the radiation irradiation conditions used in the experiment.

Table 1. Experimental conditions.

Material	HgO, PbO	
Nominal photon energy	6 MV, 10 MV	
Linearity radiation intensity	3, 5, 10, 50, 100, 200, 300, 400 MU	
Reproducible irradiation count	10 times	
Dose rate	6 MV	100, 300, 430 MU/min
	10 MV	100, 300, 400, 500 MU/min
Depth	6 MV	0.1, 0.3, 0.5, 0.8, 1, 1.3, 1.5, 1.7, 2, 2.5, 3, 5, 10, 15, 20, 25 cm
	10 MV	0.1, 0.3, 0.5, 0.8, 1, 1.5, 1.9, 2.1, 2.3, 2.5, 3, 5, 10, 15, 20, 25 cm
Source-to-surface distance	100 cm	
Field size	10 × 10 cm ²	

Evaluation

In this study, reproducibility and linearity were measured to evaluate precision and accuracy. In addition, dose rate independence and PDD were evaluated to analyze the response characteristics. Flexible skin dosimeters were irradiated ten times repeatedly for reproducibility measurements. The signals obtained from the first beam were normalized to evaluate the response characteristics of repeated irradiations. Reproducibility assessment can be expressed in RSD based on the amount of the acquired signals. The RSD was calculated as follows:

$$\text{RSD}(\%) = \left[\left\{ \sum (X_i - X_{Ave})^2 / n \right\}^{0.5} / X_{Ave} \right] \times 100,$$

where X_i and X_{Ave} are the measured signal value and mean average signal value, respectively. Moreover, n is the number of measurements. The evaluation criteria were set within 1.5% of the RSD value corresponding to the 95% confidence level^{16–19}.

The linearity result was evaluated through the coefficient of determination (R^2) of the linear regression that irradiated radiation by gradually increasing the dose in 3, 10, 50, 100, 200, 300, and 400 MU under 50 MU/min conditions. The evaluation criteria for R^2 were not less than 0.9990^{12,13}. The reproducibility and linearity results were analyzed to evaluate the stability of the signals and the possibility of developing a flexible skin dosimeter.

The dose rate independence was evaluated by increasing the doses gradually by irradiating from 1 to 400 MU under 100, 300, and 430 MU/min at 6 MV and 100, 300, 400, and 500 MU/min at 10 MV. The

measured signals were normalized to 200 MU, and the RSD (n=3) for 100 MU measurements was calculated and compared to the diode. The result value of the diode was used in the other study that followed the same experimental method¹⁷.

PDD was obtained by increasing the Slab Phantom thickness from 0.1 cm to 25 cm. The results were normalized to calculate the percentage based on the $D_{\max}$ point and compared with the thimble chamber.

Results

Reproducibility

Reproducibility was analyzed to evaluate the stability of the flexible skin detector signal made of a monoxide material and silicone binder. Figure 1 shows the reproducibility results from repeated irradiation.

After analyzing the reproducibility by irradiating radiation ten times, the relative standard deviation (RSD) value of the HgO flexible skin dosimeter was 1.7230% and 2.3421% at 6 MV and 10 MV, respectively. The RSD value for the PbO flexible skin dosimeter was 1.4016% and 1.4843% for 6 MV and 10 MV, respectively.

Linearity

Linearity was analyzed to evaluate the accuracy of the output signals according to the irradiation dose. Figure 2 shows the results of linearity according to the irradiation dose. The left and right graph graphs show the signal values at 6 MV and 10 MV energy, respectively.

The linearity assessment showed that the R^2 value of the HgO flexible skin dosimeter was 0.9999 and 0.9986 at 6 MV and 10 MV, respectively. The R^2 value of the PbO flexible skin dosimeter was 0.9994 and 0.9992 at 6 MV and 10 MV, respectively.

Dose rate in dependence

The dose rate independence was evaluated, analyzing a value related to the response characteristics by dose-rate.

Figure 3 presents the linearity graph according to the dose at each dose rate for the HgO flexible skin dosimeter. The graph on the left is at 6 MV energy, and the graph on the right is at 10 MV energy. The RSD by dose-rate at 100 MU showed that the HgO flexible skin dosimeter was 0.51% and 2.00% at 6 MV and 10 MV, respectively.

Figure 4 shows that the dose increases at each dose rate for the PbO flexible skin dosimeter. The figure shows the signal value obtained from 6 MV energy (left) and 10 MV energy (right). The RSD by dose-rate

at 100 MU showed that the HgO flexible skin dosimeter was 0.36% and 0.37% at 6 MV and 10 MV, respectively.

Percent depth dose

PDD was obtained by measuring the dose at depth and increasing the slab phantom from 0.1 cm to 25 cm. Figure 5 shows the PDD measurement results of the flexible skin detector.

The PDD result of the flexible skin dosimeter shows the ideal $D_{\max}$ value at the $D_{\max}$ point for 6 MV and 10 MV energy to represent the ideal PDD graph. In particular, for the PDD value at 10 cm 6 MV, HgO was present at 69.98%, and PbO at 71.15%. Compared to the PDD value of the thimble chamber that of the HgO and PbO was different by 2.4% and 3.75%, respectively. At 10 MV, HgO was observed at 72.24%, and PbO was 73.02%. When compared these values with the PDD of the thimble chamber, the difference was 0.14% and 0.92%, respectively.

Discussion

In this study, HgO and PbO were analyzed at 6 MV and 10 MV energy to evaluate their applicability as flexible skin detectors. The reproducibility measurement of HgO showed an RSD of 1.7230% at 6 MV and 2.3421% at 10 MV. The results for the HgO also showed linearity. In this study, the RSD was higher than the baseline of 1.5%, indicating that the signal is unstable.

In contrast, PbO materials were present at 1.4016% at 6 MV and 1.4843% at 10 MV. These results indicate that the signal is stable because it satisfies a 95% confidence interval with values below the 1.5% threshold¹⁶.

In the linearity analysis, HgO showed very good linearity with a value of 0.9999 at 6 MV. However, at 10 MV, the result was 0.9986, which is lower than the benchmark of 0.9990. In contrast, PbO showed the excellent linearity of 0.9994 at 6 MV and 0.9992 at 10 MV. Consequently, the graph was linear with respect to the dose.

Concerning the dose rate independence evaluation, the RSD value for the HgO was 0.51% at 6 MV and 2.00% at 10 MV. Moreover, the RSD value for the PbO was 0.36% at 6 MV and 0.37% at 10 MV. In other studies, the standard deviation of the HgI₂-, diamond-, and silicon diode-based dosimeter for 6 MV energy was 4.1%, 4.3%, and 0.3%, respectively. When the results are compared with those of the manufactured flexible skin dosimeter at 6 MV, the latter has a similar or better dose rate independence than other dosimeters¹⁶.

When comparing and analyzing the PDD value at 10 cm depth of the thimble chamber, the difference between HgO and PbO represented 2.4% and 3.75%, respectively, under 6 MV conditions. At 10 MV energy, the difference between HgO and PbO was 0.14%, and the difference between PbO was 0.92%. These results could be due to experimental variables in the experimental set-up and air gap generation using the

slab phantom. The drop in results of HgO is thought to be due to the charge of the flexible skin detector remaining in the electric field after the study.

The irregular particle size and silicone binder of the HgO material used in the manufacture of flexible skin dosimeters are not evenly mixed. Thus, resulting in a space between the two materials, which is believed to cause unstable results, such as the above, because of the capturing effect of electric charges¹⁷. In the future, it is necessary to supplement the problem after a sufficient roll-mill process.

Conclusion

In this study, a flexible skin dosimeter was produced in the form of a film for the measurement of skin dose according to human body curvature. In addition, the applicability of the flexible skin detector was evaluated on the photon by analyzing the reproducibility, linearity, dose rate duration, and PDD.

The results of evaluating the signal stability of the flexible skin dosimeter for both HgO and PbO substances were similar to the PDD of the thimble chamber. The reproducibility of HgO was 1.7230% and 2.3421% for 6 MV and 10 MV, respectively. Linearity was measured at 0.999999 and 0.9986 for 6 MV and 10 MV, respectively. Linearity according to the dose rate was 0.75% and 2.00% for 6 MV and 10 MV, respectively. The evaluation results for PbO were as follows. Reproducibility was measured at 1.4016% and 1.4843% for 6 MV and 10 MV, respectively. Moreover, linearity according to the dose rate was 0.36% and 0.9992, for 6 MV and 10 MV, respectively. Except for the 6 MV linearity, the signal stability of PbO showed to be adequate compared to that of HgO. These results suggest that PbO materials are highly prone to be applied to flexible skin dosimeters.

These results are useful in the field of radiation therapy, especially in areas where radiation measurements are challenging due to human curvature. The proposed dosimeter can be used in radiation detection areas as a flexible and functional device.

Declarations

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Author contributions

J. B. Chung, J. K. Kang, T. S. Yu, J. E. Rah, J.K. Kim and M.W. Lee contributed design and discussion of the research and preparing the manuscript. S.W. Yang, M.J. Han, S.K. Park and J.Y. Kim all the experiment.

Competing interests

The authors declare no competing interests.

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Figures

Figure 1

Reproducibility of flexible skin dosimeters at 6 MV (left) and 10 MV (right).

Figure 1

Reproducibility of flexible skin dosimeters at 6 MV (left) and 10 MV (right).

Figure 2

Linearity of flexible skin dosimeters at 6 MV (left) and 10 MV (right).

Figure 2

Linearity of flexible skin dosimeters at 6 MV (left) and 10 MV (right).

Figure 3

Linearity according to dose rate for the HgO flexible skin dosimeter at 6 MV (left) and 10 MV (right).

Figure 3

Linearity according to dose rate for the HgO flexible skin dosimeter at 6 MV (left) and 10 MV (right).

Figure 4

Linearity according to the dose late for the PbO flexible skin dosimeter at 6 MV (left) and 10 MV (right).

Figure 4

Linearity according to the dose late for the PbO flexible skin dosimeter at 6 MV (left) and 10 MV (right).

Figure 5

PDD of the flexible skin dosimeter at 6 MV (left) and 10 MV (right).

Figure 5

PDD of the flexible skin dosimeter at 6 MV (left) and 10 MV (right).

Figure 6

Experimental set-up.

Figure 6

Experimental set-up.