Original Article

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Feasibility Study of Source Position Verification in HDR Brachytherapy Using Scintillating Fiber

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The position verification of the radiation source utilized in brachytherapy forms a critical factor in determining the therapeutic efficiency. Currently, films are used to verify the source position; however, this method is encumbered by the lengthy time interval required from film scanning to analysis, which makes real-time position verification difficult. In general, the source position accuracy is usually tested in a monthly quality assurance check. In this context, this study investigates the feasibility of the real-time position verification of the radiation source in high dose rate (HDR) brachytherapy with the use of scintillating fibers. To this end, we construct a system consisting of scintillating fibers and a silicon photomultiplier (SiPM), optimize the dosimetric software setup and radiation system characteristics to obtain maximum measurement accuracy, and determine the relative ratio of the measured signals dependent upon the position of the scintillating fiber. According to the dosimetric results based on a treatment plan, in which the dwell time is set at 30 and 60 s at two dwell positions, the number of signals is 31.5 and 83, respectively. In other words, the signal rate roughly doubles in proportion to the dwell time. The source position can also be confirmed at the same time. With further improvements in the spatial resolution and scintillating fiber array, the source position can be verified in real-time in clinical settings with the use of a scintillating fiber-based system.

Key Words: Brachytherapy, Dwell position, Scintillating fiber, SiPM

Introduction

Brachytherapy is a type of radiotherapy that is designed to remove tumors with the use of gamma or beta rays emitted from a radioisotope during its decay by positioning it close to the tumor site.[1,2] Unlike external radiotherapy, in which healthy organs are inevitably exposed to radiation depending on the beam path, brachytherapy, also called internal radiation therapy, ensures direct dose delivery to a tumor from the radioisotope implanted near the tumor, thus radically reducing the beam path and unnecessary exposure of the surrounding healthy tissue or organs. Moreover, the average energy released during the decay of Ir-192 (which is the normally used radiation source for brachytherapy) is 380 keV, which is substantially lower than the energy range of MeV typically used for radiotherapy. Further, the beam dose decreases drastically with increasing distance from the source, thereby resulting in quasi-zero damage to healthy organs. In other words, brachytherapy can directly deliver therapeutic radiation to a tumor without radiation passing through surrounding healthy organs. Not only does this reduce the risk of damage to healthy organs, but it also enhances the convenience of patients by re-

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ducing the total duration of radiotherapy and related costs by enabling low-fraction treatment with higher doses per fraction.[3)] Since brachytherapy has demonstrated superior therapeutic efficiency for cervical, prostate, breast, and skin cancer via removal of tumors without causing any noticeable damage to healthy tissue and organs, attempts have been made to apply it to other types of cancer.[4)] Given that brachytherapy involves implanting radioactive "seeds" into the body, it is noteworthy that if the seeds are not placed correctly in the planned tumor position and placed close to a healthy organ instead, the resulting radiotherapy has little therapeutic effect and the healthy organ involved is subject to the risk of developing various complications due to the delivered high-dose radiation. As such, ensuring the source position accuracy is of vital importance for the therapeutic success of brachytherapy.[5)]

Plastic scintillators provide dosimetric accuracy because they have no temperature dependency in the measurement environment, and they do not "over-respond" to low-energy radiation because of the corresponding low atomic number of the plastic scintillator.[6)] The plastic scintillating optical fiber used in this study also has such properties and emits scintillation light when irradiated because the microfine impurities contained in plastic react with ionizing radiation. The amount of light thus released is proportional to the energy deposited, which can be used for dose verification.[7-9)] Both plastic scintillating fibers and optical fibers lend themselves well to miniaturization and weight reduction to the millimeter scale, and the use of an optical fiber for transmitting light with a readout system affords greater user convenience because the distance between the measurement position and the readout system does not affect measurement. Further, the distance-dependent light intensity attenuation can be compensated for at the rate of 1 dB/m.

In radiation therapy, films or glass dosimeters are commonly used to measure radiation doses. The use of such devices involves a separate post-irradiation reading, which makes real-time dosimetric verification impossible. Moreover, films cannot be reused, thus incurring additional cost at each use. In contrast, a scintillating fiber can provide real-time verification of emitted light at the moment of irradiation and can be reused without any additional cost. Here, we attempted to study the feasibility of using plastic scintillating fibers for checking the dose delivery accuracy by verifying the source position during brachytherapy.

Materials and Methods

1. Scintillating fiber and optical fiber

We performed dosimetry using the scintillating fiber BCF-12 and optical fiber BCF-98 (Saint-Gobain S.A., France). Both BCF-12 and BCF-98 are plastic fibers with a square cross-section (1×1 mm). BCF-12 has a polystyrene-based core with a refractive index of 1.60 and density of 1.05. It has an acrylic cladding with a refractive index of 1.49 and thickness making up about 4% of the fiber size. With a scintillation efficiency of 2.4% and trapping efficiency of 4.4%, BCF-12 emits ~8,000 photons/MeV, of which only about 4% are stored for signal generation.[10)] The fiber emits blue light exhibiting an emission peak at 435 nm, and its signal transmission efficiency in dosimetry is improved over long fiber lengths. BCF-98, which is used as an optical fiber for transmitting the scintillating light generated from BCF-12, exhibits an average light intensity attenuation of 1 dB/m when transmitting the scintillating light of 435 mm emitted from BCF-12.[11)]

2. SiPM-based measurement system

The abbreviation SiPM refers to the silicon photomultiplier, which is a solid-state single-photon-sensitive device based on the avalanche photodiode (APD) with an embedded photocurrent amplifier.[12,13)] Although its performance level is similar to that of a photomultiplier tube (PMT), with a photo-detection efficiency (PDE) in the range of 20~50% and its gain (G) amounting to ~10^6, its voltage range of 20~100 V (15~75 times lower than that of a PMT) and its small size make it a promising candidate for applications involving compactness, lightness, and robust mechanical design. The SiPM-based system also requires a Matrix-EVB Communication Board, front-end electronics board, and sensor array for measuring the radiation-induced signals (Fig. 1).

The sensor array is composed of a 12×12 SiPM array and linked to the front-end electronics board via a 50-way flexible printed circuit cable. The front-end electronics board receives 144 SiPM signals and amplifies them, and subsequently, the signals are digitized and converted to information with a programmable threshold discriminator. The resultant data are then analyzed by the Matrix-EVB Board, and the signal outputs are received at the interface of the connected PC. Besides the PC, the Matrix-EVB Communication Board is connected to a power supply to receive the operating voltage. The PC settings can be configured to optimize the pre-experimental signal measurement (Fig. 2) so that suitable data can be selected from the measured data acquired by the Matrix-EVB Communication Board for post-experimental result analysis (Fig. 3).

The proposed system adopts a method of obtaining dosimetric information by measuring the scintillating light from the BCF-12 generated by the gamma rays emitted from Ir-192 after PC-setting optimization is performed for measuring Ir-192 signals. Radiation-induced light generated from the BCF-12 is transmitted to the sensor array via the BCF-98, and the received signals are amplified in each SiPM connected to each fiber. The amplified signals are subsequently converted into electrical signals by the front-end electronics board and stored in the Matrix-EVB Communication Board. The pre-configured settings ensure that the desired signals are filtered from the stored signals, thus enabling the verification of Ir-192 source information in the PC interface.

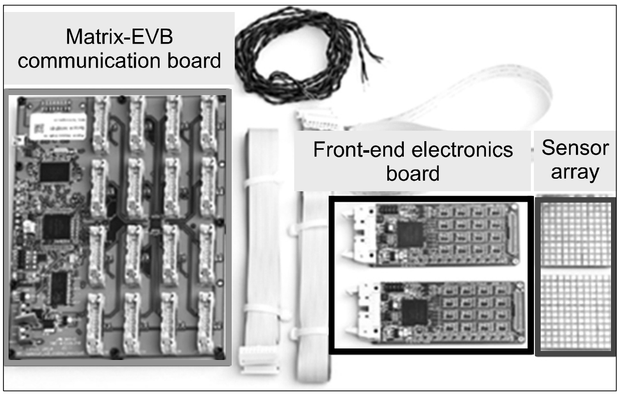
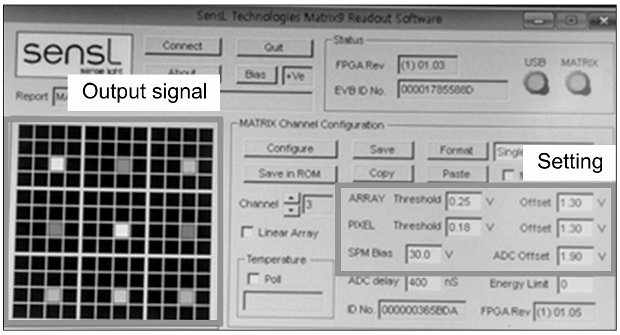


Fig. 1. Components of the silicon photomultiplier (SiPM) system used in the study.



Status
FPGA Rev (1) 01.03
EVB ID No. 00001785588D
Channel 3
☐ Linear Array
ARRAY Threshold 0.25 V Offset 1.30 V
PIXEL Threshold 0.18 V Offset 1.30 V
SPM Bias 30.0 V ADC Offset 1.90 V
ADC delay 400 nS Energy Limit 0
ID No. 000000365BDA FPGA Rev (1) 01.05

Fig. 2. Software for using silicon photomultiplier (SiPM) system provided by SENSL.

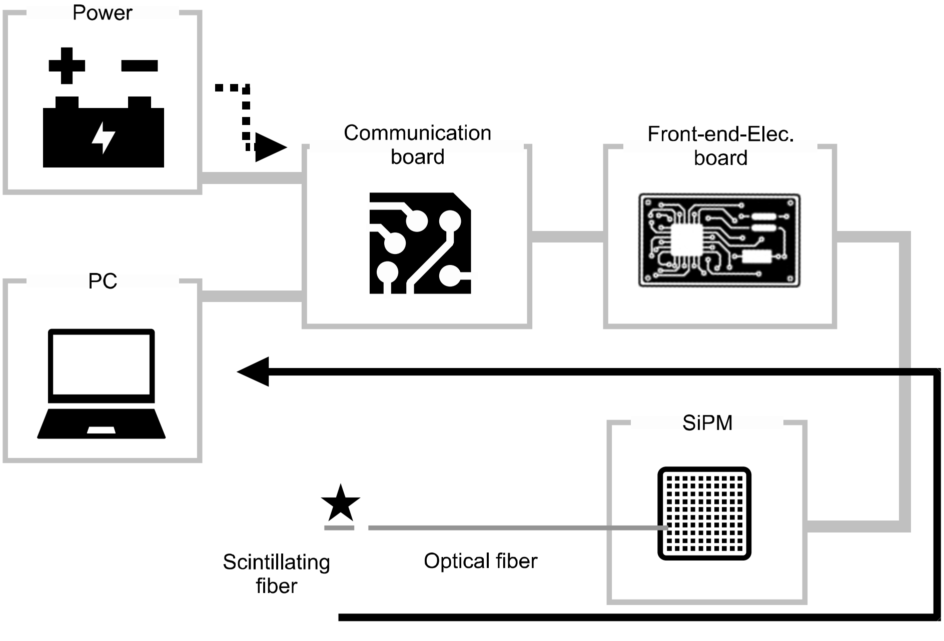


Fig. 3. Overall schematic of the system used in the study (Grey-Connection line, Dotted arrow-Input, Dark arrow-Output, Star-Source).

3. Central tendency of radiation data obtained using scintillating fiber and SiPM system

Given that an SiPM is more commonly used in relation to diagnostic than therapeutic radiation, we examined the characteristics and central tendency of the measurement data for therapeutic radiation using a linear accelerator before examining the signals from Ir-192, which is a commonly used radioisotope in brachytherapy.

We measured the light and signals generated from a scintillating fiber while varying the doses and dose rates of 6-MV and 10-MV photon beams using a linear accelerator and examined the central tendency of the obtained data. The source-to-surface distance (SSD) and field size (FS) were set at 100 cm and 10 cm×10 cm, respectively, for the linear accelerator. After placing a scintillating fiber in the middle of the field and overlaying a solid water phantom with a thickness of the build-up matching 6 MV and 10 MV (i.e., for each beam condition), we examined the dose-dependent central tendency of the acquired data, increasing the dose from 20 to 50, 75, 100, and, 300 MU at a fixed dose rate of 600 MU/min. In addition, data dependency on dose rate change was examined by increasing the dose rate from 100 to 200, 300, 400, 500, and 600 MU/min at fixed doses of 6 MV and 10 MV.

4. Ir-192 signal measurement depending on distance from source with single scintillating fiber

A single scintillating fiber polished to a 1-cm length and glued to the optical fiber was connected to one SiPM of the 144-SiPM array. After configuring the dwell time of the radiation source at one dwell position to 100 s, we measured scintillating signals by increasing the distance between the source (Ir-192, radioisotope for brachytherapy) and the scintillating fiber from 0 to 2.5 cm over regular increments of 0.5 cm (0, 0.5, 1, 1.5, 2, 2.5) in order to identify the characteristics of the signal intensity depending on the distance between the source and the scintillating fiber for dosimetry.

5. Source dwell position verification using a one-dimensional scintillating fiber array

Prior to verifying the source dwell position with a one-dimensional scintillating fiber array, we determined the optimal settings for PC processing to obtain multi-channel signals from a scintillating fiber connected to a multi-channel system. To this end, we connected three scintillating fibers arrayed at 1-cm intervals to the SiPM system and obtained signals varying according to the distance from each channel. The optimal settings for obtaining multi-channel signals were determined by comparing the central tendencies of the signals measured with increasing distance with those of the distance-dependent signals measured using the single fiber with the optimal software settings, as established in the previous experimental phase of the study.

The source dwell position verification experiment comprised the following steps: i) fabrication of the scintillating fiber board with five 1-cm scintillating fibers arrayed at 1-cm intervals; ii) fabrication of the scintillating optical board by connecting the five abovementioned scintillating fibers to their respective optical fibers and shielding the scintillating fibers with black tape to protect them from stray light sources; iii) connection of the five optical fibers to their respective SiPMs (Fig. 4); iv) measurement of the signals from each scintillating fiber using the SiPM system according to the treatment plan for the radiation source to dwell at the positions of the second and fourth scintillating fibers for 30 and 60 s, respectively. As a result, we ascertained that the proposed system could be used for source position verification and dose delivery accuracy based on the dose change that is dependent upon the dwell time at the source dwell position.

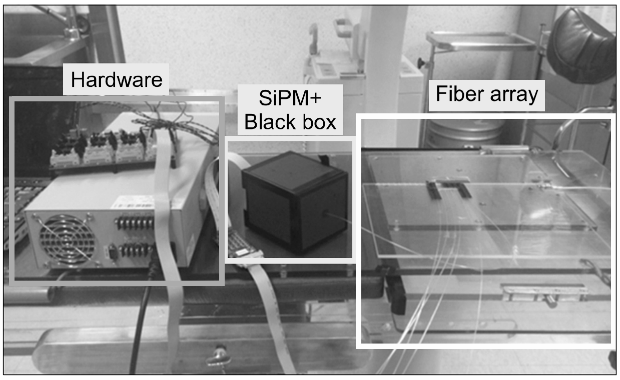


Fig. 4. Photograph of the actual setup used in the study.

Results and Discussion

1. Dose-dependent signal linearity verification in dosimetry

The signals from the scintillating fibers were measured for the 6-MV photon beam, with increase in the dose from 20 to 300 MU (20, 50, 75, 100, 125, 150, 175, 200, 250, and 300). As a result, it was verified that the number of signals of scintillating light generated from the scintillating fibers increased linearly (735, 1804, 2691, 3586, 4457, 5375, 6243, 7096, 8885, and 9881 in that order). The number of signals measured with the 10-MV photon beam under the same conditions also increased linearly (526, 1695, 2315, 3331, 4217, 4989, 5825, 6664, 8470, and 9312) in a pattern similar to that of the 6-MV photon beam (Fig. 5).

2. Dose-rate-dependency verification in dosimetry

The dose-rate-dependent signal measurement was confirmed to be constant since we obtained a low deviation of 11.43 (number of signals: 3561, 3570, 3595, 3581, 3579, and 3575) when the dose rate was varied (100, 200, 300, 400, 500, and 600 MU/min, in that order) under 6-MV, 600-MU conditions. Under the 10-MV, 600-MU conditions as well, the deviation was as low as 15.97 (number of signals: 3347, 3357, 3363, 3371, 3382, and 3390), similar to the 6-MV case, thus demon-

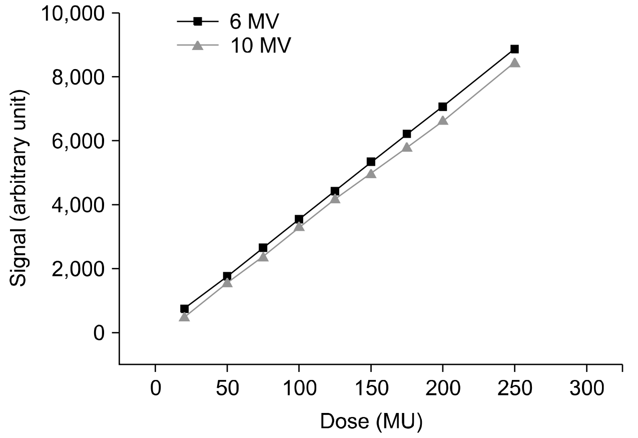


Fig. 5. Output signal as a function of the dosage in our radiotherapy experiment.

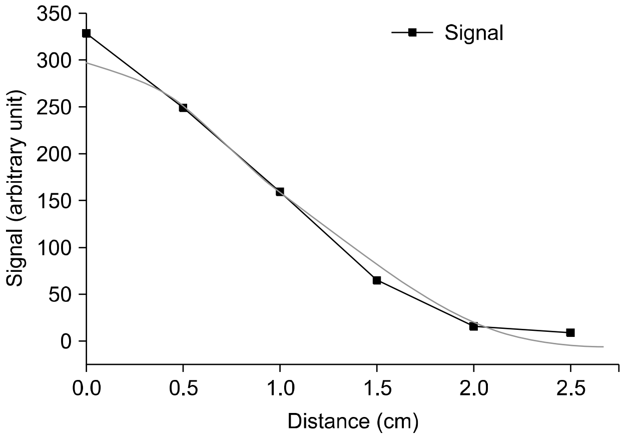


Fig. 7. Output signal as a function of the distance between fiber and source (Red line-Exponential fitting of the signal).

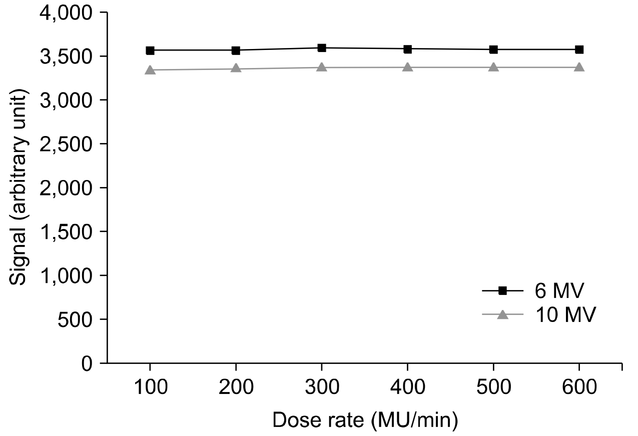


Fig. 6. Output signal as a function of the dose rate in our radiotherapy experiment.

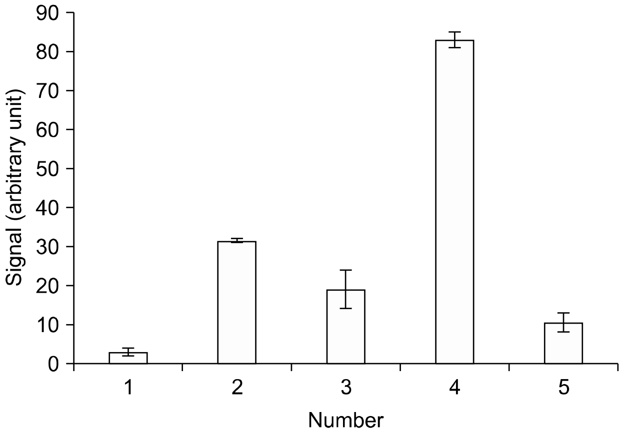


Fig. 8. Measured signal for different dwell times at two dwell positions.

strating that the number of signals remains constant under different beam conditions (6 and 10 MV) and dose rates (100～600 MU/min) (Fig. 6).

To conclude, we confirmed that almost steady data were obtained despite varying dose rates at both energy levels of 6 MV and 10 MV and that the proposed dosimetric system has no dose-rate dependency for therapeutic radiation generated by a linear accelerator.

3. Ir-192 signal measurement depending on distance from source with single scintillating fiber

We confirmed that the number of signals measured rapidly decreases (329, 204, 175, 60, 16, and 10) as the distance between the radiation source and scintillating fiber increases (0 to 0.5, 1, 1.5, 2, and 2.5 cm in that order) (Fig. 7). This is consistent with the result of a previous study,[14)] which reported that the number of signals from the radioisotope Ir-192 rapidly decreased with the dose expressed in the number of the signals from the radioisotope Ir-192 rapidly decreased with increasing distance. This result verifies the validity of the proposed system for Ir-192 dosimetry and the efficacy of the proposed system for verifying the source dwell position accuracy, drawing on the relationship between the dose rate and signals from scintillating fibers.

4. Source dwell position verification using one-dimensional scintillating fiber array

The numbers of signals measured with the use of five scintillating fibers arrayed at 1-cm intervals under the conditions of two source dwell positions and dwell times of 30 and 60 s at each position were 3, 31.5, 19, 83 and 10.5 in respective dwell position. The number of data 31.5 and 83 were obtained at the measured positions of dwell times of 30 and 60 s, respectively. The value at 60 s marked over a two-fold increase rate comparing with 30 s. If the measurement was executed to two plans with the dwell time 30 and 60 s, respectively, the dose and the value would increase a two-fold matched the increase rate of the dwell time. When the source dwelt at one position, it influenced the other position as well as the dwelling position because of the two dwell positions. So, ratio was not accurately matched with change of the dwell time. Nevertheless, a peak was shown at the dwell position from the graph (Fig. 8) and we demonstrated the feasibility of using the relative rate of signals depending on the measurement position of the scintillating fiber as a proxy for source dwell position verification. But, when the dwell position and time are several, study about influence between the dwell positions is acquired for an accuracy.

Conclusion

In this study, we tested the reliability of a scintillating-fiber-based dosimetric system for verifying the position of a brachytherapy radiation source. Currently, the quality control of the position accuracy of a brachytherapy radiation source is not performed during each treatment session in real-time, but periodically at specified intervals.[15)] Because an irradiated scintillating fiber emits light and the signal analysis can be performed on-site immediately after radiation, the time requirement for source position verification with the proposed system is drastically lesser than with conventional methods. Moreover, the readout system using scintillating fibers and a SiPM system is small and easy to use, enabling a rapid and accurate pre-treatment check of the beam path and thus enhancing dose delivery accuracy. This study was conducted to evaluate the feasibility of using a scintillating fiber for dosimetry. Given that the proposed system consists of scintillating fibers arrayed at 1-cm intervals, currently yielding a resolution insufficient for clinical use, its spatial resolution can be improved by narrowing the intervals of scintillating fibers in a follow-up study. Furthermore, the distance between source and fiber should be reduced for more accurate signal measurement, which can be best achieved by inserting the fiber into the patient's body near the radiation source. Thus, our research team intends to develop a modified brachytherapy applicator that has an additional function of inserting a scintillating fiber. By refining the present simplified scintillating fiber array and designing the system for individual application for patients, it is expected that the source position information obtained in real-time during patient treatment can be used to prevent brachytherapy-related accidents.

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