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Monte Carlo Design and Simulation of a Grid−type Multi−layer Pixel Collimator for Radiotherapy: Feasibility Study

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1. Introduction

The radiation therapy treatment technique has been quickly and correctly updated by engineering developments based on several experiments in the clinical field. In the case of the multi−leaf collimator (MLC), the operation of a moving leaf has been used for field shaping to pass radiation for radiotherapy [1]. The MLC leaf could be positioned by connecting a stepping motor to the leaf's terminal [2]. If the radiation therapy plan data is read as an input to a processing computer, an applied electronic signal can be used to command several leaves to move in a pattern simultaneously.

The collimation method for a pixel unit that is used in this research is the method of a grid-type pixel collimator (GTPC). Basically, the grid frame, which is used to hang the attenuation cover, is arranged on a layer. The pixel cover's geometry is determined by using calculations based on Monte Carlo simulations. The basic pixel cover is a flat panel with a square pattern and is composed of a tungsten material to attenuate the radiation gradually. In addition, the attenuation can be controlled electronically by opening and closing the cover. When the micro direct current (DC) motor, which is connected to the pixel cover in the grid frame, shows an 'On' electronic signal, the rotation of the motor closes the pixel cover. Certainly, grid frames in the radiation beam path are also applied to the radiation shielding. The closed pixel cover attenuates radiation regularly because the more the pixel is closed. the better the attenuation as the radiation beam passes. Many layers, including the pixel cover complex, allow effective intensity attenuation; hence, the number of layers needs to be defined using a Monte Carlo calculation to determine the degree of the attenuation. Due to the cover's turning radius, the space between the upper layer and the lower layer should be filled with air along the length of the pixel cover. Several pixel covers form a pixel complex in a layer as a square grid pattern. When radiation exposes a layer containing the pixel complex, the area of the proposed radiation beam can be built by driving each pixel individually.

When a specific tumor pattern is placed on a critical organ such as an eye ball, the collimator complex will form the shape of the tumor exactly because the movement of each pixel cover is controlled by an electronic signal [3]. In addition, the other floor collimator complex will also be changed to a pattern with the same specific tumor shape as the pixel unit. Then, the radiation beam can pass through the shaped area in the collimator toward the tumor. In the process of radiation therapy, if radiation intensity modulation is required at a particular area, some of the opened pixel collimator covers can be closed to achieve more radiation attenuation. Because the status of the pixel cover is changed by operating the DC motor connected to the cover in real time, fast radiation intensity modulation and effective target guidance is expected from the Monte Carlo simulation results. In order to confirm the feasibility of field applications of different collimator systems with a MLC and to construct an actual GTPC model for radiation therapy, we calculated the construction factors. In addition, some GTPC's performances based on MC simulations were reported with a basic MLC model.

2. Methods and Results

Opening and shutting type pixel covers are rotated using micro motors (axis length of motor = 4 mm, diameter = 1 mm and rated torque = 0.025 mNm) located at the cover's terminal (Fig. 1). If a pixel cover is raised by a motor, when the DC motor is supplied with enough voltage, the rated torque needs to larger than the material torque of the cover which has a moment of inertia equal to that of a rectangular plate.

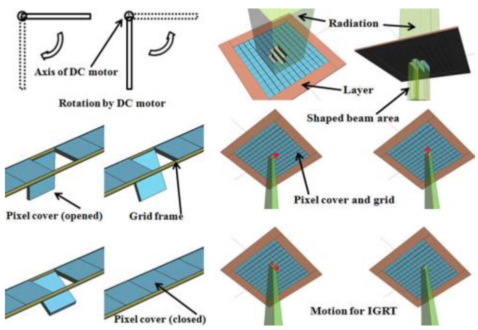

Fig. 1. The principle of the pixel cover operation. The blue cover could attenuate radiation regularly. General drawing of a grid type multi-layer pixel collimator (GTPC), showing open pixels to form the radiation beam's area and to partially attenuate the radiation and the pixel cover's movement for target guidance.

The number of layers was set using a Monte Carlo n−particle (MCNPX version 2.5.0, LA−CP−05−0369) simulation tool after the thickness of the each pixel cover had been determined. In the determination of the thickness, two conditions must be considered to construct the system. First, the thickness is the same as the pixel cover and the grid frame width. When the pixel cover is thick, the delivery dose can be more seriously affected by the thickness. If each pixel cover is thicker, the line artifact in the portal image will be thickened. Thus, the efficiency of dose delivery will be decreased greatly by only a small difference in the thickness. Second, the entire structure magnitude and material torque should be considered for fast operation compared to the MLC leaf's motion. When the collimator structure is installed in the therapy instrument, it must not disturb the therapy trace (length ≤ 30.0 cm). In addition, the material's torque should be set within the DC motor's output torque:

The radiation source was defined as a flattened and extended pattern with a direction from the MCNPX code (sdef function) [4]. An attenuation plate (tungsten, 17.50 g/cm^3, 40.0 × 40.0 × 1.0 mm^3) was added step by step to the radiation source. The radiation beam passes through the attenuation plate and is deposited at a detector (CsI(Tl), density = 4.51 g/cm^3). The distance between the source and the surface of the detector was 100.0 cm. The attenuation plate was placed above the surface of the detector at a 20.0 cm distance.

In the simulation, for the concurrence with the MLC's specifications, the pixel cover size was set to be equal to the leaf size of the MLC (5.0 mm); also, the pixel number of one layer (matrix = 32 × 32, 5.0 × 5.0 × 1.0 mm^3, tungsten, 17.50 g/cm^3) is in accordance with the number of leaves at one side of the basic MLC (32 pairs, 64 leaves) used in this study [5]. The grid frame (1.0 × 1.0 × 16.0 mm^3, 32 grid frames on a layer, tungsten (17.50 g/cm^3) 20%, copper (8.94 g/cm^3) 60%, aluminum (2.70 g/cm^3, 20%) in the middle of the collimation area and the folded pixel covers were also considered. Because of the geometrical limitation in simulation, many layers, including the pixel complex, could not be realized in one space filled with air. In one air space (cell card), it was not possible to simulate over 30 layers. From the previous construction research on the pixel cover, at least 52 layers were required for attenuation up to 2%. For accurate simulation, only 30 layers with the pixel complex were simulated in only one air space.

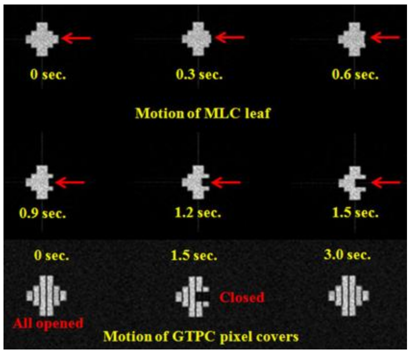

Fig. 2. Real time portal image of each collimator's moving pattern: (a) Multi-leaf collimator (MLC)'s leaf movement for 3.3 sec, and (b) Grid type multi−layer pixel collimator's (GTPC's) operation pattern for the same time.

In the GTPC system, radiation intensity modulation was achieved by each pixel's opening and closing. The momentary movement of several pixel covers could provide a fast radiation intensity modulation. In addition, when the effect of the target's motion on radiation exposure is considered, the pixel covers will be folded or unfolded to adjust the shape and the intensity in a moment. Figure 2 shows portal images of the MLC and the GTPC for radiation intensity modulation. The leaf's moving pattern was observed from the dynamic MLC's (DMLC) portal image. The average leaf speed was set as 11 mm/sec. A couple of leaves moved to the inside for 1.5 second, the leaf position was held for 0.3 second, and the leaves returned to the original positions for 1.5 second. However, the GTPC's covers were operated at the same leaf positions as those of the MLC. The 120 covers applied (4 covers × 30 layers) were folded at 1.5 second, and the covers were opened together at 1.8 second. The absorbed dose was measured at portal area in both cases. In the case of the GTPC, because there is influence of line artifact as grid frame and folded pixel cover, the absorbed dose data for two cases (no grid and grid) were evaluated. The flux of radiation changed according to the position of the leaf or pixel covers [6]. When an ideal dose curve is considered, difference from the ideal curve may appear for both the GTPC and the MLC.

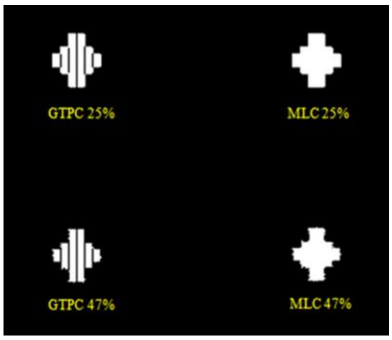

Fig. 3. Portal image with applied threshold method for both the grid type multi−layer pixel collimator (GTPC) and the multi-leaf collimator (MLC). The entire

value, which was below the threshold value, was saturated at 0.

The particular percentage range was set at 25.0%−47.0%. Figure 3 shows the threshold value applied to the original portal image. From each threshold image, the geometric error for the GTPC was calculated using MLC's geometric data. Because the error depends on the MLC's model and because no similar model exists to compare with GTPC's performance, an absolute evaluation standard could not be found. However, an optimum level comparison is possible by using MLC modeling simulations.

If several layers, including the pixel complex, are stacked, the collimator structure can be operated as a radiation therapy collimator similar to that of the MLC. Each pixel cover operates individually by using each applied electronic signal. When radiation intensity modulation is required at a specific area, the required dose is delivered by regulating the number of folded pixel covers. In addition, the particular shape required for radiation to pass through is maintained by moving each pixel cover. An even shape can be maintained by tracking a target that is moving due to respiratory motion or cardiac impulse motion. The motor's rated torque should be larger than the material's torque to raise the pixel cover connected to the motor. For a 1 mm thick pixel cover made of tungsten, the intrinsic mass is 0.4375 g. The pixel cover's torque was calculated as 0.011 mNm. Based on this value, the motor can lift the tungsten cover.

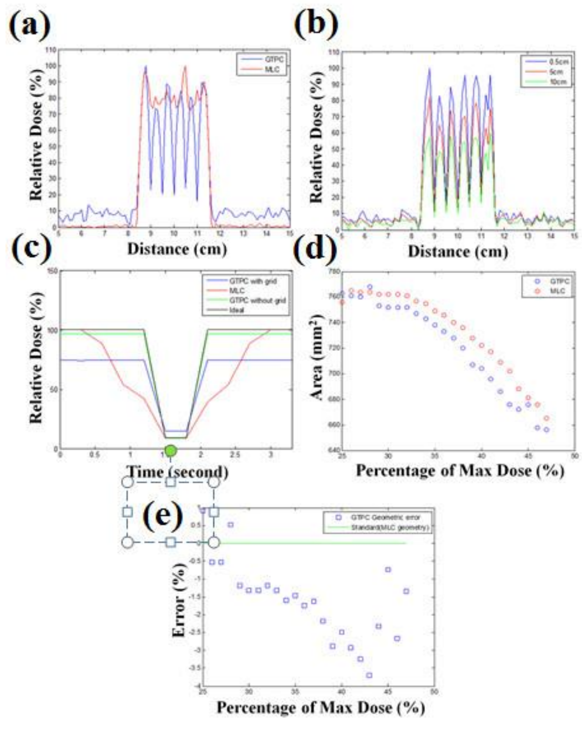

Fig. 4. Lateral dose profile data from a water phantom, radiation intensity modulation results, and geometric agreement based on dose level from 25% to 47% of the maximum absorbed dose. (a) Relative dose profiles at the middle area of a grid type multi−layer pixel collimator (GTPC) and a multi-leaf collimator (MLC). The horizontal axis label 'Distance' means the exposed range (cm). (b) Relative dose profiles for various depths for only the GTPC. (c) Radiation intensity modulation trends for the GTPC and MLC for 3.3 sec. (d) Area depending on dose level for both the GTPC and the MLC. (e) GTPC's geometric difference compared with MLC's geometric accuracy (standard).

In order to confirm the dose arrangement in the water phantom, we only used a lateral dose profile. Two types of lateral dose profiles are present in the water phantom's dose without any filtering process (Fig. 4(a)). The first dose profile was measured at the same dose arrangement line (1 cm from surface) for both the GTPC's and the MLC's portal image based on the absorbed dose. Noticeable characteristics in the graph are the total attenuated dose due to the blocked area and the grid frame. At the blocked part of the MLC's leaf, the radiation attenuation level was below 2%. Because radiation attenuation was only affected by 30 layers in the GTPC, the attenuation level of the blocked part of the GTPC's layer was over 10%. In addition, because indirect radiation from the extended source was deposited at the grid frame part of the detector, the attenuation level of the grid frame was shown to be over 20%. The second lateral dose profile shows the dependence of the dose arrangement on the depth of the water phantom without the filtering process. The relative dose percentages were measured at 0.5 cm, 5 cm, and 10 cm from the water phantom's surface (Fig. 4(b)).

The GTPC's fast radiation intensity modulation and efficient target guidance were based on the pixel unit's movement. In the case of a DMLC, the fast leaf movement in real time leads to a radiation intensity modulation. Also, the leaf's pattern on the target would change according to the movements of several leaves. The radiation intensity modulation obtained using the DMLC has a high accuracy for transferring a limited dose, and the performance had previously been demonstrated in several scientific studies. In order to apply the maximum dose at the tumor and the minimum dose at the normal tissue, the radiation intensity modulation method is required in the radiation therapy field. The DMLC's function was simulated by using MCNPX. The variation of the mean value of the absorbed dose over a limited area is reported in Fig. 4(c). The black line in the graph refers to the ideal pattern that needs to be followed by the radiation's intensity. The DMLC's line (red line) shows a slow modulation of the leaf pattern compared to that of the ideal line. However, because there is no obstacle to the delivery of radiation in the opened field, the objective dose percentage shows good agreement with the ideal line (percentage error < 0.0100%). In the case of the GTPC's dose trend, a fast motion response is shown, as well as an almost exact agreement (97.0000% agreement) with the ideal line, at the excluded grid frame area. However, if a dose calculation with the affected frame is applied from the overlapped part of the grid frame, a large percentage error results (74.8892% agreement) at the area including the line artifact. In addition, the objective dose percentage differs from the ideal value by 5.7710%. Because of its faster response compared to that of the MLC's response (29.6%), the GTPC system can be applied in high speed radiation therapy with intensity modulation radiation therapy and image−guided radiation therapy. A dose calculation algorithm, which can compensate for the effect of the line artifact for only the GTPC modality, is needed.

Because the physical geometric area on the detector was almost the same for both the GTPC and the MLC, the quantitative geometry evaluation was done using radiation transmission images based on dose level (Fig. 4(d)). The absorbed area increasingly changes to a small field for both the GTPC and the MLC. The maximum radiation dose of more than 25% was definitely absorbed as 763 mm^2 (GTPC) and 756 mm^2 (MLC). In addition, a maximum radiation dose of more than 47% was definitely absorbed as 656 mm^2 (GTPC) and 665 mm^2 (MLC) at the detector. This fluctuation was more remarkable in the GTPC portal image than in the MLC portal image (Fig. 4(e)). Because indirect radiation can be absorbed more easily at each layer and the grid frame than at the MLC's gate, the geometric difference between the GTPC and MLC could result, and a high dose level will be reduced more rapidly at the GTPC portal image. From these factors, we confirmed the feasibility of using GTPC to provide more sensitive and precise radiation intensity modulation than the MLC collimation system can provide.

The collimation method for the GTPC system is an operating mode of each pixel cover. Because many pixel covers are restricted by the grid, the grid will influence when the dose is delivered to the target. In addition, because a plane source was used to simulate the GTPC, the spread factor of radiation should be considered to apply the GTPC system in the clinical field. If the spread factor to be optimized, the additional simulations are required. In a further study, the research on the development of a more sophisticated GTPC model that includes the spread factor will be performed.

3. Conclusions

In this study, to determine the possibility of field applications and to evaluate the intrinsic performance of the GTPC, which is different from the MLC, we used Monte Carlo simulation for MLC modeling. The GTPC could simultaneously provide momentary radiation intensity modulation with target guidance, and it was constructed to realize a complex geometry for tumor tracking with pixel unit attenuation. However, because the line artifact appeared due to the grid frame and folded pixel cover, even though the entire pixel cover was open, some errors in dose delivery arise due to the line artifact. Thus, a proper radiation treatment planning system that considers the influence of the line artifact for only the GTPC is required. The possibility of clinical applications and a optimum performance level of the GTPC must be determined. In conclusion, this research was a feasibility study, and more specific research related to the GTPC system should be done.

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