

Multi-layer energy filter for realizing conformal irradiation in charged particle therapy

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A new type of filter for charged particle radiotherapy is developed to reduce unwanted dose transfer to the normal tissues around a tumor. The new filter can make a static irradiation field where the width of the spread-out Bragg peak (SOBP) is two-dimensionally adjusted. That makes the field conformal to the tumor three-dimensionally. The filter is made of many layers produced by using stereolithography. The layer has a miniaturized structure that has geometrical similarity to the conventional ridge filter. Shapes of cone and pyramid are also usable for the unit-cell constructing the layer. The spread of the field in the depth direction is decided by the thickness of the filter, or by the number of layers. The experimental result of the irradiation using the ridge-type construction shows a good agreement with an estimate by the Monte Carlo calculation. By combining this technique with intensity modulation that has lateral position dependence, the conformal irradiation can be achieved by a simple procedure. © 2000 American Association of Physicists in Medicine. [S0094-2405(00)00902-0]

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I. INTRODUCTION

From a viewpoint of reducing the unwanted irradiation on normal tissues near the target region, dose localizing is one of the important subjects in radiotherapy. A heavy charged-particle beam (proton and heavy ion) has characteristic advantages by their superior dose distribution. Nevertheless, high dose transfer to the normal tissues near the target is unavoidable in the irradiation by the conventional technique for the charged particle therapy, where the depth-directional width of the dosed area is uniformly equal to the maximum thickness of the tumor. For realizing the ideal irradiation field conformed to the target volume, sophisticated techniques based on beam scanning or energy scanning have been developed,¹⁻⁴ which makes the irradiation field by accumulation or convolution of divided fields. In the case that these techniques are applied to the moving target, the undesirable probability of misplacing the dose on the boundary of the small fields appears by the movement of the organ caused mainly by respiration. Even though gated irradiation synchronized with the movement is adopted, the displacement of the target region is not small as compared with the size of the divided field. Making a static or quasi-static field conformed to the target is a practical goal in this problem.

As a technique to control spread of the Bragg peak for conformation to the target, an uneven ridge filter was proposed.⁵ The filter was designed to realize conformal irradiation by a combination with intensity modulation that has

lateral position dependence. Because of its divided construction and its designing parameters that have lateral position dependence, there is complexity in preparing the filter for the respective patient in the actual treatment.

In this work, a new solution for the problem is proposed. The new energy filter achieves variable spread of the depth-directional peak in irradiated dose distribution by changing the thickness of the filter. In other words, in the conformal irradiation, the shape of the thickness of the filter corresponds to the outward shape of the target region. Furthermore, by its miniaturized structure and its close placement to the patient, the filter realizes controllability for the localized and steep changing of the spread in the target.

II. THE CONCEPT OF THE NEW FILTER

Conventional range modulation by a passive ridge-shape filter makes an even width of the SOBP in the dose distribution by mixing several beams having different residual ranges. To realize lateral changing of the spread, which means three-dimensionally conforming the field to the target, the concept of the energy mixing is improved in steps illustrated in Fig. 1. Geometrical similarity in the thickness pattern of the absorbing material of the conventional ridge filter remains in the miniaturized unit-cell of the multi-layer filter. The energy filtering with many layers realizes easy controllability of the dose spread by changing the number of the layers. Furthermore, controllability of steep changing of the

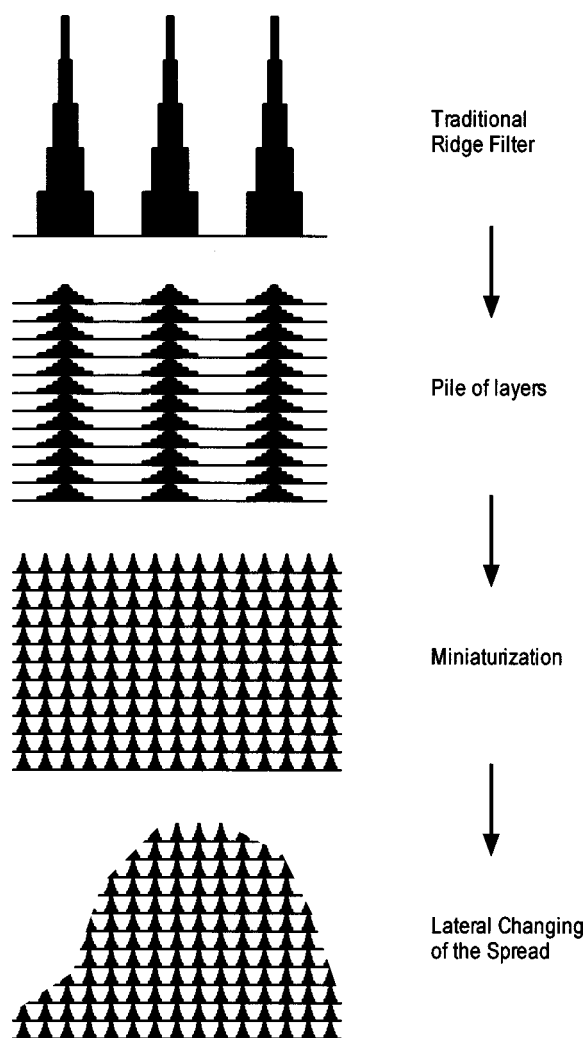


FIG. 1. Conceptual scheme of the multi-layer filter. Changing of the structure and function from the conventional filter to the new filter.

spread is achieved by the miniaturization of the pattern. Instead of the ridge, shapes of cone and pyramid are usable for the construction of the unit-cell.

For a different spread of the SOBP, a different set of the mixing factors of beams is necessary in designing this type of energy filter. That is the reason why the designing parameters of the uneven ridge filter have lateral position dependence.⁵ In case of the new filter, the structure of an additional layer for an increment of the thickness should be optimized to compensate the change of the parameters in order to realize the spread flat top of the peak in the dose distribution. By this optimization, changing the number of layers does not influence the flatness of the irradiation. In this paper, a simplified method for the compensation is proposed, where the filter has two regions with different shapes of the cell.

To make the structure of the new filter with sufficient accuracy, a formative technique using hardening of epoxy resin with laser light scanning is adopted, that is the stereolithography.⁶ The filter having lateral changing of the thickness can be formed in two ways. As the first method,

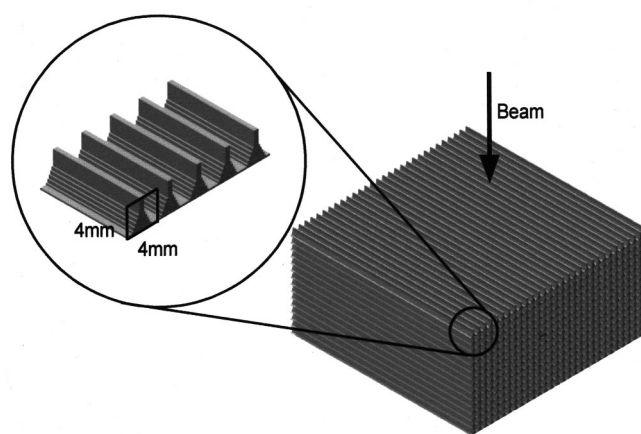


FIG. 2. Schematic drawing of a block including many layers of the ridge-type filter.

the structure can be formed by the stereolithography only, for both the miniaturized structure and the outward form of the filter. The target shape should be included in the data that decide the laser scanning in this method. In the case of another method, the multi-layer structure is formed in the shape of a block by the stereolithography. The outer shape of the block will be shaved in order to obtain a desirable shape for conformation to the target. In this work, the latter is applied to the experiment to demonstrate the function of the new filter. The schematic drawing of the block is shown in Fig. 2.

The distance between the filter and the patient should be large enough to reduce the dose fluctuation originating in the pattern of thickness. In order to get a sufficient space for mixing beams scattered by the conventional ridge filter, the distance reaches 2 or 3 m. The size of the unit-cell of the new filter is 4 mm height and 4 mm width in this work as shown in Fig. 2. Therefore, the new filter can be set near the bolus (range compensator), or close to the patient.

The lateral changing of the SOBP makes unevenness of the dose in the lateral direction.⁵ This is due to the change of the energy density deposited over the spread. In order to avoid the unevenness in the field, lateral intensity changing should be combined with the method using the new filter. As one of the simple methods of realizing the intensity changing, a relatively narrow beam with Gaussian distribution is useful to emphasize the intensity at the center region where the spread of dosed region is large in many cases. As a demonstrative test of the conformal irradiation by the intensity changing, an assumptive Gaussian distribution is applied to a two-dimensional Monte Carlo calculation in Sec. V.

III. DESIGNING OF THE MULTI-LAYER FILTER

A prototype of the new energy filter is designed for experimental demonstrations that show controllability of the spread of the dosed region. In the prototype, all layers have the same structure that is optimized for 60 mm SOBP, for simplicity in forming the multi-layer construction. That will cause a small distortion in depth-directional flatness of the

SOBP, excepting 60 mm spread. The functions of the prototype are investigated by disregarding this small inferiority in the dose distribution.

A. Calculating method for the dose distribution

A simplified method of Monte Carlo calculation has been developed to estimate the three- and two-dimensional dose distribution for the proton therapy.⁷ By the two-dimensional calculation, the geometrical parameters are obtained for the new filter with the ridge-type structure. The calculating model uses the experimental depth-dose distribution for a broad parallel beam. Therefore, the method effectively incorporates energy losses due to electronic stopping and nuclear collisions, energy deposition by secondary particles and loss of the primary particles by nuclear reaction. This is a hybrid method including both of the broad parallel beam methods and the Monte Carlo technique. The energy deposition on the track of the charged particle is calculated continuously by using the depth-dose distribution in consideration of the water-equivalent length of the medium, without random number. The pass straggling by multiple scattering is calculated by random numbers following the Highland equation using the radiation length of the medium. The emittance parameters of the incident beam are considered as the initial distribution of random numbers expressing the beam positions and angles. By this method, the path straggling in the dense part and lateral beam spreading in a cavity are introduced consistently.

In the two-dimensional calculation, the miniaturized structure of the new filter is considered as a stack of thin rods (0.2×0.2 mm² cross section). This means the shape is figured by many steps with a minimum size of 0.2 mm. The structure of the bolus and fine collimator is also considered as a stack of small rods (1×1 mm² cross section) as well as the filter.

In order to determine the parameter of the incident beam, in advance, two-dimensional calculations are performed together with simple experiments using a broad proton beam collimated by a slit with a 100 mm gap. For the experiments, a broad beam with energy of about 180 MeV is formed by a single scatterer in the vertical beam line of the Proton Medical Research Center (PMRC), University of Tsukuba. In this beam line, the proton beam is delivered from the KEK 500 MeV booster synchrotron. The emittance parameters (pencil angle and dispersion) are decided to consistently explain the changing of the lateral penumbra of the dose distribution in a water phantom. The pencil angle of the beam is set to 0.65 degrees in standard deviation. The dispersion of the beam is set to 0.012 degrees/mm for the condition.

The program for the calculation is coded by FORTRAN on an Alpha-533 MHz computer system. It takes about 30 minutes to calculate a typical dose distribution formed by a million events.

B. SOBP made by the new filter

A ridge-type structure is designed for the new filter having the shape of a block shown in Fig. 2. The outward form

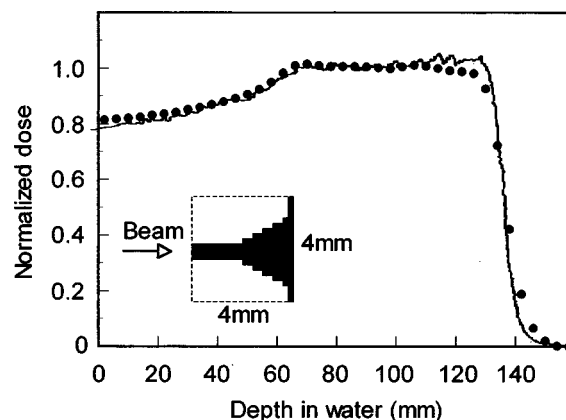


FIG. 3. Calculated SOBP (closed circles) and the experimental result (solid line) for a multi-layer filter. The shape of the unit-cell of the filter is shown in the inset of the figure. The layers are piled 15 times for 60 mm SOBP.

of the block with 15 layers takes the size of 60 mm cube. Each layer has a base plane 0.2 mm thick. Thus, the base planes make a 3 mm even component of the absorber thickness in the block. The total spread of the Bragg peak depends on the variation of the absorber thickness (57 mm) and the water-equivalent length of the epoxy resin. The shape of the unit-cell is iteratively modified until the Monte Carlo calculation matches the desired SOBP. The shape of the unit-cell is illustrated in the inset of Fig. 3. In the design, the initial shape of the cell is obtained from the pattern of thickness optimized by the simple least square method using only straight-going broad beams with 6 different residual ranges. Dose deposition is calculated in a water phantom set on the end of the beam line. The estimate of the depth dose distribution by the Monte Carlo calculation (200,000 events) is shown as closed circles in Fig. 3. In the calculation, 60 mm water-equivalent energy degrading by a range shifter is included.

The setup estimated by the calculation is realized in the vertical beam line with the new filter made by the stereolithography. In Fig. 3, a solid line is the experimental result measured by a small silicon-diode detector scanned in a water phantom. The difference between the experimental result and the estimate by the Monte Carlo calculation is less than 5% of the peak.

IV. CALCULATION AND EXPERIMENTS FOR A CYLINDRICAL TARGET

A. Experimental setup for a cylindrical target

Figure 4 is the schematic drawing of an experimental setup to make a dose distribution for a cylindrical target, whose axis is perpendicular to the beam axis. The conventional ridge filter (a) and the new filter (b) are applied to the irradiation. The broad beam is supplied by the single scatterer method in PMRC as described above. The diameter of the target is set to 60 mm in the water phantom adopted as a simplified model of a patient body. In the conventional setup, the position of the ridge filter (water-equivalent 60 mm spread) is set at 4.4 m upstream of the target. In both setups,

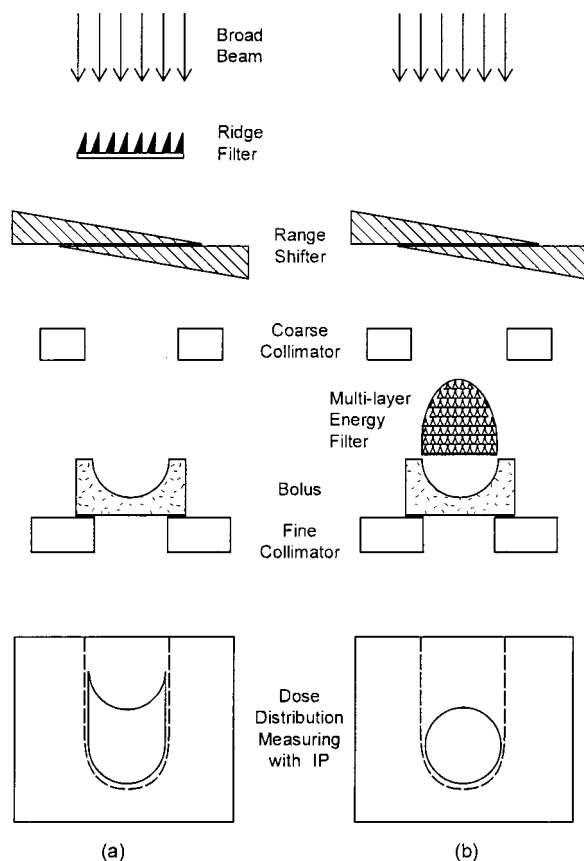


FIG. 4. A schematic drawing of the experimental setup using a conventional ridge filter (a) and a multi-layer filter with a ridge shape (b). The target has a cylindrical shape whose axis is perpendicular to the beam axis.

the position of the collimator is about 150 mm upstream of the target. The aperture of the fine collimator is 60 mm square. The range shifter is set to 60 mm in water-equivalent length. The upper side outward form of the bolus is shaped to half the cylindrical target, which makes the distal isodose distribution conformal to the target. In the setup (b), the new filter is set on the bolus. The outward form of the multi-layer filter is machined to follow the vertical thickness $t(x)$ of the target,

$$t(x) = 2(r^2 - x^2)^{0.5} \text{ (mm)}, \quad r = 30 \text{ mm},$$

where x (mm) is the lateral position on the filter.

B. Calculations

By the two-dimensional Monte Carlo calculation, the dose distributions for both setups are estimated before the experiment. The results of the calculation are drawn in Fig. 5 as painted contour maps for the setups (a) and (b). The dose is normalized in the maximum value on the center region of the target. In this calculation, the effect of the conventional ridge filter is approximately considered as the mixing of 6 beams having different residual ranges. In the mixing, the probability for respective range is calculated by random numbers following the optimized fractions for the conventional filter. The structure of the bolus is considered as a stack of thin rods with a 1 mm square cross section. In the calculation, the

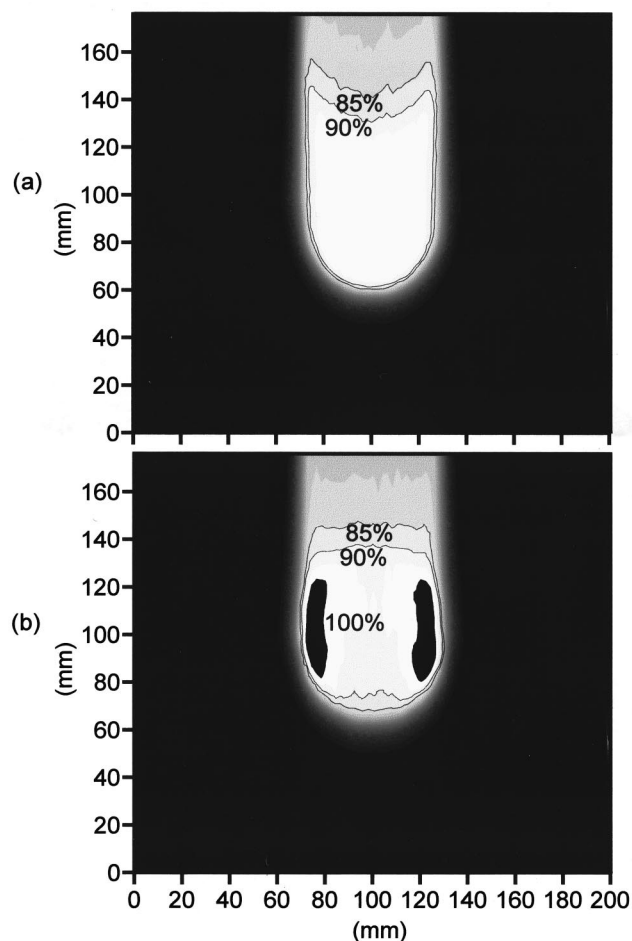


FIG. 5. Calculated dose distributions for the experimental setups (a) and (b) drawn in Fig. 4. Painted contour maps are divided in regions with a differential step of 5% dose deposition. The boundaries are drawn at 85 and 90%. The regions with over 100% dose are indicated by black pieces.

water phantom is supposed as a medium of the target region which is divided into many rods with a 2 mm square cross section to get the dose distribution. The structure of the multi-layer filter is considered as a stack of thin rods ($0.2 \times 0.2 \text{ mm}^2$ cross section) as described above. The number of the beam incidences is one million, respectively. In the result for the conventional ridge filter, two triangle-shape regions with over 90% dose are observed just upstream of the target. The result for the new filter has two regions with over a 100% dose (the black piece on the target). This is due to the condensation of energy deposition in the narrow peak.

C. Experimental results

In order to measure two-dimensional dose distribution in the setup, an imaging plate (IP, BAS-III 2025, Fuji Film Co., Ltd.) is applied with a plastic phantom.^{8,9} In the measuring system, the IP is sandwiched by the acrylic resin plates with a 10 degree tilting angle to the beam axis.

The experimental results given by proton irradiation are shown in Fig. 6 for both setups. The depth-directional position of the measurement is converted to the water-equivalent length by using the IP tilting angle and the water-equivalent

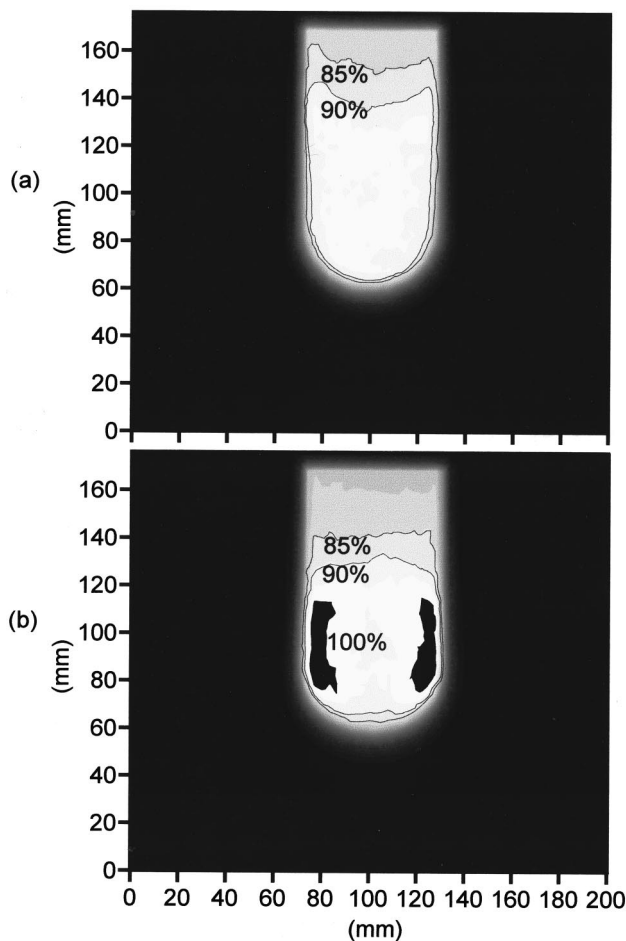


FIG. 6. Experimental results of the dose distribution measured by an imaging plate for the setups (a) and (b) drawn in Fig. 4. Painted contour maps are divided in regions with a differential step of 5% dose deposition. The boundaries are drawn at 85 and 90%. The regions with over a 100% dose are indicated by black pieces.

length of the acrylic resin. By the previous works, it was clarified that the dose measurement by using an IP for clinical proton beams had a disagreement with the result measured by an ion chamber in the distal peak region because of its LET dependence.⁹ By this reason, an estimate error of several percent is supposed in the dose measured. Within the limits of the accuracy, the experimental results have good agreement with the Monte Carlo estimates.

V. CAPABILITY OF THE CONFORMAL IRRADIATION

The irradiation method by the new filter has usefulness in controlling the spread of the depth-dose distribution by the thickness of the filter, and in making a uniform field conformed to the target by lateral intensity changing. The latter is confirmed in Fig. 7 by assumptive intensity distribution. To make the figure, a two-dimensional Monte Carlo calculation is performed by using a lateral Gaussian function with 130 mm fwhm as an intensity distribution of incident beams. A conformal dose distribution to the target region is achieved by this simulation.

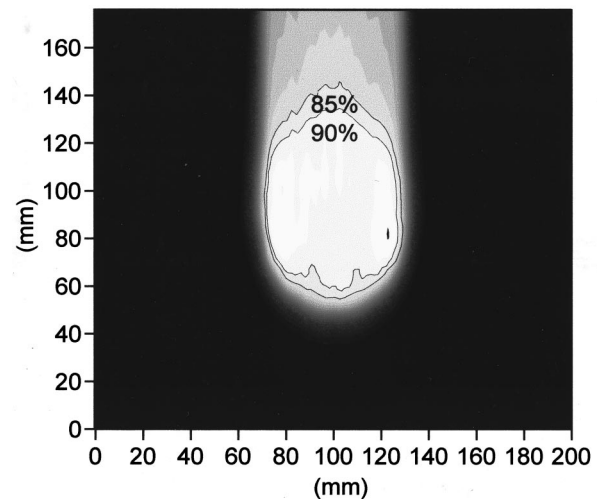


FIG. 7. An assumptive calculation with a lateral Gaussian distribution of the beam incident for the experimental setup (b) in Fig. 4. Painted contour maps are divided in regions with a differential step of 5% dose deposition. The boundaries are drawn at 85 and 90%.

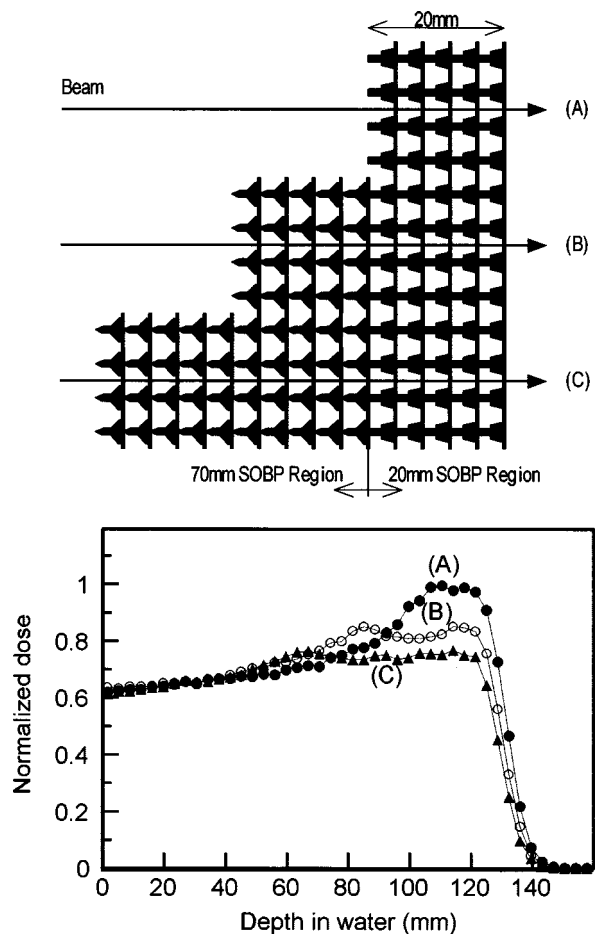


FIG. 8. (a) Cross section view of the filter which has two regions with a different shape of the cell. Three arrows indicate the passes for 20, 40 and 60 mm SOBPs. (b). Experimental results of the depth dose distribution measured by IP for three passes in Fig. 8(a). The experimental technique is the same as that used for Fig. 6.

In the case of actual three-dimensional irradiation for the cancer treatment, a relatively narrow beam with the proper width can compensate the decrease of the dose on the center region of the target. If the distorted field made by an additional filter is canceled by its own optimized structure, small scatterers or absorbers are also usable for the intensity compensation. In the case that the dynamic field is permissive, a moving multi-leaf collimator can perform the intensity modulation in the lateral direction.⁵ On the other hand, as an ideal method, a desired quasi-static field can be realized by fast beam scanning with lateral intensity modulation. This is the future subject to complete the new system for the conformal irradiation on a moving target.

By the filter having a uniform structure including one pattern of the shape of the unit-cell, the field suffers distortion of the depth-directional flatness in the SOBP. This is due to the difference between the optimized patterns of the thickness for a narrow spread and a wide spread of the peak as described above. For the procedure to get the proper outward shape of the filter by machining a block prepared before, the design of the cell pattern should be changed with the position in the depth direction to compensate the distortion. As a simple method, a region designed for large spread (70 mm SOBP) is piled on a region designed for narrow spread (20 mm SOBP) in a block, where a 70 mm SOBP region has 40 mm thickness and a 20 mm SOBP region has 20 mm thickness. The cross section view of the filter is shown in Fig. 8(a) with the outward shape to make three different SOBPs. In the figure, the shape of the cell is deformed to distinguish two regions easily. The experimental results given by using the filter are drawn in Fig. 8(b) for 20 (A), 40 (B) and 60 (C) mm SOBP. It is confirmed that the flat top of the peak can be obtained for three cases. This means the filters for a respective patient in the actual treatment can be made by machining one type of block prepared before.

The influence of the tilt angle, between the incident beam and the perpendicular axis of the new filter upon the dose

distribution is investigated in an experimental way. It is clarified that the 0.5 degree tilt makes local an overdose of about 5% on the flat top of the distribution.

VI. CONCLUSION

The new energy filter for charged particle therapy can control the lateral changing of the depth-directional spread of the irradiation field by the thickness of the filter. By using outline data conformed to the target in the cancer treatment, the outward form of the filter can be designed easily. To get full advantage of this filter, the technique of lateral intensity modulation to make a static or quasi-static uneven field should be refined for three-dimensional irradiation on a moving organ.

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