Three-dimensional conformal irradiation with a multilayer energy filter for proton therapy

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The first experimental evidence of three-dimensional conformal irradiation is performed by using a new type of filter developed for charged particle radiotherapy. The new filter can yield a static irradiation field where the width of the spread-out Bragg peak is adjusted to the target as a two-dimensional continuous function in the transverse plane. The filter is made of many layers produced by using stereolithography. In the filter, a structure with two regions with different shaped miniaturized ridges is adopted to get a flat dose profile on the spread-out peak. A conformal field around a spherical target is realized by a filter that has a shape corresponding to the outward form of the target. [DOI: 10.1063/1.1333047]

I. INTRODUCTION

A heavy charged-particle beam (proton or heavy ion) has the characteristic advantage of superior dose localization by irradiation from one or a few directions. Using the conventional technique for charged particle therapy with energy filters, unavoidable dose deposition appears on the upstream normal tissues near the target. For realizing an ideal irradiation field conformal with the target volume, sophisticated techniques based on beam scanning or energy scanning were developed in which the irradiation field is formed by accumulation or convolution of divided fields.[1–4] By applying these techniques to a moving target, there is an undesirable probability of misplacing the dose at the boundary of the divided field. Even though gated irradiation synchronized with the movement can be adopted, the displacement of the target region is considerable. As a practical solution to this problem, new types of energy filters were developed[5,6] to realize static conformal irradiation with a proton beam.

The multilayer energy filter[6] achieves variable spread of the peak in the irradiated dose distribution in the depth direction as the filter thickness changes. This causes the dose in the lateral direction to vary, because the energy-deposition rate, which is related to the spread of the dosed area in the depth direction, varies. To realize an ideal irradiation field with the filter, the beam intensity must be modulated in the lateral direction with the changing spread. In our previous work, a two-dimensional conformal irradiation was shown for a target on the assumption that the intensity modulation was achieved. To get this result, the experimental data were modified by applying a supposed function of lateral intensity distribution for the incident beam. To get real experimental evidence of three-dimensional conformal irradiation, an additional technique to realize the intensity modulation should be applied to the irradiation. In the present work, in order to perform the first experiment in which three-dimensional conformal irradiation is achieved with a filter, the intensity is modulated by a coaxial scatterer.

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II. MULTILAYER ENERGY FILTER FOR THREE-DIMENSIONAL CONFORMAL IRRADIATION

To achieve a lateral change in the width of the spread-out Bragg peak (SOBP), to three-dimensionally conform the field to the target, a miniaturized structure was adopted for the new filter.[6] The shape of the unit cell of the new filter is geometrically similar to the conventional ridge filter shown in Figs. 1(a) and 1(b). The mixing of beams with different residual ranges is achieved by the position-dependent variation of the thickness. The new energy filter has many layers and it is easy to control the dose spread by changing the number of layers. A schematic drawing of part of the filter including some layers of the ridge-type structure is illustrated in Fig. 1(c). Instead of the ridges, cones and pyramids can also be used for the construction of the unit cell. To make the new filter, a formative technique named stereolithography is used, which applies hardening of epoxy resin with scanned laser light.

For the new filter, two intrinsic problems have to be solved to get flatness of the dose in the target.[6] First, to change the spread of the SOBP, a different set of mixing factors of the beams is necessary. In other words, the design of the cell pattern should be changed for different thicknesses of the filter. The problem can be overcome by using two regions designed for a narrow and a large spread of the SOBP.[6] Second, the condensation of the energy deposited in the narrow SOBP should be compensated by a lateral intensity modification. In this work, the compensation is per-

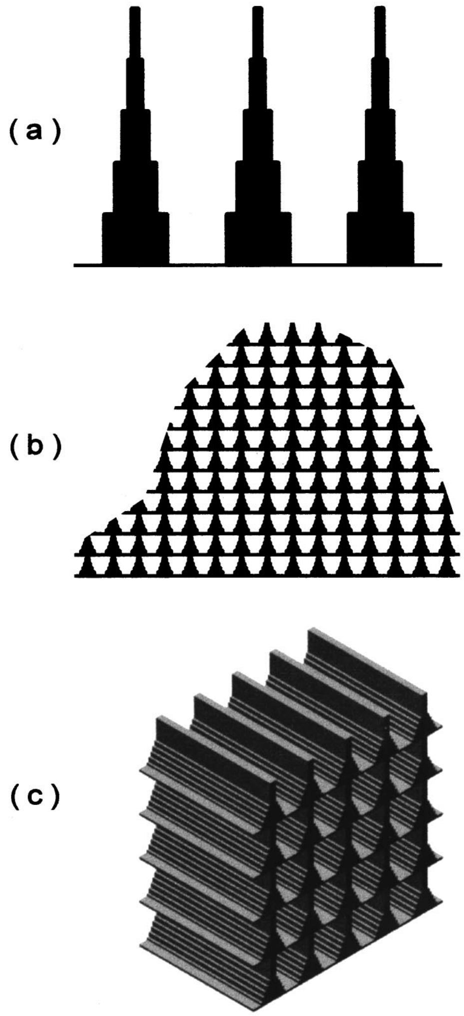

FIG. 1. Schematic drawing of energy filters. (a) Traditional ridge filter. (b) Multilayer filter. (c) Three-dimensional image of part of the new filter.

formed by a coaxial scatterer to make an intense region at the center of the target.

For the present experiment, the filter is designed with two regions. One region designed for a large spread (70 mm SOBP) is placed on a region designed for a narrow spread (20 mm SOBP), where the 20 mm SOBP region is 20 mm thick. It was confirmed that a flat top of the peak in the dose distribution could be obtained by this structure.[6] The outer shape of the block shown in Fig. 2 is designed for a spherical target with 60 mm diameter. The size of the unit cell of the new filter is 4 mm height and 4 mm width. In Fig. 2, the upper side outward form of the bolus is shaped to be hemispherical.

III. EXPERIMENT AND RESULTS

The experimental setup is drawn schematically in Fig. 3. The coaxial scatterer is designed to increase the dose in the center region by about 10% with 20 mm full width at half maximum. The scatterer has equal water equivalent thicknesses for the inside and outside materials. The distance between the coaxial scatterer and the target was 2.5 m. The collimator is an aperture of 60 mm diameter on a thick brass plate set 150 mm upstream of the target. To measure the three-dimensional dose distribution in the setup, a stack of imaging plates (IPs) (IP, BAS-III 2025, Fuji Film Co., Ltd.)[7,8] was utilized with a solid phantom (Mix-DP, 10 mm thickness). Ten sets of IPs and the phantom were stacked alternatively for the measurement. In this work, no compensation was made for the effect of proton scattering by the IPs.

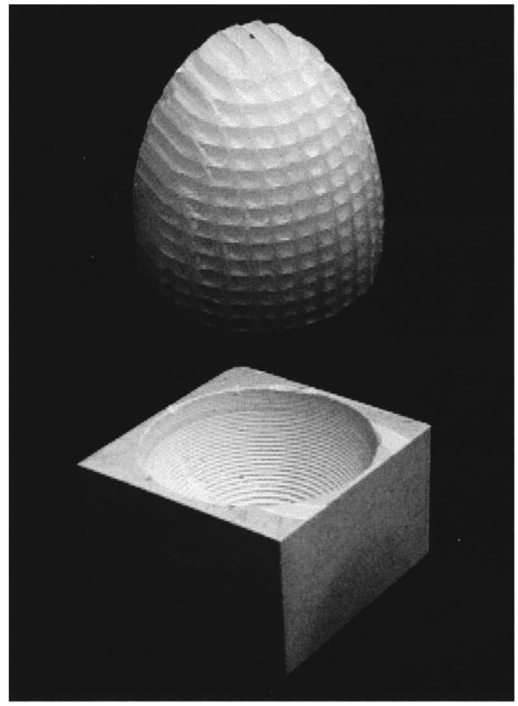

FIG. 2. Three-dimensional image of the new filter and the bolus designed for the conformal irradiation on a spherical target.

A broad beam with energy of about 180 MeV was formed by the scatterer in the vertical beam line of the Proton Medical Research Center (PMRC), University of Tsukuba. The proton beam was delivered from the KEK 500 MeV booster synchrotron.

The experimental result given by the proton irradiation is shown in Fig. 4. The dose distribution data on a plane along the center axis are used to show the two-dimensional image of the dose distribution. Because of the scattering effect and the LET dependence of sensitivity,[8] the estimated error in the dose measurement is thought to be several percent. A cross section of the target is shown as a hatched region in the figure. A conformal dose distribution is demonstrated by the 90% contour curve surrounding the target.

IV. DISCUSSION

In this work, a three-dimensional conformal irradiation field in a spherical target was successfully obtained by using a coaxial scatterer. In an actual situation of cancer treatment, the shape of the target is not likely to be a simple sphere. Therefore, the scatterer must be designed using a sophisticated algorithm, which includes the scattering effect and the three-dimensional distribution of the water-equivalent density in the target.

Intensity modulation by the beam scanning method is another solution by which conformal irradiation with a

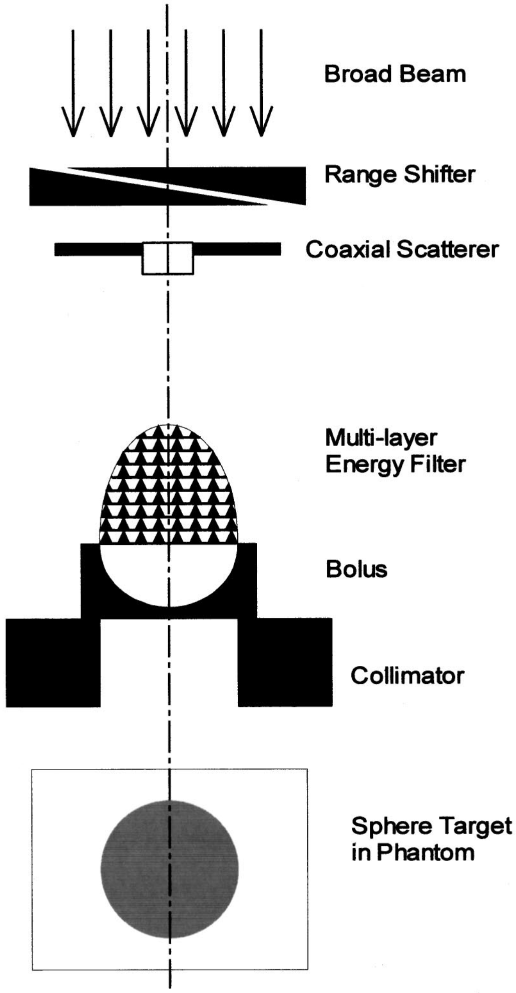

FIG. 3. Schematic drawing of the experimental setup for three-dimensional conformal irradiation.

multilayer energy filter can be achieved. Controllability of the lateral dose distribution can be obtained by scanning-velocity modulation, irradiation-time modulation, or intensity modulation. For the purposes of irradiation on a stationary organ, the method seems suitable for the actual treatment in the facilities where scanning is already put to practical use. In the case of a moving organ, considerable fluctuation in the dose distribution is unavoidable. The following techniques must be investigated for the beam scanning method with the new filter: (1) gated irradiation restricted to a short period corresponding to a specific phase of the organ motion, (2) fast beam scanning to make at least one cycle during the period.

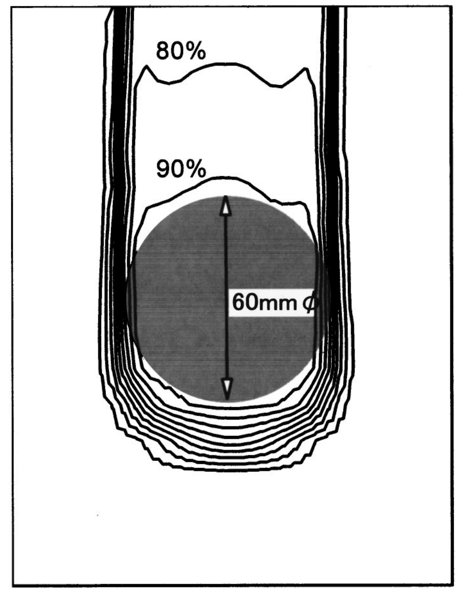

FIG. 4. Experimental result of the dose distribution measured by a stack of imaging plates. Data are interpolated from the three-dimensional data on a plane along the beam axis.

A partial intensity supplement by using a multileaf collimator is also one of the solutions used for routine treatment.[5] In this method, a second irradiation with a small intensity is supplemented in the center region only, where the intensity is insufficient because of the energy deposition in a relatively wide SOBP. By the accumulation of the irradiation, small step-shaped dose fluctuations will appear along the second irradiation.

The techniques for the intensity control should be refined for actual cancer treatment to take full advantage of this filter for conformal irradiation on a moving organ.

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