DEVELOPMENT OF THREE-DIMENSIONAL DOSE VERIFICATION SYSTEM USING A FLUORSCENT SCREEN IN ION BEAM THERAPY

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Abstract

For quality assurance (QA) of therapeutic ion beams, QA tool having high spatial resolution and quick verification is required. The imaging system with a fluorescent screen is suitable for QA procedure. We developed a quick verification system (NQA-SCN) using a fluorescent screen with a charge-coupled device (CCD) camera for the sake of two dimensional dosimetry. The NQA-SCN is compact size to attach to irradiation port and water column. Several types of corrections were applied to the raw image obtained by the NQA-SCN. Our goal is to use the NQA-SCN for three-dimensional dose verification. In carbon-ion therapy, the fluorescent light is decreased by suffering from quenching effect due to the increased linear energy transfer (LET) in the Bragg peak. For the use of three-dimensional dose verification, as a first approach, we investigated the quenching effect of carbon-ion beam in water. Also, to evaluate the performance of NQA-SCN, we carried out experiments concerning QA procedures.

INTRODUCTION

Recently, to make the best use of physical and biological characteristics of therapeutic ion beam, three-dimensional (3D) pencil-beam scanning technique [1-3] has been implemented at some facilities. It has been utilized since 2011 at the Heavy Ion Medical Accelerator in Chiba (HIMAC), in the National Institute of Radiological Sciences (NIRS) [4]. In the scanning irradiation method, since the 3D dose distribution is achieved by superimposing doses of individually weighted pencil beams, any change in the scanned beams will cause a significant impact on the irradiation dose. Therefore, quality assurance (QA) procedures and tools for making refined measurements to verify the characteristics of the pencil beams (e.g. size and position) must be developed. For this purpose, we developed a verification system using a fluorescent screen with a charge-coupled device (CCD) camera, which we called the QA-SCN [5, 6], originally proposed by Boon et al [7, 8]. The QA-SCN is a very useful tool for QA of scanned ion beam because of a high spatial resolution and a quick verification at many points in the irradiation field.

On the other hands, in NIRS, the rotating gantry has developed to improve the dose conformity and less sensitivity to range uncertainties [9]. While the rotating gantry can be rotated 360 degrees, there are small errors due to gantry angle dependence of beam. Thus, a verification system which can be attached on the gantry nozzle is necessary for the commissioning of the rotating gantry and its QA. However, the QA-SCN is large to cover wide viewing field and heavy to maintain rigid. Additionally, the fluorescent light is decreased by suffering from quenching effect due to the increased linear energy transfer (LET) in the Bragg peak. It is difficult to use the QA-SCN for verification of 3D dose distribution in water. To overcome these problems, we developed the NQA-SCN. The NQA-SCN is very compact size. As a first approach, we investigated the response of the NQA-SCN to carbon-ion for various doses, dose rate and different linear energy transfer (LET) values. In this paper, the results of the QA measurements obtained by using the NQA-SCN are described.

MATERIALS AND METHODS

Design of NQA-SCN

A schematic of NQA-SCN system was shown in Fig. 1. The NQA-SCN consists of a fluorescent intensifying screen, a CCD camera, a mirror, camera controllers and a dark box to protect against surrounding light. The mirror is located at 60 degrees relative to the beam axis. The distribution of fluorescent light is reflected by a mirror and is observed by a CCD camera, which is installed at -60 degrees relative to the beam axis. The path length to the CCD camera from the fluorescent screen is about 400 mm. The CCD camera installed in the NQA-SCN is the type BU-41L (Bitran Corp., Japan). The CCD resolution is 1360 × 1024 pixels and the pixel size of the CCD is 6.45 μm × 6.45 μm. The CCD camera allows for the measurements of a 2D light output with a large dynamic range by digitizing optical signals at 14 bits. To decrease thermal noise, the CCD chip is cooled to -1°C by the Peltier cooling unit. A focal length of a lens (V. S. Technology Corp., Japan) is 12 mm. To block direct fluorescent light from the screen, the light shield is placed near the lens. The viewing field and the aperture of the dark box cover an irradiation field of 220 × 220 mm^2. A fluorescent intensify screen, which the phosphor (ZnS: (Ag, Al)) with thickness of about 40 μm is coated on FR-4 board with thickness of 500 μm, is mounted at the entrance face. To verify a light yield difference for different screen positions depending on the coating thickness, we also used the two different types of screen for the flat field correction described later.

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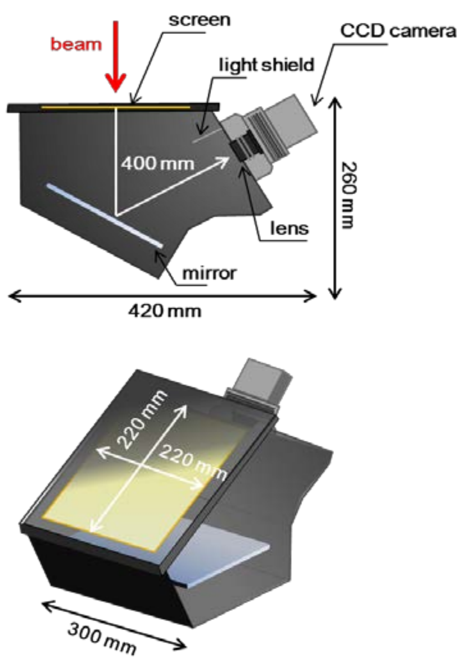

Figure 1: Schematic of the NQA-SCN system.

Image Correction Process

Figure 2 shows the flow chart of the image correction process. After the irradiation, all of the detected images are transferred to a data server at once, and the image processing is started. First, the background data are subtracted from the original image. The background noise level and its time dependence were measured. The background noise level was an almost constant without dependent on measured time. To suppress any spike noises, we apply a median filter in a 3 × 3 window to the image after subtraction. For both rotation correction and distortion correction, a simple correction formula correlated with lateral positions, x and y was applied [6]. To derive the parameters for this formula, we used the calibration board made of aluminum. The calibration board has multiple small holes (121 holes), which are located every 20 mm on the plane. The size of a hole is φ0.2 mm. Figure 3 shows layout of rotation and distortion correction with the calibration board. As shown in Fig. 4, the distortion caused by the lens was derived from the difference between geometric positions of holes and the center of gravity obtained by natural light passed through multiple holes. Simultaneously, the pixel spacing is converted to the actual spacing in millimeters. To convert the pixel spacing of the images into an actual size, the values are fitted to above formula as lateral positions, x and y. To reduce the variations of the output caused by lens vignetting and the difference in the thickness of the screen, we apply the flat field correction by using the radiochromic film Gafchromic EBT2 film as a reference. Figure 5 shows profiles of a uniform irradiation field without the flat field correction. To check the variations of the output due to positions, we compared the result measured by ZnS: (Ag, Al) with that obtained with the other fluorescent screen (Type HG-M2, Gd2O2S: Tb, Fujifilm Corp., Japan) in this figure. The result measured by ZnS: (Ag, Al) fluctuate due to a weak fluorescent light. However, this fluctuation is tolerable for verification of the uniformity. Although the result measured by Gd2O2S: Tb was affected by the difference in the thickness of the screen, the difference between the result by ZnS: (Ag, Al) and that by EBT2 was within 3% at 1-sigma. Therefore, in this study, the flat field correction was not used.

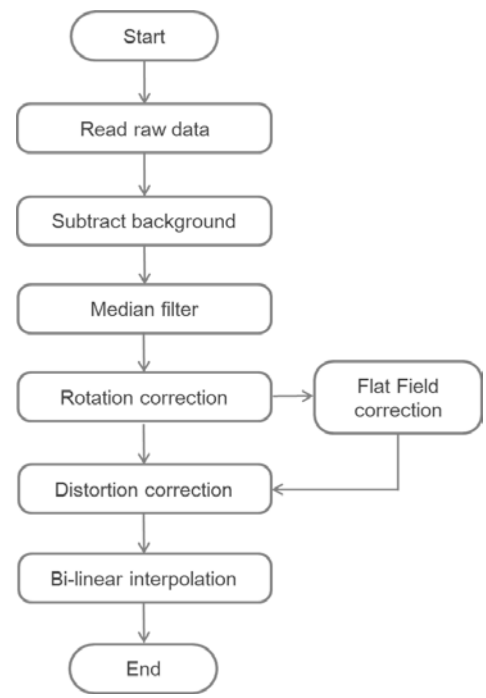

Figure 2: Flow chart of image correction process.

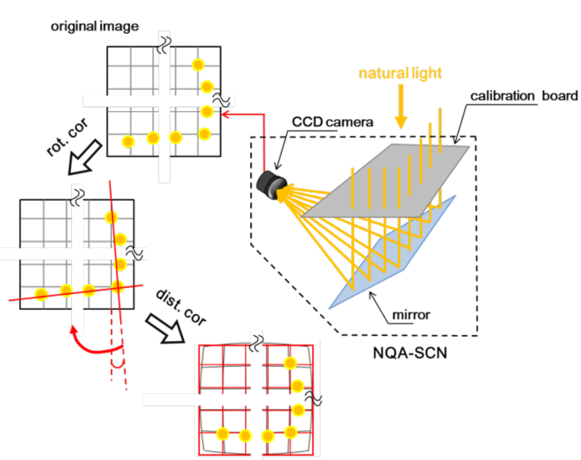

Figure 3: Schematic of the rotation correction and the distortion correction. Parameters for both corrections are derived from the image obtained with the calibration board.

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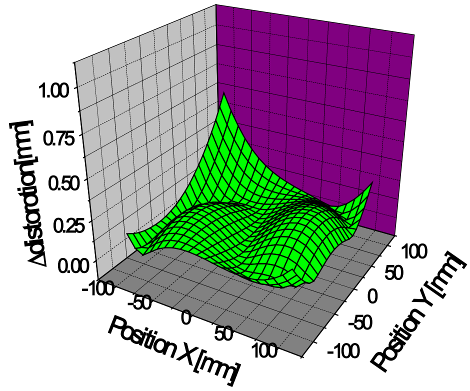

Figure 4: Difference between the center of gravity measured with the calibration board and the prescribed lateral positions.

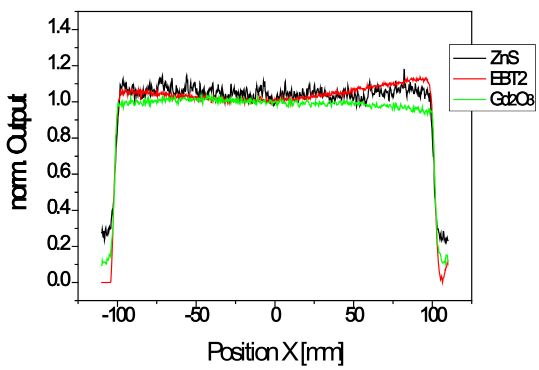

Figure 5: The profiles of a uniform field measured by the two different fluorescent screens and EBT2.

Experimental Setup

All experiments were performed in the new treatment facility at NIRS-HIMAC, equipped with all the instruments indispensable for 3D scanning irradiation, including a scanning magnet, range shifter, ridge filter and beam monitors [3]. For depth scanning, the hybrid depth scanning method [10] was employed, in which 11 beam energies were used in conjunction with the range shifter.

For measurement in water, as shown in Fig. 6, the NQA-SCN was attached to an accordion-type water phantom. The accordion-type water phantom was reported previously [11]. Only a simplified explanation is given here. Measurement depth for the accordion-type water phantom can be changed from 30 mm to 300 mm by remote control.

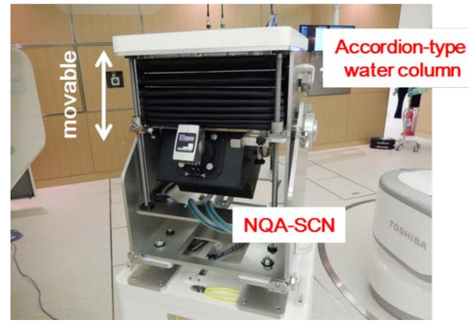

Figure 6: Photograph of experimental setup for the depth dose distribution in water.

RESULTS AND DISCUSSION

The first step was to check the linearity of dose, dose rate and LET in relation to light output. We measured the fluence with the NQA-SCN positioned on the isocenter without any water phantom. Figure 7 shows the linearity of applied dose and light output for single spot irradiation with three different incident energies. Even in small count region, the relation between dose and light output for three different energies is linear. Linearity for different dose rate is shown in Fig. 8. We confirmed that the relation for different dose rate turned out to be linear.

Several types of QA measurements must be performed to check the beam position, 2D intensity modulation and the effect of hysteresis for therapeutic scanned ion beams. The scanned beam position is directly affects the delivered dose distribution. Thus, we confirmed the accuracy of the position for scanned beam by using the NQA-SCN. Figure 9 shows differences between the measured and prescribed positions for irradiation fields, ±80 mm. The results show the accuracy of ±0.2 mm at 1-sigma. To verify the dose dependence of the beam size, we derived the size from the measured results of the spot irradiation. The variation of the beam size was less than 0.06 mm at 1-sigma.

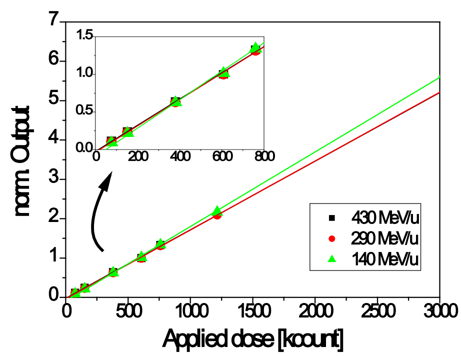

Figure 7: Linearity of applied dose and light output for single spot irradiation with different incident energy: 430, 290, 140 MeV/u.

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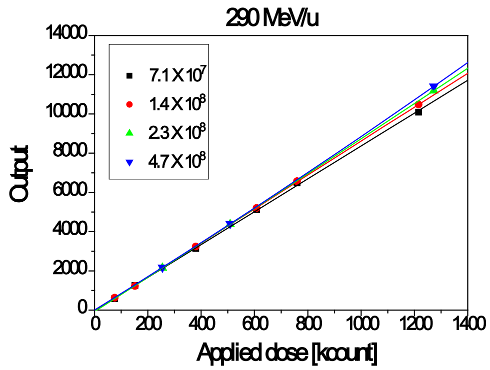

Figure 8: Linearity of applied dose and light output for single spot irradiation with different dose rate.

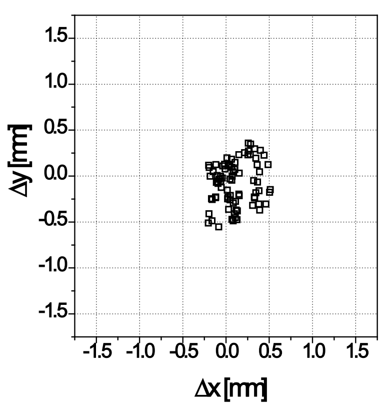

Figure 9: Differences between the measured and prescribed position obtained by using a large spot irradiation field, ±80 mm.

To measure the depth brightness distribution in water, the NQA-SCN was attached to an accordion-type water phantom in Fig. 6. Even for water phantom attached the NQA-SCN, the speed of a change in depth keeps 5 mm/s. Figure 10 shows the depth brightness distribution measured by the NQA-SCN. In same figure, the measured brightness distribution is compared to depth dose distribution measured by the large-plane ionization chamber (IC) [12]. NQA-SCN data was normalized to match the IC data at a depth of 30 mm. Compared to the result measured by the IC, the increase of quenching effect was significant for the LET dependence of the light output toward the Bragg peak region. For correct of quenching effect [13], we derived a ratio the result measured by NQA-SCN to that measured by the IC. The ratio increased steeply from the distal-falloff region to the tail region. It seems that dose contribution in the tail region is dominated by the lighter fragments with low LET from a qualitative viewpoint. While the depth brightness distribution was normalized to 1 at the entrance region, LET dependence of light output at the entrance region is small, as shown in Fig. 7. Effective area of the NQA-SCN is larger that of IC, background noise of the NQA-SCN at entrance may be overestimated.

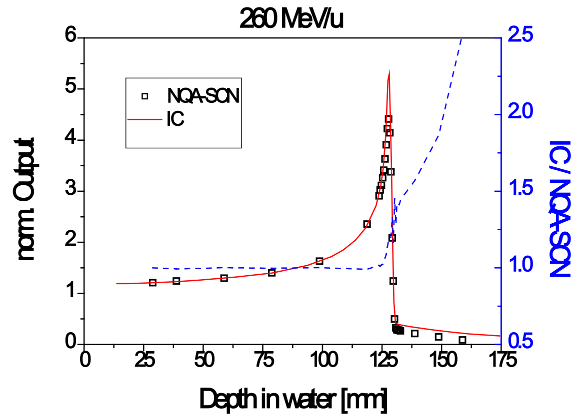

Figure 10: The depth brightness distribution in water (open square) and the depth dose distribution measured by the ionization chamber (solid line). Both distributions normalized at a depth of 30 mm. The dashed line shows a ratio the result measured by NQA-SCN to that measured by the ionization chamber.

CONCLUSIONS

We developed the compact dose verification system with a fluorescent screen and a CCD camera, so-called the NQA-SCN. We confirmed that the NQA-SCN could be used as a useful tool for QA procedures of therapeutic scanned ion beam. Additionally, we investigate the response of the NQA-SCN to carbon-ion for doses, dose rate and LET. In further research, we will assess the performance of the NQA-SCN for 3D dose verification.

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