The Properties of Beam Intensity Scanner (BInS) for Dose Verification in Intensity Modulated Radiation Therapy

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Patient dose verification is one of the most important responsibilities of the physician in the treatment delivery of radiation therapy. For the task, it is necessary to use an accurate dosimeter that can verify the patient dose profile, and it is also necessary to determine the physical characteristics of beams used in intensity modulated radiation therapy (IMRT). The Beam Intensity Scanner (BInS) System is presented for the dosimetric verification of the two dimensional photon beam. The BInS has a scintillator, made of phosphor Terbium-doped Gadolinium Oxysulphide (Gd_2O_2S:Tb), to produce fluorescence from the irradiation of photon and electron beams. These fluoroscopic signals are collected and digitized by a digital video camera (DVC) and then processed by custom made software to express the relative dose profile in a 3 dimensional (3D) plot. As an application of the BInS, measurements related to IMRT are made and presented in this work. Using a static multileaf collimator (SMLC) technique, the intensity modulated beam (IMB) is delivered via a sequence of static portals made by controlled leaves. Thus, when static subfields are generated by a sequence of abutting portals, the penumbras and scattered photons of the delivered beams overlap in abutting field regions and this results in the creation of "hot spots". Using the BInS, inter-step "hot spots" inherent in SMLC are measured and an empirical method to remove them is proposed. Another major MLC technique in IMRT, the dynamic multileaf collimator (DMLC) technique, has different characteristics from SMLC due to a different leaf operation mechanism during the irradiation of photon and electron beams. By using the BInS, the actual delivered doses by SMLC and DMLC techniques are measured and compared. Even if the planned dose to a target volume is equal in our experimental setting, the actual delivered dose by DMLC technique is measured to be larger by 14.8% than that by SMLC, and this is due to scattered photons and contaminant electrons at d_{max}.

Key Words: IMRT, BInS, Dose verification

INTRODUCTION

In conformal radiotherapy, it is essential to deliver radiation beams that conform to the planning target volume (PTV) while sparing organs at risk (OAR) and surrounding normal tissue. This clinical treatment has been achieved via various methods. For example, blocks can be used to generate desired beam shape for the treatment. However, in many cases, beam shaping alone is not enough for creating conformal dose distribution, and intensities of the delivered beams need to be modulated by compensators. The techniques of multileaf collimator (MLC) in IMRT have been developed rapidly and may replace both the blocks for beam shaping and compensators for intensity modulated beams (IMBs). The techniques and concerns relating to MLC in IMRT have actively been

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studied and reviewed.[1)]

There are two basic MLC techniques available for clinical treatment delivery. In dynamic MLC technique (DMLC), IMBs are delivered by moving the collimator leaves during irradiation.[2-5)] While in static MLC technique (SMLC), which is sometimes called "step and shoot" MLC technique, IMB is delivered by irradiating a sequence of static portals made by controlled leaves. Both techniques have advantages and disadvantages when applied to clinical treatment. For example, delivery by DMLC in IMRT is more efficient while SMLC takes longer treatment time in general. However verification in planning and delivery procedures is complicate for DMLC due to the complexity accompanied by leaf motion. For SMLC, precise dose delivery and easy verification is possible since leaves are not moving during irradiation.

In order to verify delivered dose in IMRT before it is applied to a patient, various dosimeters such as radiographic film, diode, ion chamber and electronic portal imaging device (EPID), have extensively been studied. Among them, charge-coupled device (CCD) camera based EPIDs are a promising tool for dose verification due to their high acquisition rate, reliability, good signal to noise ratio, high resolution and durability under irradiation.[6-9)] Most of the EPIDs consist of a Gadolinium Oxysulphide (Gd_2O_2S:Tb) fluorescent phosphor screen preceded by a metal screen like stainless steel and a CCD camera for optical fluorescent signal acquisition. We have developed an improved EPID named Beam Intensity Scanner (BInS) equipped with custom-made software. The BInS has a scintillator, made of phosphor terbium-doped Gadolinium Oxysulphide (Gd_2O_2S:Tb), to produce fluorescence from the irradiation of photon and electron beams. These fluoroscopic signals are collected and digitized by digital video camera (DVC) and processed by our custom made software to express relative dose distribution profile in 3 dimensional (3D) plot. According to various tests performed by our group, the BInS shows strong linearity as a dosimeter and has negligible self-noise. Furthermore, it can measure even a low dose portal image and irregular shaped beams. Therefore the BInS can be used as an accurate dosimeter for clinical Quality Assurance and basic researches in IMRT.

As an application of the BInS, three measurements related to IMRT are presented in this work: study of Aluminum-Lucite phantoms, inter-step hot spots, and comparison of delivered dose in SMLC and DMLC. In the study of Aluminum-Lucite phantoms, we investigate phantoms made of Aluminum and Lucite using the BInS. Since Aluminum and Lucite are considered as bone and tissue equivalent materials respectively, dose measurements of fields attenuated by these phantoms may show the influence of bones on the field attenuation. In the study of inter-step hot steps, we investigate hot spots appearing in the abutting field regions in SMLC. These hot spots make the actual delivered dose to the target inaccurate and cause degradation of the original treatment plan. Using the BInS, inter-step hot spots in SMLC are measured and visualized in 3D dose profile. And an empirical iterative method to remove them is presented. The two major MLC techniques in IMRT, SMLC and DMLC, have different characteristics due to different leaf operation mechanism. In the comparison of delivered dose in SMLC and DMLC, the BInS measures the actual delivered doses by each technique to make a quantitative comparison. This result is confirmed by other dosimeters like ionization chamber (PTW, N31006) and radiographic film (Kodak XV2).

MATERIALS AND METHODS

1. The BInS and its linearity

There is considerable interest in the application of EPIDs to dosimetry and the verification of the IMRT produced by SMLC and DMLC. The BInS is an EPID consisting of a fluorescent screen (scintillator), a reflector, a CCD digital video camera, and a personal computer as described in Fig. 1. The scintillator is a 1.8mm thick stainless steel plate coated with a layer (1.5 mm thick) of terbium-doped Gadolinium Oxysulphide (Gd_2O_2S:Tb) to produce fluorescence from the irradiation of photon and electron beams. Various characteristics of this scintillator, such as linearity of the optical signal to the irradiation pulse, the effect of accelerator pulse repetition frequency on the optical signal and long-lived luminescence (after-glow), has been studied in numerous literatures[6,10)] and proved to produce accurate optical signal for clinical application. The scintillator, irradiated perpendicularly with the photon beam from the Gantry Head, generates fluorescent signals according to the positions of incoming

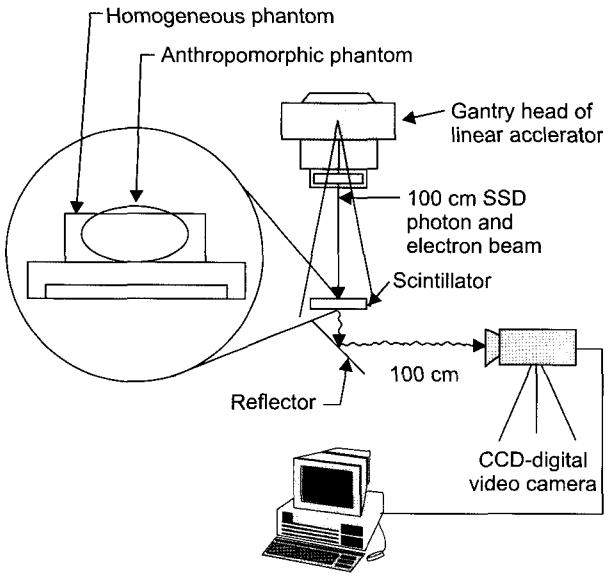

Fig. 1. The schematic diagram of the BInS. The CCD digital video camera is connected to the computer to analyze data from the scintillator.

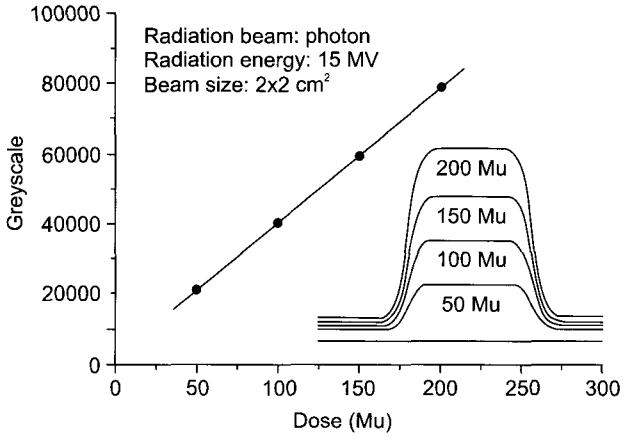

Fig. 2. The linearity of the output readings of the BInS in arbitrary light intensity units. Calculation values are functions of the relative absorbed dose in the monitor unit. The insert figure shows that the magnitudes of the beam profiles are proportional to absorbed doses.

photons and charged particles. Positioned under the scintillator, the reflector reflects optical signals at right angle to the CCD-digital video camera. The CCD-digital video camera is placed at 100 cm away from the center of the reflector surface to protect it from the scattered photons from the Gantry Head. The CCD-digital video camera acting as the acquisition device of fluorescent signal in the BInS system could capture 30 frames/second. Captured and digitized signals are sent to the personal computer with a video capture card for data storage and analysis. The CCD in the digital video camera has an array of 600×600 light sensitive elements (pixels) and the brightness of a pixel is proportional to the intensity of the radiation beam at the corresponding point in the scintillator. Custom made software in the PC converts the brightness of pixels due to irradiation into numerical data and performs data analysis. Compared with commercially available EPIDs, the BInS has several strong points. First, the raw BInS images of 600×600 active pixels are resampled to 125×125 elements in our custom made software to obtain numerical data. If necessary, the resolution of the BInS can be increased by sampling more pixels. Second, the BInS is installed with a CCD-digital video camera instead of a CCD as in EPIDs. Using the zoom function in digital video camera, the data acquisition by the BInS is more flexible than conventional EPIDs. Third, the BInS is able to visualize the measured beam profile in 3D plots. Due to this visualization, the correlation between the details of a phantom and the measured beam profile becomes clear.

In order to use the BInS as a radiation dosimeter, it is necessary to check the linearity of BInS readings with respect to various doses. We obtained data to check linearity of the BInS using 15 MV small beam of size 2×2 cm^2. The scintillator of the BInS was placed at SSD of 100 cm. And the linearity line was determined by function fitting.

2. Study of Aluminum-Lucite phantoms

As an application of the BInS on IMRT, we studied phantoms with an Aluminum (Al) block placed above (Al-up phantom) and below (Al-down phantom) the L-shaped Lucite block. The details of each block is given in Fig. 3. Since Aluminum and Lucite are considered as bone and tissue equivalent materials respectively, dose measurements of fields attenuated by these phantoms may have implication on the radiation fields attenuated by bones. These two phantoms were placed at SSD of 100 cm and irradiated by 15 MV photon beam of size 12×12 cm^2. The attenuated beam profiles by these phantoms were measured and compared with.

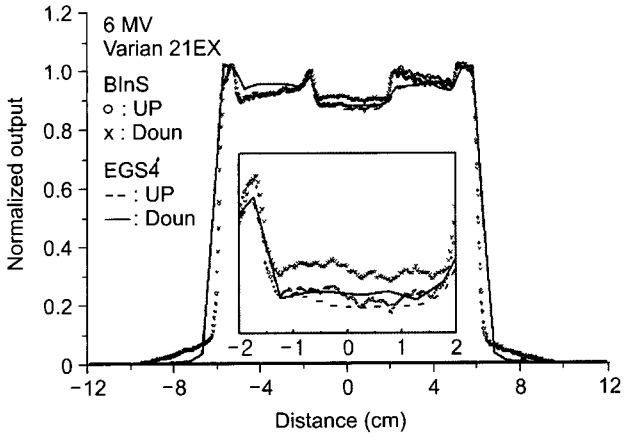

Fig. 3. Measurements of the Al-Lucite phantoms by the BInS. The normalized profiles detected are plotted with respect to the 50 Monitor unit (MU). The data is due to a 15 MV photon beam of size 12×12 cm^2. The BInS could detect such a small dose difference due to the switching of the phantom materials. Monte Carlo simulation in dashed and solid lines confirms this result.

3. Hot spots at the inter-step in SMLC

It is a well-known fact that SMLC delivery is very sensitive to leaf position accuracy.[11] When static subfields are generated by a sequence of abutting portals in SMLC, the penumbras of delivered beams overlap in each abutting region and result in the creation of hot spots. These hot spots make the actual delivered dose inaccurate and need to be measured. The physical origin of subfield penumbra is due to rounded leaf edges as pointed out by an earlier work.[12] The scattered photons and charged particles, that is called contaminant electrons from the rounded leaf edges, contribute mostly to these spots. In order to investigate the inter-step hot spots, MLC was set to create a step-like dose by a sequence of abutting fields (nominal size of 2×1 cm^2) with increasing intensities (10, 20, 30, 40 MU). The BInS measured the actual delivered dose at 100 cm SSD to make IMB profile for this setting.

4. Comparison of delivered dose by SMLC and DMLC

The two major MLC techniques used in IMRT these days, SMLC and DMLC, have advantages and disadvantages if applied to clinical treatment. The continuous leaf motion of DMLC enables efficient and accurate beam delivery possible, but makes the related quality assurance harder. On the other hand in SMLC, the desired plan has to be approximated with a sequence of static fields. Thus degradation of the treatment planning is unavoidable, but quality assurance is less demanding. In addition to the contrasting features mentioned, the actual delivered dose by each technique needs to be measured and studied. An earlier work[13] compared dose distributions by SMLC technique with that by DMLC for two clinical cases. Another study[14] investigated the effects of the number of levels and spatial resolution on SMLC by comparison with DMLC results.

In this work using the BInS, we compare delivered dose by SMLC to DMLC and other dosimeters such as radiographic film (Kodak XV2) and ion chamber (PTW, N31006). For the study, Varian 21EX was set to deliver the same dose at the rate of 300 MU/min to a target area of 1.5×10 cm^2 at d_{max} in three different modes: Open, SMLC and DMLC. In Open mode, a field of size 1.5×10 cm^2 made by a proper leaf opening was irradiated to deliver 20 MU. In SMLC mode, the intended field of 1.5×10 cm^2 was divided into 10 subfields by proper leaf setting. And the total integrated dose of 20 MU was delivered to each sub field of size 1.5×1.0 cm^2. In DMLC mode leaves making dynamic portal moved in approximate speed of 0.2 cm/sec to deliver the same amount of dose to the target area of size 1.5×10 cm^2. In all three modes, the planned doses per unit area were set to be equal. We measured the delivered dose by these three modes at SSD of 100 cm using the BInS. To compare with the result by the BInS, measurements by ion chamber of 0.6 cm^3 (PTW, N31006) and radiographic film (Kodak XV2) were also made. For the film measurements, the films were irradiated under 1.5cm thick Lucite at SSD of 100 cm. For the ion chamber, measurements were made in a water tank with surface level at SSD of 100 cm. The ion chamber scanned the beam at d_{max} (1.5 cm from the water surface) by motorized fixation moving perpendicularly to the beam axis. Thus all three dosimeters, the BInS, film, and ion chamber, were exposed to the beam at d_{max}.

All the above studies were carried out on a Varian 21EX Millennium accelerator fitted with 120 leaves. Mainly 6 and 15 MV photon beams, with field size adjusted by photon collimators from 1.0×1.0 to 10.0×10.0 cm^2, were used in this work.

RESULTS AND DISCUSSIONS

In order to check the linearity of the BInS, the grayscale value detected by the BInS is plotted in Fig. 2 with respect to the reference dose in Monitor unit (MU). We obtain the linearity line by function fitting. The measured points fit well with the calculated line within $1 \pm 0.5\%$. Neither supra-nor infra-linearity exists in spite of large monitor units absorbed. If extrapolated to zero MU, the linearity line intersects the y axis (axis for Gray scale) at a point close to the origin. It means the BInS has negligible self-noise. In addition to the linearity check, it is necessary to calibrate the conversion of a pixel readings to portal dose. A typical calibration involves comparison of the BInS reading with the reference dose determined independently by other dosimeters like ion chamber.[11] Currently, our group is developing an improved version of BInS that uses a light emitted diode (LED) as the calibration standard.

In Fig. 3, dose profiles of the attenuated beams by the Al-up and Al-down phantoms are plotted with respect to 50 MU. According to this result, the normalized dose of the beam attenuated by the Al-down phantom is bigger than that by the Al-up phantom. The Al-up phantom may attenuate photons more than the Al-down phantom. Monte Carlo simulations on these phantoms, shown in dashed and solid lines in Fig. 3, confirm these measurements by the BInS. To the best of our

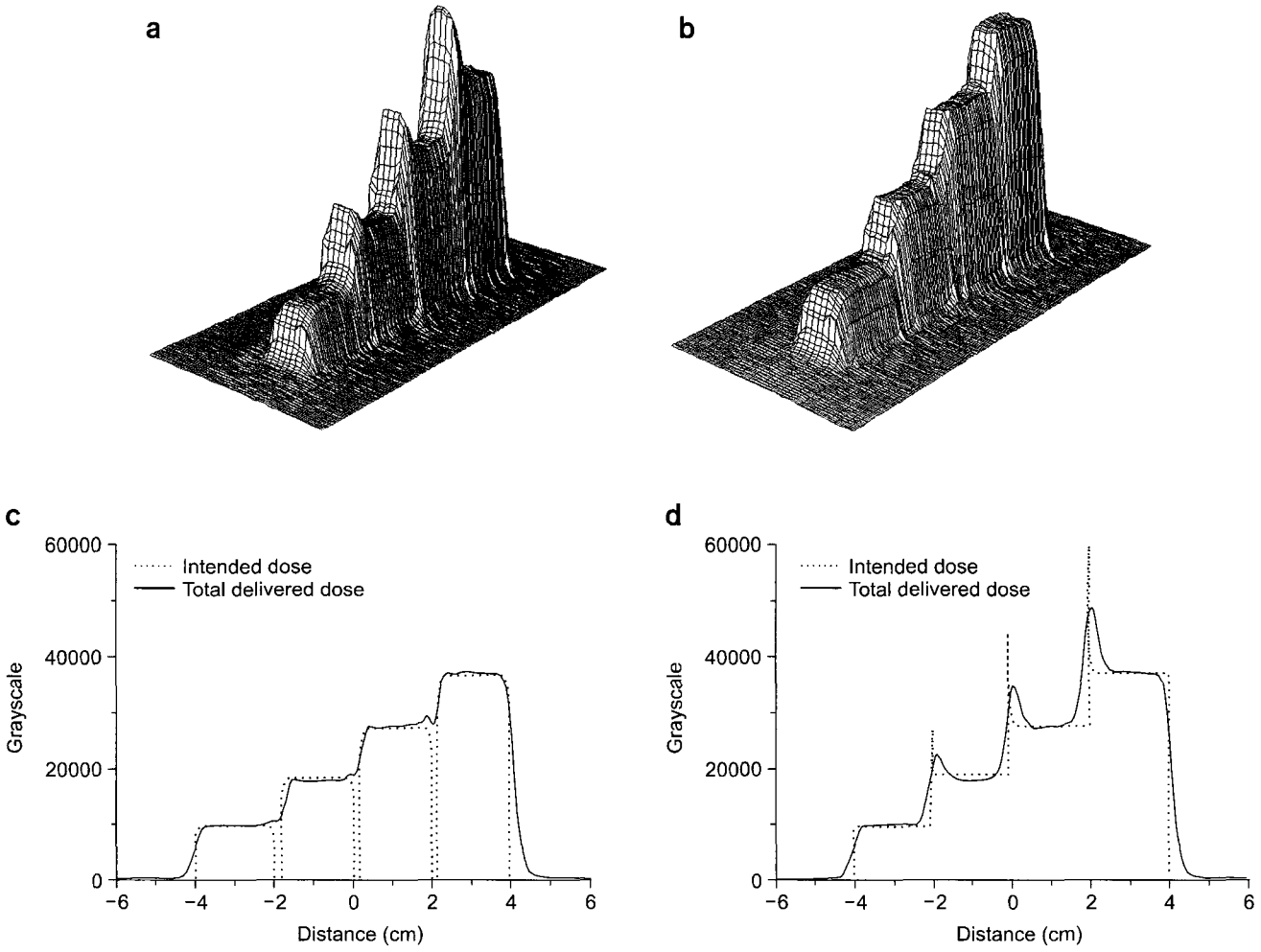

Fig. 4. Intensity modulated beam profile of a three dimensional step dose. (a) 3D-dose distribution with hot spots. (b) Hot spots were eliminated by adjusting the leaf spacing sequence. (c) 2D-dose distribution of the intended and the delivered dose without hot spots. (d) 2D-dose distribution of the intended and the delivered dose with hot spots.

knowledge, no other detectors except the BInS can measure such a small dose difference caused by the switch of the phantom 'materials.

In Fig. 4-a, the dose profile plotted in 3D shows inter-step hot spots in abutting field regions in SMLC. In Fig. 4-d, dotted and solid lines represent the intended dose on computer for IMRT treatment planning and the measured dose by the BInS at d_{max} respectively. Obviously, it is desirable to remove these hot spots for the sake of accuracy of dose delivery. After studying measurements by the BInS, we introduce artificial gaps between portals in treatment planning by modifying leaf positions. These gaps offset the overlap of penumbras and scattered photons in abutting fields and generate the ideal step dose without inter-step hot spots as shown in Fig. 4-b. The gap widths are determined by an empirical iteration method as 2.3, 1.9, 1.8 mm successively along the direction of leaf motion. In Fig. 4-c, the dotted line represents the intended dose with gaps on computer. Clearly there exist three cold regions due to the introduced gaps. But the solid line, representing the total delivered dose, has no cold and hot spots in the abutting field regions. According to tests performed by our group, the proper gap width to remove inter-step hot spots depends strongly on Linacs, photon energies and other parameters like SAD and SCD (source to collimator distance).

In the comparison of Open, SMLC, and DMLC modes with identical plan dose, the actual delivered doses measured by the BInS show significant discrepancy as in Fig. 5-a. As shown in Table 1, the delivered dose by SMLC and DMLC modes are larger by 26% and 43% than that by Open. According to the measurements to check this result, the delivered doses measured by film show even larger discrepancy than those by the BInS, because film is more susceptible to the scattered photons. On the other hand, the ionization chamber detects doses very similar to those by the BInS. Even if there exists slight variation in magnitude depending on dosimeter, the delivered dose by DMLC mode is approximately 14.8% larger than that of SMLC in our measurement setting. Therefore, clinical treatment planning must account for this variation in the

Table 1. Comparison of delivered dose in open, SMLC and DMLC modes.

Total volume (%)			
	Open	SMLC	DMLC
BInS	100	126	143
Film	100	133	152
Normalized dose (%) for ionization chamber (PTW, N31006)			
	Open	SMLC	DMLC
	100	128	147

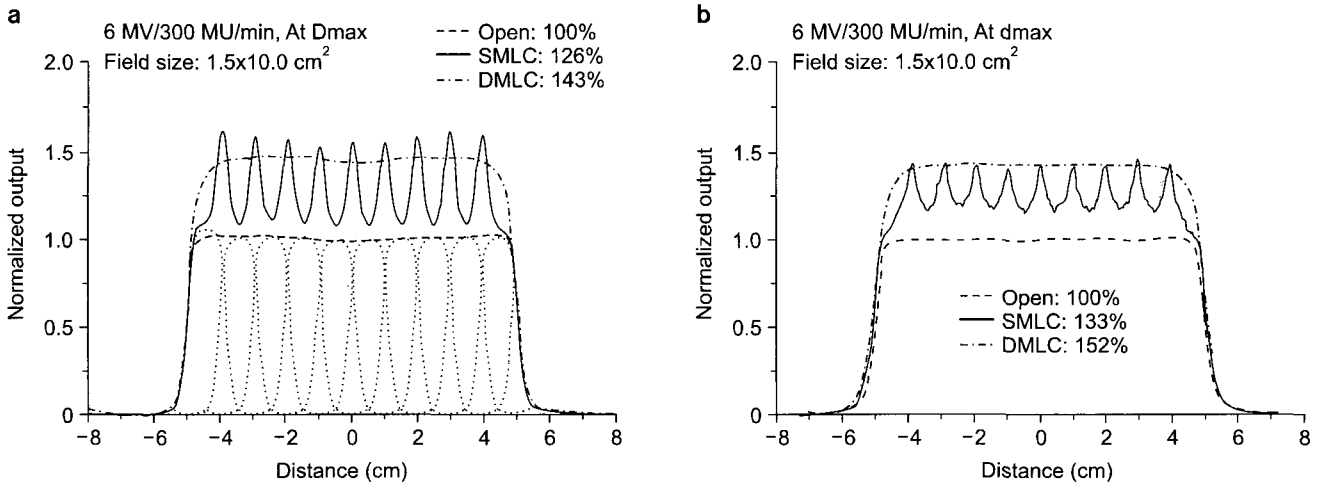

Fig. 5. (a) 2-D dose distribution measured by BInS for Open, SMLC and DMLC modes. (b) 2-D dose distribution measured by film (Kodak XV2) for Open, SMLC and DMLC modes.

delivered dose. The physical origin of this variation is the different mechanisms to operate leaves. In Open mode, penumbras appear only at field boundaries. On the other hand, there are discrete abutting field overlaps in SMLC. As shown in Fig. 5, the nine hot spots from 10 subfields explain why the delivered dose by SMLC is about 20% larger than that by Open. In DMLC, the delivered dose by hot spots is even larger than SMLC because the boundary of subfield of size 1.5×1 cm^2 is sweeping across the field of size 1.5×10 cm^2. Thus boundaries of the sweeping subfield are over-exposed to the irradiation due to penumbras and scattered photons. An earlier work[15] compared DMLC with SMLC employing different numbers of levels and different spatial resolutions. And they claimed that the significant discrepancies found in SMLC, between the desired and the delivered intensity profiles, were due to several factors, such as rounded leaf edge, transmission through the leaf end and the extra-focal radiation.

CONCLUSIONS

The dosimetric characteristics of the BInS demonstrate that it could be one of the most accurate detectors for large beam used in IMRT and small photon beam used in Stereotactic Radiation Therapy (SRT). The BInS can visualize relative dose distribution accurately in 3D plot by means of the digitized fluoroscopic signals for irregular fields used in IMRT. In view of the results achieved so far, we conclude that the BInS system may play an important role for the dose measurements in SMLC, DMLC and 3D dose in solid water phantom, irrespective of the beam size.

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방사선 세기 조절 치료에서 선량을 규명하는 데 사용된 BInS System의 특성

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방사선 치료과정에서 가장 중요한 것은 환자에게 조사된 흡수선량을 검증하는 것이다. IMRT에 사용되는 방사선의 물리적 특성을 결정하고 환자에 조사된 선량분포를 검증할 수 있는 정밀한 선량 측정 장치가 필요하다. 본 연구에서 2차원 광자선의 선량검증을 위해 만들어진 BInS (Beam Intensity Scanner)에 관하여 논의한다. BInS에 있는 Scintillator는 광자선이나 전자선에 조사되면 형광을 발생하는 Gd_2O_2S:Tb를 주성분으로 한다. Scintillator에서 발생된 형광은 디지털 비디오카메라에 의해 수집되어 디지털 신호로 바뀌고 자체 제작한 소프트웨어에 의해 분석되며 상대적인 선량분포가 3차원 그림으로 표시된다. BInS가 IMRT에서 사용가능한지를 알아보기 위하여 치료에 관련된 몇 가지 측정을 하였다. IMRT의 주요 작동방식 중의 하나인 SMLC (static multileaf collimator) 방식에서는, leaf들의 동작을 통제하여 만들어지는 여러 개의 정적 조사면적(static portal)을 통하여 IMB (intensity modulated beam)이 만들어진다. 따라서 여러 개의 정적 조사면적이 연달아 맞닿아 있는 경우, 연속된 두 조사면적의 경계면에서 penumbra와 산란된 광자들이 겹쳐지고 따라서 hot spot이 생기게 된다. 이와 같이 SMLC 방식에서 나타나는 inter-step hot spot들의 존재를 BInS를 이용하여 측정하여 가시화하였고 또한 그것들을 제거하는 실험적 방법도 제시하였다. IMRT에서 사용되는 다른 주요한 작동방식인 DMLC (dynamic multileaf collimator)는 광자선이나 전자선을 제어하는 leaf의 작동방식이 다르기 때문에 SMLC 방식과는 다른 특성을 보인다. 따라서 BInS를 이용하여 SMLC와 DMLC 방식에 의해 실제로 target에 투사된 선량을 측정 비교하였다. 비록 같은 선량을 target 부위에 투사하기로 계획했을지라도, 실제로는 산란된 광자와 전자들 때문에 DMLC 방식에 의한 선량이 SMLC 방식에 의한 선량보다 14.8%나 큰 것으로 측정되었다.

중심단어: 세기조절 방사선치료, BInS, 흡수선량검증