Characteristics of Photon Beam through a Handmade Build-Up Modifier as a Substitute of a Bolus

Sung Joon Kim*, Seoung Jun Lee*, Su Ho Moon*, Ki Ho Seol[†], Jeong Eun Lee[†]

Department of Radiation Oncology, *Kyungpook National University Hospital,
[†]Kyungpook National University School of Medicine, Daegu, Korea

We evaluated the effect of scatter on a build-up region based on the measured percent depth dose (PDD) of high-energy photon beams that penetrated a handmade build-up modifier (BM) as a substitute of bolus. BM scatter factors (S_{BM}) were calculated based on the PDDs of photon beams that penetrated through the BM. The calculated S_{BM} values were normalized to 1 at the square field side (SFS) of 30 mm without a BM. For the largest SFS (200 mm), the S_{BM} values for a 6-MV beam were 1.331, 1.519, 1.598, 1.641, and 1.657 for the corresponding BM thickness values. For a 10-MV beam, the S_{BM} values were 1.384, 1.662, 1.825, 1.913, and 2.001 for the corresponding BM thickness values. The BM yielded 76% of the bolus efficiency. We expect BM to become useful devices for deep-set patient body parts to which it is difficult to apply a bolus.

Key Words: Build-up modifier (BM), BM scatter factor (S_{BM}), Percent depth dose (PDD), Surface dose

Introduction

Percent depth dose (PDD) of high-energy photon beams decreases as a function of depth after the beams pass through the depth corresponding to the maximum dose.[1] However, there is an initial dose build-up before the depth of maximum dose. The dose build-up effect of high energy photon beams produces the skin-sparing effect. When treating superficial tissues using high-energy photon beams, the most common method for controlling the dose distribution in the build-up region involves using a bolus.[2-6] However, with this method, achieving a uniform dose distribution is challenging because it is very difficult to attach the bolus tightly to the skin on curved parts of the patient's body, such as the neck, nose, and anus.[7] In addition, small air gaps can be generated owing to insufficient malle-

ability of bolus material in these body parts. The effect of these air gaps causes electronic disequilibrium to be re-established in this region and this could cause the dose directly to the patient's skin to decrease as the x-ray beam could produce secondary build-up.[8]

To overcome these challenges, we designed a new instrument, which we termed the build-up modifier (BM). This device, when loaded on the head of a linear accelerator, can be used with radiation coming from any direction, and it does not require a bolus to be attached to the skin. Khan et al.[1] and Sroka et al.[9] reported that placing the absorber at various distances from the surface of a water phantom with density similar to that of a human body affected the dose distribution in the build-up region. Their results confirmed that, without attaching the absorber to the skin, contamination from scattered secondary electrons allowed the researchers to control the dose in the build-up region. Analyzing the scatter effect of the BM based on the above principle and applying the quantitative analysis results to treatment planning systems for dose calculation could ascertain the BM as a very useful instrument in the field of radiotherapy. In this study, we measured the PDDs of high-energy photon beams penetrating a handmade BM and subsequently calculated the BM scatter based on these results. The

purpose of this study was to assess the effect of the BM scatter on the build-up region of PDDs in various conditions and investigate the BM applicability.

Materials and Methods

1. Construction of build-up modifier

In this study, we selected acrylic polymer, a type of epoxy resin, to serve as the BM material. Scattered secondary electrons are mostly generated by Compton scattering in high energy level over megavoltage. This is closely related to the electron density of materials, and epoxy resins are specifically known to be highly effective in generating secondary electrons.[1] Five acrylic panels were shaped into square panels that were 300 mm long and wide and had thicknesses of 1, 3, 5, 7, and 10 mm. As shown in Fig. 1, we manufactured a frame to install the acrylic panels of the BM. The lower part of the BM applicator was used for inserting the acrylic panels with dimensions of 20 mm (width)×300 mm (length)×15 mm (thickness). The upper part of the BM applicator was mounted on the linac head (Clinac 21IX, Varian, USA) using a 10 mm thick panel. The two parts of the BM applicator were connected by four rods that were 150 mm long, and the height of the lower part could be adjusted by up to 200 mm by using the control levers.
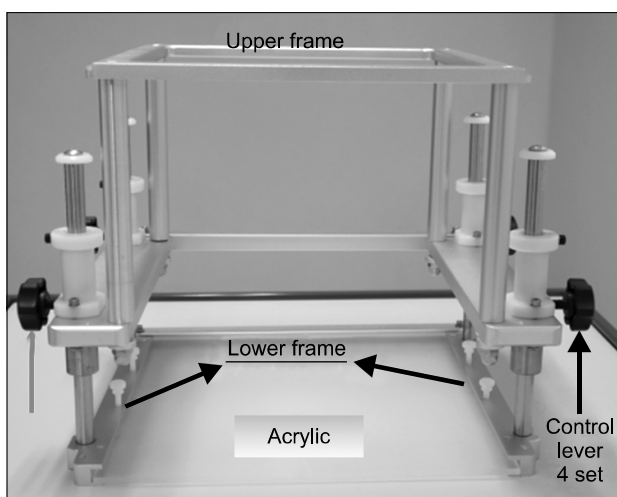
2. PDDs measurement

6- and 10-MV X-ray beams generated by a 21IX Linear Accelerator were selected for this study. The BM was positioned on the head part of a linear accelerator to measure the PDD curves for 6- and 10-MV photon beams that penetrated 1, 3, 5, 7, and 10 mm into the BM for a square field side (SFS) of 30, 40, 60, 80, 100, 120, 150, and 200 mm. As shown in Fig. 2, the distance from the X-ray source to the BM was 750 mm, and that from the source to the water phantom (Blue Phantom, IBA, Germany) was 1,000 mm. PDDs were measured using the 0.13-cc ionization chamber (cc13, IBA, Germany) shifted in the automatic phantom IBA Blue Phantom with OmniPro-Accept V7 (IBA, Germany) from the depth of 25 mm relative to the surface. The results were normalized relative to the maximal dose (100%) points. For comparison, the PDD curves were also measured by using the same method but without applying the BM.

3. Calculation of BM scatter factors

Contamination by scattered secondary electrons affects the dose distribution in the build-up region. BM scatter factors were calculated to analyze the scattering component of secondary electrons in the build-up region. For megavoltage (MV) photon beams, the total scatter at a point is frequently sepa

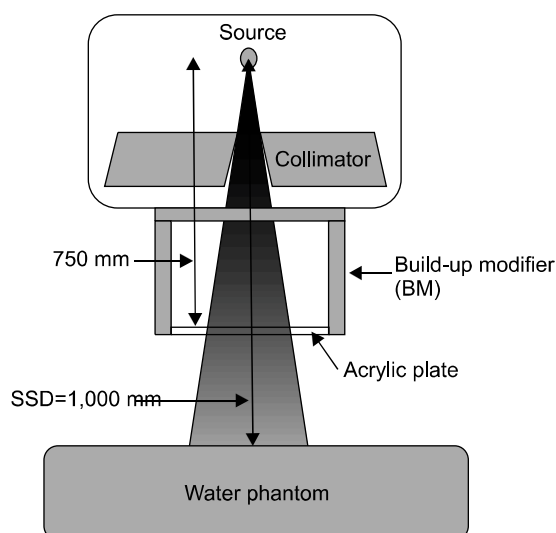**Fig. 1.** Handmade build-up modifier (BM) designed and manufactured at our institute.

Fig. 2. Schematic showing the locations of the build-up modifier (BM) and the water phantom in the linear accelerator for percent depth dose (PDD) measurements.
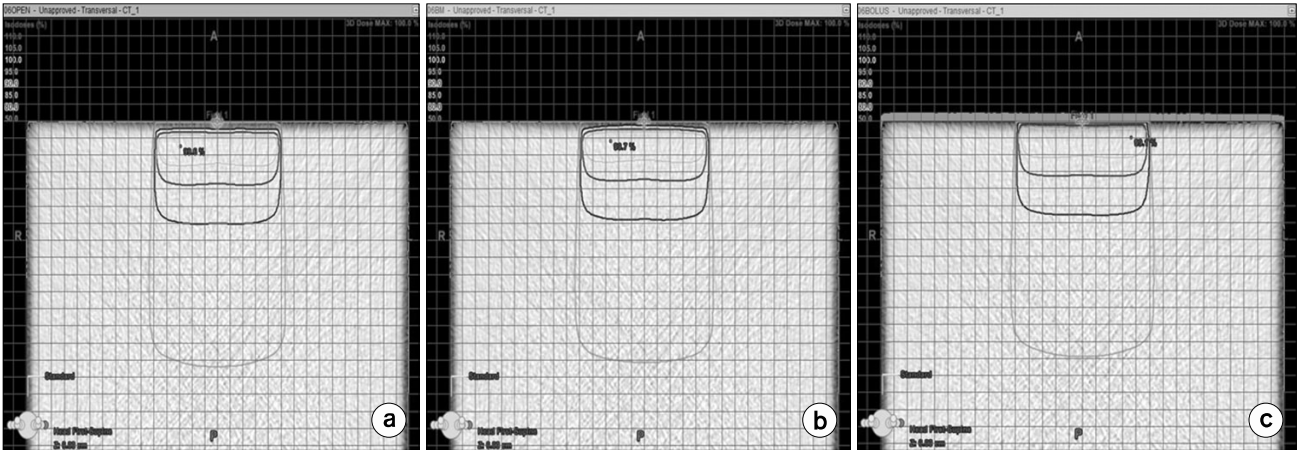
Fig. 3. Treatment plans for (a) "no build-up modifier (BM) no bolus" (open), (b) BM application (BM), (c) bolus application (Bolus), and the resulting dose distributions in Eclipse. The figures show sample treatment plans for the 6-MV photon beam in Eclipse.

rated into components from linac head assembly and phantom scatter for field dose calculation. Holt et al.[10] were the first to perform this procedure by defining the total (S_{cp}), the phantom (S_p) and the collimator scatter (S_c) factors, all normalized relative to a reference field and related through the following equation:

$$S_{cp} = S_p \times S_c \qquad (1)$$

In this study, a point dose in the water phantom in the absence of the BM was also defined by equation (1). When the BM is used, the BM scatter factor (S_{BM}) can be calculated from the following equation:

$$S_{cpBM} = S_p \times S_c \times S_{BM} \qquad (2)$$

We obtained the BM scatter factors by calculating the ratio of equation (2) to (1) for PDDs that were measured near the surface (depth of 0 mm). The S_{BM} in this study was obtained relative to the S_{cp} at SFS 30 mm without the BM that had the smallest scatter factor. In addition, the various dose parameters such as beam profiles, transmission and output factors were measured with each SFS and BM thicknesses for entering the beam data sets into radiation treatment planning system (RTPS).

4. Analysis of relative absorption dose for different depths in RTPS

The measured PDDs and dose parameters of photon beams

passing through the BM were entered into the RTPS (Eclipse V10.0, Varian, USA). Treatment plans were created using Eclipse on a solid water phantom. Fig. 3 shows the Eclipse-generated treatment plans for "no BM no bolus" scenario (open), BM application (BM), bolus application (Bolus), and the resulting dose distributions. For each plan, the relative absorption doses (RADs) were measured at depths of 0, 5, 10, 15, and 50 mm for SFS 30, 100, 150 and 200 in Eclipse, respectively. Photon beam energies of 6 and 10 MV were selected for these plans.

Results

Fig. 4 shows the selected measured PDD curves for the SFS of 200 mm and for the 6- and 10- MV photon beams, respectively, illustrating the changes that take place in the build-up region. Individual curves refer to the data obtained for different BM thicknesses. The BM thickness values are given in both figures. The PDD curves measured without the BM in the irradiated field are shown as black-square curves in both graphs. We qualitatively verified that the size of the build-up region of a photon beam that penetrated through the BM decreased with increasing BM thickness. The build-up regions decreased as the SFS size increased for the same BM thickness, and we verified that these effects became more pronounced for larger thickness.

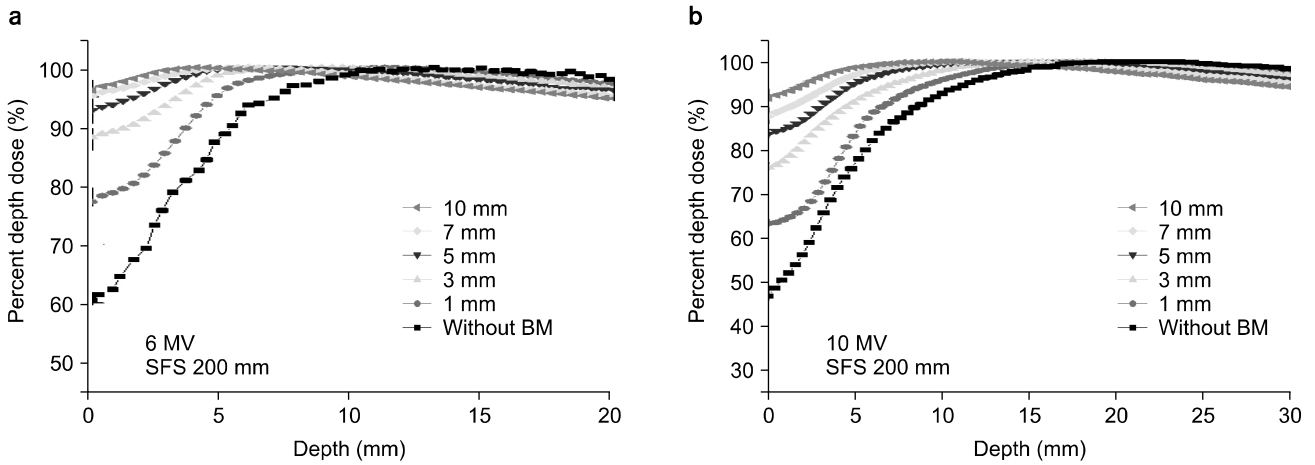The dependence of the BM scatter factor on the SFS is

Fig. 4. Percent depth dose curves for (a) 6-MV and (b) 10-MV photon beams penetrating through various build-up modifier (BM) thicknesses, for a square field side (SFS) of 200 mm.
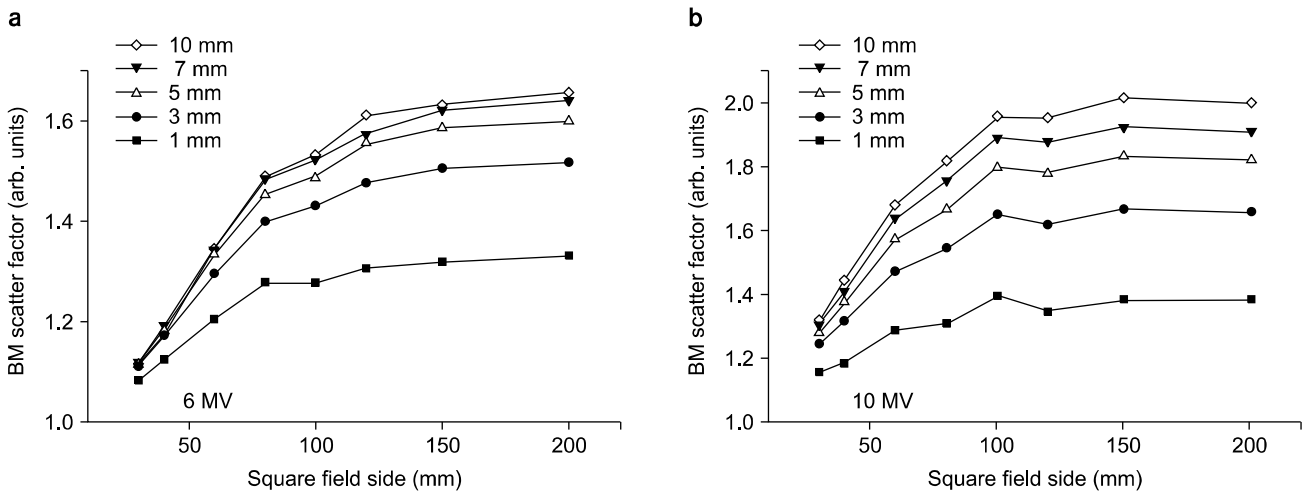

Fig. 5. Build-up modifier (BM) scatter factors for (a) 6-MV and (b) 10-MV photon beams, as a function of depth, for different values of square field side (SFS).

shown in Fig. 5a for a 6-MV beam, for different BM thicknesses. For the smallest SFS (30 mm), the S_{BM} values were 1.083, 1.110, 1.111, 1.120, and 1.120 for the BM thicknesses of 1, 3, 5, 7, and 10 mm, respectively. For the largest SFS (200 mm), the S_{BM} values were 1.331, 1.519, 1.598, 1.641, and 1.657 for the corresponding BM thickness values. The dependence of the BM scatter factor on the SFS is shown in Fig. 5b for a 10-MV beam, for different BM thicknesses. For the smallest SFS (30 mm), the S_{BM} values were 1.160, 1.250, 1.280, 1.301, and 1.320 for the BM thicknesses of 1, 3, 5, 7,

and 10 mm, respectively. For the largest SFS (200 mm), the S_{BM} values were 1.384, 1.662, 1.825, 1.913, and 2.001 for the corresponding BM thickness values.

The S_{BM} for the SFS of 200 mm (shown in Fig. 5a and b) is plotted in Fig. 6 as a function of thickness. For a 6-MV photon beam, the slope in region A is 0.1, whereas the slope in region B is 0.005; the slope in region B is close to 0, implying saturation. For a 10-MV photon beam, the slopes in regions A and B are 0.14 and 0.03, respectively, increasing more modestly with increasing thickness.
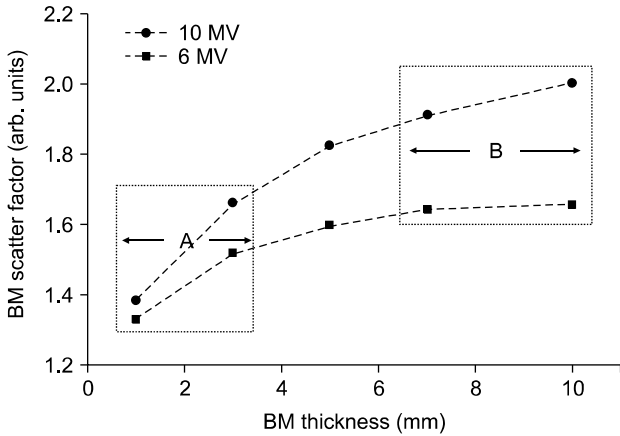
Fig. 6. Build-up modifier (BM) scatter factors at the square field side (SFS) of 200 mm, as a function of thickness.

Fig. 7 shows the RADs at different depths (0, 5, 10, 15, and 50 mm) and for different SFSs (30, 100, 150, and 200 mm) obtained for a 6-MV photon beam in different RTP scenarios: "no BM no bolus" (open), BM application (BM), and bolus application (Bolus). For the SFS of 100 mm, RAD increased by 28.5% and 37.3% at a 0 mm depth for the BM and bolus plans, respectively, compared with the open plan. The rates of RAD increase were 7.3% and 10.4% at a 5 mm depth for the BM and bolus plans, respectively. The effect on the RAD rate increase was negligible for depths increasing beyond 10 mm compared with the effect for depths less than 5 mm. Trends similar to that for the SFS of 100 mm were observed for the SFSs of 30, 150, and 200 mm. Fig. 8 shows the RADs at different depths and for different SFSs for a 10-MV photon beam

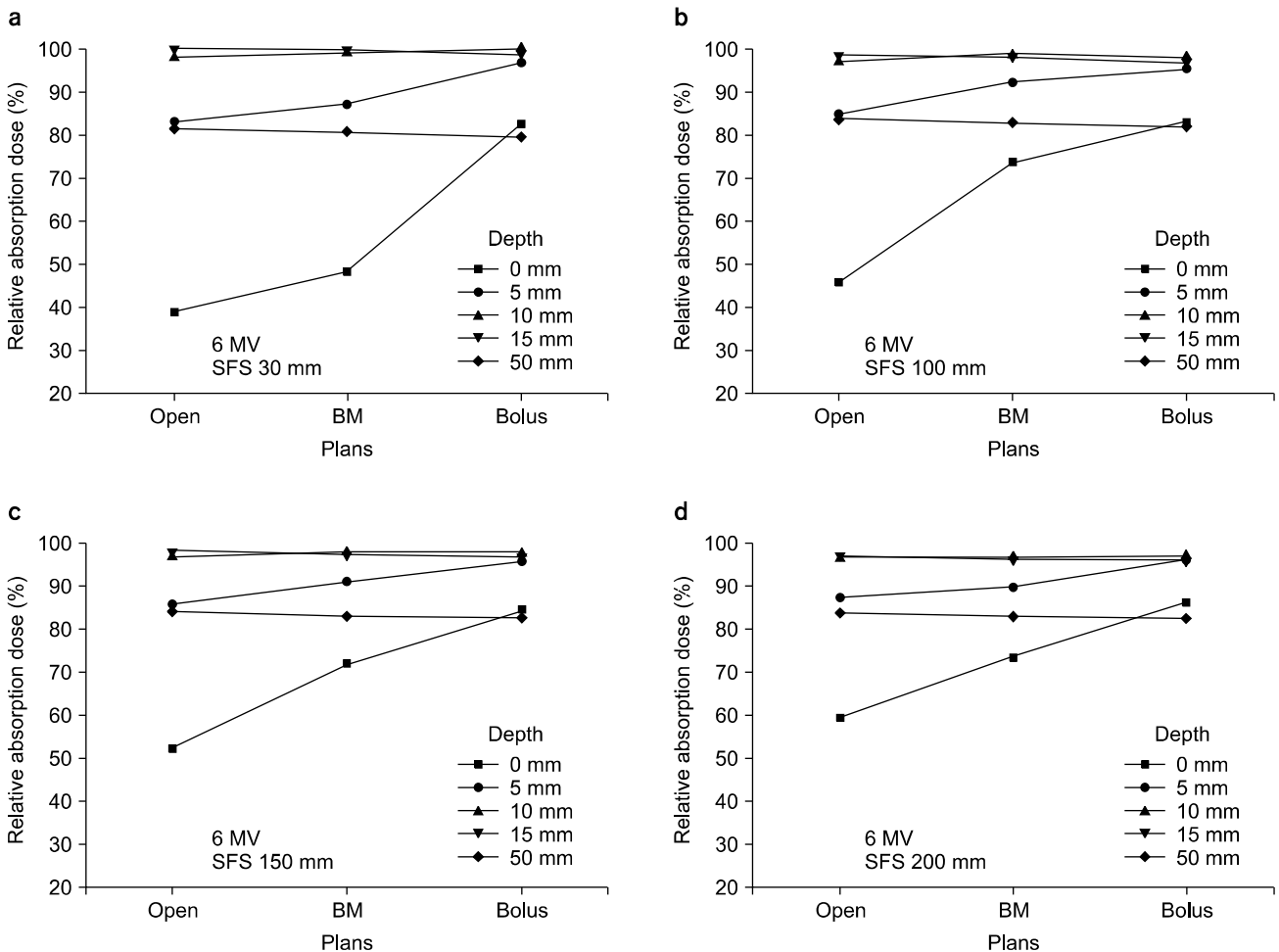

Fig. 7. Relative absorption doses at different depths (0, 5, 10, 15, and 50 mm) and for different square field sides (SFSs) ((a) 30, (b) 100, (c) 150, and (d) 200 mm), for the 6-MV photon beam in a radiation treatment planning system (RTPS).
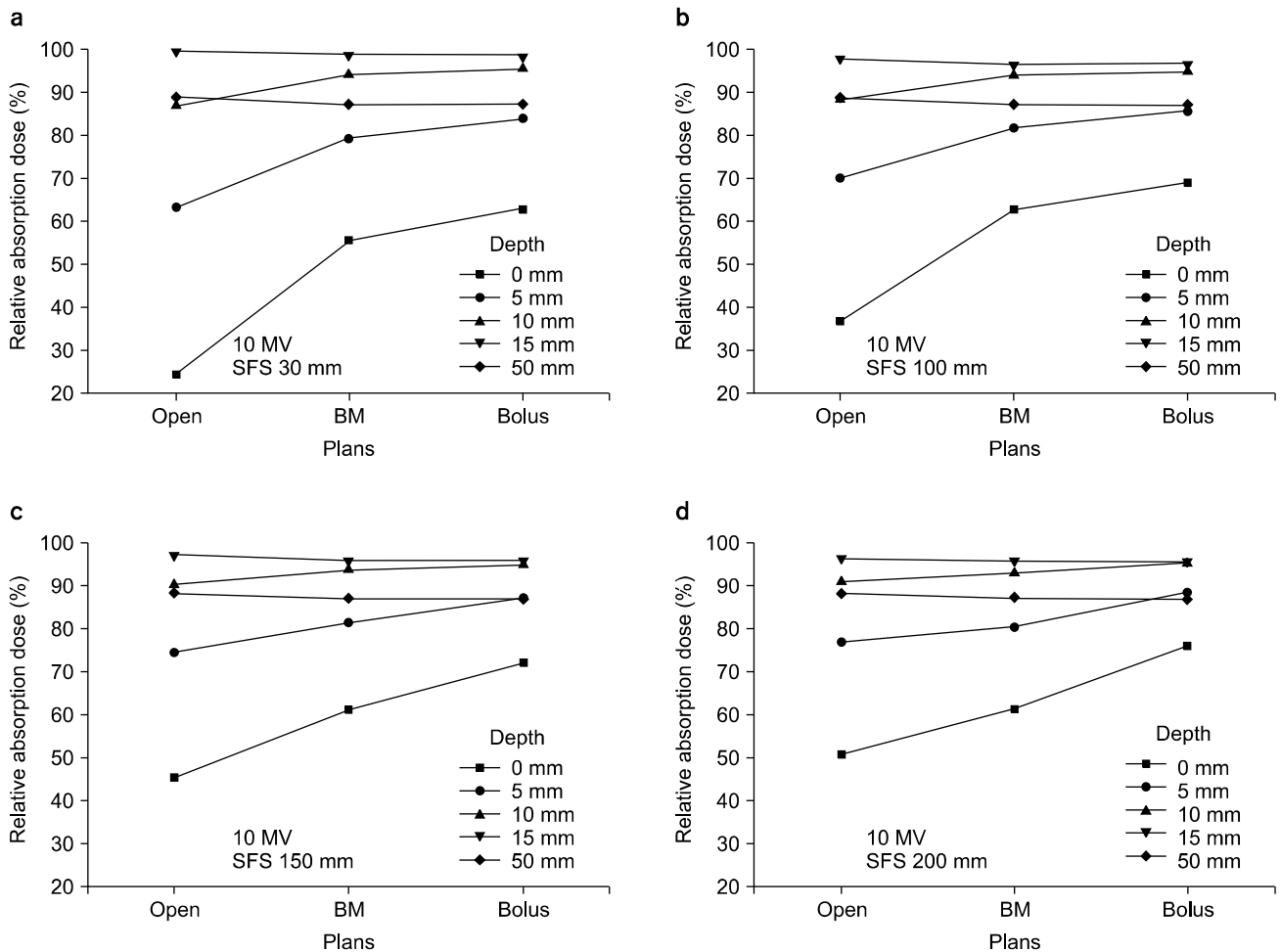
Fig. 8. Relative absorption doses at different depths (0, 5, 10, 15, and 50 mm) and for different SFSs ((a) 30, (b) 100, (c) 150, and (d) 200 mm), for the 10-MV photon beam in a radiation treatment planning system (RTPS).

in different RTP scenarios: open, BM, bolus. For the SFS of 100 mm, RAD increased by 26.1% and 32.3% at a 0 mm depth for the BM and bolus plans, respectively, compared with the open plan. The rates of RAD increase were 11.6% and 15.7% at a 5 mm depth for the BM and bolus plans, respectively. At a depth of 10 mm, the rates of RAD increase were 5.3% and 6.1% for the BM and bolus plans, respectively. The effect on the RAD rate increase was negligible for depths increasing beyond 15 mm compared with the effect for depths less than 10 mm. Trends similar to that for the SFS of 100 mm were observed for the SFSs of 30, 150, and 200 mm.

Discussion

For treatments of near surface tumors, a bolus is placed on the surface for increasing the surface dose. Because a bolus is only effective within a limited range of bolus-surface distances, positioning the bolus requires care on the part of the radiation therapist for accurate dose delivery to the surface.[7] In this study, the applied BM did not have to be placed on the patient's body. The surface dose depends on the photon beam energy, field size, beam modification devices, SSD, and angle of incidence.[7,8] These factors also depend on the electron contamination from the flattening filter, beam modifiers, and air. The results in Fig. 4 show decreasing build-up region size with increasing BM thickness. It is commonly known that all X-rays used in radiotherapy are contaminated by secondary electrons. These secondary electrons are generated by interactions between materials, such as gantry head parts and photons in the beam's path.[1] It has been reported by Johns and Cunningham

et al.[11] that photons interact with matter by photoelectric, Compton, or pair production processes. According to their study, the photoelectric effect, the Compton effect, and the pair production contribute 0%, 94%, and 6%, respectively, to the photon-matter interaction for photon beams with energies ranging from 4 MV to 10 MV. In Fig. 4a and b, a decrease in the build-up region size (or an increase in the surface dose) resulted from the Compton effect, which constituted the main interaction between the collimator, the BM, the water phantom, and the primary photon beam in the X-ray path. As the area irradiated by the photon beam increased, the probability of an absorption dose receiving the effect of the scatter dose increased. Therefore, as the SFS increased, the amount of contamination resulting from the secondary electrons scattered owing to the Compton effect increased as well, and this effect is deemed to decrease the build-up region size and increase the surface dose.

The results in Fig. 5a imply that, when the BM was used, the BM could increase the surface dose from a minimum of 8.3% to a maximum of 12% for a 30 mm SFS, while the surface dose was increased from 33.1% to 65.7% for a 200 mm SFS. In addition, the effect of increasing the surface dose for the SFSs of 4, 6, 8, 10, 12, and 15 mm resulted in the increments of 12%~17%, 20%~35%, 28%~53%, 30%~61%, and 32%~63%, respectively. This implies that a greater contamination of secondary electrons occurs for a greater BM thickness, which thereby increases the surface dose. A trend similar to that in Fig. 5a is seen in Fig. 5b. The surface dose increases by the calculated S_{BM} were 16%~32%, 18%~45%, 29%~68%, 31%~82%, 39%~96%, 38%~101%, and 38%~100% for the corresponding SFSs. In Fig. 5, for the SFS values ranging from 30 to 100 mm, the S_{BM} increased from a minimum of 19% to a maximum of 64%. The rate of increase was saturated to produce less than 1% for the SFS above 120 mm. The S_{BM} saturation did not result in the reduction in the number of scattered secondary electrons. When the SFS increased, the generation of total scattered secondary electrons also increased for the SFS above 120 mm, but the number of scattered secondary electrons reaching a particular part or point (the measurement point) became constant. Consequently, the S_{BM} appeared to be saturated.[12]

The results in Fig. 6 imply that, when the BM thickness increased, the S_{BM} did not increase proportionally, but instead exhibited a uniform S_{BM} beyond a certain thickness. The number of generated secondary electrons increased proportionally as the BM thickness increased. However, it was thought that the S_{BM} saturated above a certain thickness because secondary electrons that scattered at the BM top failed to acquire sufficient energy for reaching the measurement point. For the 10-MV photon beam, the slope in region B did not saturate. It was thought that the slope of the 10-MV beam in region B increased modestly because the transmission was higher for the 10-MV photon beam than for the 6-MV photon beam. We presume that S_{BM} saturation will be achieved at the point at which the BM thickness exceeds 100 mm.

The results in Fig. 7 and 8 demonstrated the RADs difference between the BM application and bolus application RTPS plans. The surface dose increase for BM application plans was smaller than that for bolus application plans compared with open plans. Although the surface dose increases for the BM application plans were smaller than those for the bolus application plans, the RAD increase rate on the surface was up to 28.5% compared with that of the open plan. For the bolus application plans, the RAD increase rate on the surface was up to 37.3%. As a result, the BM approximately yielded 76% of the bolus efficiency. The bolus material is often placed on a patient's skin during radiotherapy for producing a uniform dose distribution. However, due to insufficient malleability of bolus material, small air gaps can be generated.[8] The BM loaded on the head of a linear accelerator does not need to be in contact with the patient's skin. There is also an air gap between the BM and the skin, but it is possible to obtain an accurate dose distribution compared to the air gap of bolus generated randomly, because the measured beam parameters through the BM are entered in RTPS.

Conclusion

We evaluated the effect of scatter in the build-up region using a handmade BM. The S_{BM} increased both with increasing BM thickness and increasing SFS. Consequently, the BM decreased the build-up region size and increased the surface dose. However, the BM scatter did not increase over a specific BM thickness and SFS, exhibiting saturation. Although the surface

dose associated with the BM application plan was smaller than that associated with the bolus application plan, the BM yielded 76% of the bolus efficiency. We expect BMs to become a useful devices for deep-set patient body parts to which it is difficult to apply a bolus.

References

1. Khan FM: The Physics of Radiation Therapy. 5th ed, Williams & Wilkins, Baltimore, MD (2013), pp. 61-70, pp. 133-141, pp. 241-244
2. Chu JCH, Coia LR, Aziz D, et al: Dose to superficial node for patients with head and neck cancer treated with 6 MV and 60 Co photons. Radiother Oncol 21(4):257-260 (1991)
3. Niroomand-Rad A, Javedan K, Rodgers JE, Harter KW, et al: Effects of beam spoiler on radiation dose for head and neck irradiation with 10 MV photon beam. Int J Radiat Oncol Biol Phys 37(4):935-940 (1997)
4. Klein EE, Michalet-Lorenz M, Taylor M.E, et al: Use of a Lucite beam spoiler for high-energy breast irradiation. Med Dosim 20(Summer (2)):89-94 (1995)
5. Lief EP, Hunt MA, Hong LX, Amols HI, et al: Radiation therapy of large intact breasts using a beam spoiler or photons with mixed energies. Med Dosim 32(Winter (4)):246-253 (2007).
6. Hatice B, Aydın C, Murat O, Hilal A, et al: Surface dose measurements with GafChromic film for 6 and 18 MV photon beams. Phys Med 25:101-104 (2009)
7. Khan Y, Eduardo J, Udowicz, et al: Clinical and Dosimetric Implications of Air Gaps between Bolus and Skin Surface during Radiation Therapy. Journal of Cancer Therapy 4: 1251-1255 (2013)
8. Butson J, Cheung T, Yu P, et al: Effects on skin dose from unwanted air gaps under bolus in photon beam radiotherapy. Radiation Measurements 32: 201-204 (1999)
9. Sroka M, Regula J, Lobodziec W, et al: The influence of the bolus-surface distance on the dose distribution in the build-up region. Repo Practi Oncol And Radiother 15: 161-164 (2010)
10. Holt JG, Laughlin JS, Moroney JP, et al: The extension of the concept of tissue-air-ratios (TAR) to high-energy X-ray beams. Radiology 96:437-446 (1970)
11. Johns HE, Cunningham JR: The Physics of Radiology. 4rd ed. Springfield, IL (1983)
12. McKerracher C, Thwaites DI, et al: Phantom scatter factors for small MV photon fields. Radiotherapy and Oncology 86: 272-275 (2008)

Bolus를 대체하기 위해 자체 제작된 선량상승영역 변환기를 투과한 광자선의 특성

*경북대학교병원 방사선종양학과, [†]경북대학교 의학전문대학원 방사선종양학교실

김성준* · 이승준* · 문수호* · 설기호[†] · 이정은[†]

본 논문에서는 자체 제작된 선량상승영역 변환기(build-up modifier, BM)을 투과하는 high energy photon beam의 심부선량백분율(PDD)을 특성을 측정하고 이 결과를 토대로 BM 산란인자(BM scatter factor, S_{BM})를 계산하였다. 다양한 조건에서 BM scatter가 PDD의 Build-up region에 미치는 영향을 평가하고 BM의 유용성을 알아보는 것이 본 연구의 목적이다. S_{BM}는 BM을 사용하지 않은 SFS 30 mm에서 측정된 산란인자의 값을 1로서 정규화 하였다. 가장 큰 SFS 200 mm의 경우, 6 MV 광자선을 사용할 때 S_{BM}는 두께에 따라 각각 1.331, 1.519, 1.598, 1.641, 그리고 1.657이었다. 10 MV 광자선에는 각각 1.384, 1.662, 1.825, 1.913, 그리고 2.001이었다. BM의 효과는 bolus의 최대 76% 효율을 가지는 것으로 나타났다. Bolus를 밀착시키기 어려운 특정적 부위에 대해 BM은 그 대안으로써 효과적인 장치가 될 수 있을 것으로 기대된다.

중심단어: 선량상승영역 변환기(BM), BM 산란인자(S_{BM}), 심부선량백분율(PDD), 표면선량