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이 논문을 의학 박사 학위논문으로 제출함

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# Reduction of superficial radiation dose with bolus in passive scattering proton beam therapy

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**Purpose**

In passive scattering proton beam therapy, scattered protons from the snout and aperture increase the superficial dose, however treatment planning systems (TPSs) based on analytic algorithms (such as Proton Convolution Superposition) are often inaccurate in this aspect. This additional dose can cause permanent alopecia or severe radiation dermatitis. This study aimed to evaluate the effect of bolus on the superficial radiation dose in passive scattering proton beam therapy.

**Methods**

We drew a clinical target volume (CTV) and a scalp-p (phantom), and created plans using a TPS for a solid water phantom with and without bolus. We calculated the dose distribution in the established plans independently with Monte Carlo (MC) simulation and measured the actual dose distribution with an array of ion chambers and radiochromic films. To assess the clinical impact of bolus on scalp dose, we conducted independent dose verification using MC simulation in a clinical case.

**Results**

In the solid water phantom without bolus, the calculated scalp-p volume receiving 190 cGy was 20% with TPS but 80% with MC simulation when the CTV received 200

cGy. With 2 cm bolus, this decreased from 80% to 10% in MC simulation. With the measurements, average superficial dose to the scalp-p was reduced by 5.2% when 2 cm bolus was applied. In the clinical case, the scalp-c (clinical) volume receiving 3000 cGy decreased from 74% to 63% when 2 cm bolus was applied.

**Conclusion**

This study revealed that bolus can reduce radiation dose at the superficial body area and alleviate toxicity in passive scattering proton beam therapy.

**Keywords : Proton therapy, Monte Carlo, Scattered protons, Bolus, Scalp**
**Student Number : 2011-30539**

# 목차

# 1. Introduction

It is well known that treatment planning systems (TPSs) based on analytic algorithms (such as Proton Convolution Superposition) have limitations on dose calculations in proton beam therapy (1). It is also known scattered protons from the snout and aperture have dosimetric impact (2,3). A previous study (4) revealed that these scattered protons could increase the entrance dose in clinical practice, but commonly used TPSs do not accurately calculate this dose.

A range compensator tailors the beam, stopping distribution, and enables the dose to conform to the distal shape of the target volume (5). A previous study showed the dose from scattered protons can be reduced with a thicker range compensator (4). However, a thicker range compensator increases the risk of collision and uncertainty in dose calculation.

Bolus is often used in electron beam therapy to flatten out irregular surfaces, reduce electron penetration in parts of the field, or increase surface dose. Ideally, bolus material is equivalent to tissue in relative stopping and scattering power (5). We hypothesized that applying bolus on the body surface instead of a thicker range compensator could also reduce the superficial dose from scattered protons. This study aimed to evaluate the effect of bolus on the superficial radiation dose in passive scattering proton beam therapy.

# 2. Methods

## 2.A. Treatment plan

We created virtual treatment plans with a TPS (Eclipse 13.7, Varian) using the Proton Convolution Superposition algorithm (6) based on computerized tomography (CT) images of a solid water phantom (SP34, IBA) with and without bolus (Radiation Oncology Material, Republic of Korea). The relative proton stopping powers were measured using a multilayer ionization chamber (Zebra, IBA) as 1.03 and 0.95 for the solid water phantom and bolus, respectively. We drew a clinical target volume (CTV) in the shape of an upside-down three-tiered cake with 4, 3, and 2 cm radii and 2 cm depth for each tier. This CTV was placed at a depth of 1 cm from the surface. We

defined a superficial volume 2 cm in radius and 5 mm in depth as the “scalp-p (phantom)” (Fig. 1). The aperture and range compensator were designed to cover the CTV taking into consideration the snout size (10 cm diameter), milling compensation (1.2 cm drill bit), and minimum thickness of the range compensator (2 mm). The area corresponding to the scalp-p in the range compensator was the thinnest area. The distance from the end of the range compensator to the top of the solid water phantom was fixed at 8.5 cm. The plans were normalized to deliver 200 cGy to a minimum of 95% of the CTV. The range of the proton beam was adjusted to cover the CTV. The plan was evaluated using a dose distribution and a dose-volume histogram (DVH). The DVH is a plot of the volume (Y-axis, %) of a given structure receiving a certain dose or higher, as a function of dose (X-axis, cGy) (5).

## 2.B. Dose verification based on MC simulation

MC simulations generally exhibit more accurate dose calculations than TPSs in proton therapy because they consider all the components in the beam pathway, such as the range modulator, collimators, snout, aperture, and range compensator, whereas TPSs consider them in a limited way. In previous studies (7,8), a MC simulation system based on a particle simulation tool (TOPAS) (9) for passive scattering proton therapy was developed and validated for independent dose verification of treatment plans. In this study, we used that MC simulation system to conducted MC simulation for each treatment plan, and the results were imported into the TPS for comparison and analysis. The imported dose was normalized to the dose at the middle of the spread-out Bragg peak.

## 2.C. Measurement of superficial dose

To verify the effect of bolus on the superficial dose, we measured the dose distribution in the solid water phantom with an array of ion chambers (MatriXX, IBA) and radiochromic films (EBT3, GaFchromic) using the IBA proton therapy machine at our center. The used MatriXX was calibrated using a farmer-type ionization chamber (Farmer chamber model 30013, PTW Freiburg) considering relative biological effectiveness of 1.1 for protons. The measurement was performed at 4 mm depth in

consideration of the equivalent thickness of the MatriXX and dimensions of the scalp-p. The aperture and range compensator, composed of brass and poly methyl methacrylate (PMMA), respectively, were manufactured as indicated in the plan and mounted to the snout. The irradiated films were scanned and radiation doses were determined using the RIT software (Radiological Imaging Technology, Inc., Colorado Springs, CO, USA) with calibration curves previously determined using a farmer-type ionization chamber (Farmer chamber model 30013, PTW Freiburg).

The TPS and MC calculated 2D dose distributions were imported to the MatriXX operating software (OmniPro-ImRT, IBA). The TPS and MC calculated and measured dose distributions were interpolated using 1 mm spacing and aligned to match the center. The converted dose distributions were compared in orthogonal profiles and 2D gamma index analysis.

Gamma index analysis is widely adopted for patient-specific quality assurance to evaluate agreement between calculated and measured dose distributions by utilizing the percent dose difference and distance to agreement (DTA) (10). In this study, we conducted gamma index analysis to evaluate the difference in doses measured using MatriXX with and without bolus. For this purpose, the DTA was fixed at a minimum (1 mm), and the gamma index analysis was repeated with varying dose difference criteria.

## 2.D. Simulation in a clinical case

To assess the clinical impact of bolus on scalp dose, we performed MC simulation in a clinical patient who had been treated at our center without bolus. The patient was a 37-year-old female with WHO grade III, MGMT methylation (+) anaplastic astrocytoma at the right frontal lobe. She underwent subtotal tumor removal and received postoperative proton beam therapy (6000 cGy in 25 fractions) with temozolomide. We drew a “scalp-c (clinical)” as a 5 mm deep superficial volume where the proton beam entered. For the Hounsfield unit (HU)-assigned bolus contour in the MC simulation, we created virtual CT images from the original CT images using in-house software. The software recognized bolus contour and filled the inside of the contour with the assigned HU value. Finally, parts of the original CT images were overwritten with these filled contour images. The MC simulation was conducted using

these virtual CT images. Normalization in the MC simulation was adjusted so that 100% of the prescribed dose covered 95% of the CTV.

# 3. Results

## 3.A. MC simulation

### 3.A.1. Difference between TPS and MC calculated dose

We compared the TPS and MC calculated scalp-p dose for the plan without bolus. The calculated scalp-p volume receiving 190 cGy was 20% with TPS but 80% with MC simulation [Fig. 2(a)]. The differences between the TPS and MC calculated dose received by 50% and 5% of the scalp-p volume (D50% and D5%) were 5 and 15 cGy, respectively. These dose differences are thought to be due to the limitations of the TPS analytical algorithm. In particular, the additional dose due to scattered protons from the snout and aperture is not included in the TPS calculation.

### 3.A.2. MC simulation of bolus effect

To demonstrate the effect of bolus on superficial dose, we compared MC simulation results from plans with and without bolus. The scalp-p volume receiving 190 cGy decreased from 80% without bolus to 30% with 1 cm bolus [Fig. 2(b)]. The differences between no bolus and 1 cm bolus D50% and D5% were both 5 cGy. When bolus thickness was increased from 1 to 2 cm, the scalp-p dose reduction was more prominent. The scalp-p volume receiving 190 cGy was 10% with 2 cm bolus [Fig. 2(c)]. The difference between no bolus and 2 cm bolus D50% and D5% were both 10 cGy. These results indicate that bolus reduced the scalp-p dose and this effect was greater with 2 cm bolus than 1 cm.

### 3.A.3. Comparison of TPS and MC calculations with bolus

With 2 cm bolus, the effect of scattered protons was reduced, which also reduced the difference between the TPS and MC calculations (Supplementary Fig. 1).

The remaining difference was thought to be due to the limitations of the TPS calculation, mainly the differences in the calculation of the scattering at the edge of the compensator.

## 3.B. Verification with measurements

### 3.B.1 Comparison of TPS and MC calculations and measurements

To verify the reduction in superficial dose due to bolus, we compared TPS and MC calculated dose distributions with those measured using MatriXX and films. Figure 3 presents the TPS vs. MC vs. MatriXX vs. film scalp-p doses for the no bolus, 1 cm bolus, 2 cm bolus, 1 cm bolus with 1 cm air gap, and 1 cm bolus with 2 cm air gap treatment plans. When the lower spatial resolution (7 mm) of MatriXX was considered, the doses from the MC simulation and those measured using MatriXX and film were consistent with each other for all plans.

However, the TPS calculated scalp-p dose without bolus was smaller than the others by about 2.7% [Fig. 3(a)]. This was because the scattered protons from the snout and aperture were not included in the TPS analytical algorithm. With an air gap, the TPS calculated scalp-p dose was also smaller than the others [Fig. 3(d) and 3(e)]. This was considered to be due to the limitation in the TPS dose calculation with an air gap.

### 3.B.2. 2D analysis of measured dose distribution

We conducted a 2D gamma index analysis using MatriXX to evaluate how bolus affected the measured scalp-p dose. For this purpose, the DTA was fixed at a minimum (1 mm), and the region of interest (ROI) was set at the central 4 × 4 cm area to exclude the difference in the lateral penumbra [Fig. 4(a)]. The red area in the figure indicates the area that did not satisfy the criteria. Table 1 presents the MatriXX measurement accordance rates on gamma analysis for various criteria; (1) 3% and 1 mm, (2) 2% and 1 mm, and (3) 1% and 1 mm. Accordance between scalp-p dose with no bolus and 2 cm bolus was only 20.15%, even with 3% and 1 mm criteria, meaning the dose difference in the ROI exceeded 3%. In the beam profile, the average dose in the ROI was reduced by 5.2% with 2 cm bolus [Fig. 4(b)]. The dose difference in the

ROI between no bolus and 1 cm bolus was about 2.6%, and the accordance rate, depending on the dose criteria (3% and 2%), accurately reflected this dose difference.

## 3.C. Effect of an air gap

### 3.C.1. Difference between TPS and MC calculated dose

When applying bolus to an irregular surface, such the ear, there can be an air gap between bolus and body surface. Therefore, we simulated this condition with our bolus and solid water phantom. With a 1 cm air gap between bolus and solid water phantom, the calculated scalp-p volume receiving 190 cGy was 0% with TPS and 30% with MC simulation [Supplementary Fig. 2(a)]. The differences between the TPS and MC calculated D50% and D5% were 5 and 10 cGy, respectively. This might be due to inaccurate TPS dose calculation caused by the air gap between bolus and solid water phantom.

In the MC simulation, dose reduction by bolus was not compromised by the air gap. There was no difference in the scalp-p dose with or without the air gap in the MC simulation [Supplementary Fig. 2(b)].

### 3.C.2. Verification with measured results

To verify the measurements, the measured dose in the plans with and without bolus were compared. Even with a 3% and 1 mm threshold, the accordance rate on gamma analysis was almost 100% between 1 cm bolus vs. 1 cm bolus with an air gap (Table 1). Thus, we can assume that the air gap did not affect the scalp-p dose.

## 3.D. Simulation in a clinical case

### 3.D.1. Difference between the TPS and MC calculated dose

The dose distribution and DVH with no bolus are presented in Fig. 5(a). The calculated scalp-c volume receiving 3000 cGy was 58% with TPS and 74% with MC simulation. This finding is consistent with the previously mentioned limitations of the

TPS calculation.

### 3.D.2. MC simulation of bolus effect

The dose distribution and the DVH with 2 cm bolus are presented in Fig. 5(b). The scalp-c volume receiving 3000 cGy decreased from 74% to 63%. With 1 cm bolus, the scalp-c volume receiving 3000 cGy was 65% [Supplementary Fig. 3(a)]. The scalp-c dose decreased when bolus thickness was increased from 1 to 2 cm [Supplementary Fig. 3(b)]. These findings are in line with those from the solid water phantom.

In Fig. 5(b), the scalp-c DVH curves with no bolus and 2 cm bolus crossover at two points, at 2200 cGy and 4600 cGy. The first crossover at 2200 cGy is because of the reduction of scattered protons by the 2 cm bolus. A portion of the volume which received a high dose due to scattered protons with no bolus shifted to receiving a low dose with 2 cm bolus. The second crossover at 4600 cGy is not easy to explain. It may have been due to the forced normalization. Another explanation is that scattered protons with low energy were absorbed by the scalp-c when 2 cm bolus was applied, resulting in a higher dose, whereas when the scalp was exposed to the air, these scattered protons with low energy were not absorbed. In Supplementary Fig. 3(b), there is no crossover at high dose with 1 cm and 2 cm bolus, which suggests that there was no difference between 1 cm and 2 cm bolus in terms of absorption of scattered protons with low energy.

## 3.E. MC simulation of snout size effect

To demonstrate the effect of snout size on superficial dose, we compared MC simulation results from plans with different snout sizes: 100 mm, 180 mm, and 250 mm. The scalp-p volume receiving 190 cGy decreased from 75% with the 100 mm snout to 15% with the 180 mm snout [Supplementary Fig. 4(a)]. The difference between the 100 mm and 180 mm snout D50% was 10 cGy. When the snout size increased from 180 mm to 250 mm, the scalp-p dose reduction effect was slightly greater [Supplementary Fig. 4(b and c)]. This phenomenon was due to the lowering of the density of scattered protons delivered to the scalp-p volume when a broader snout was applied.

# 4. Discussion

The present study was designed to determine whether bolus applied on the body surface could reduce the superficial radiation dose from scattered protons in passive scattering proton beam therapy. The results of our study confirm this hypothesis. To our knowledge, this is a novel finding with great clinical impact.

Permanent alopecia can be a critical toxicity that hinders the return to society for pediatric and young adult patients after cancer treatment. In our simulation in a clinical case, 2 cm bolus reduced the scalp-c volume receiving 3000 cGy by 11%. Considering that permanent alopecia may be correlated with dose exposure of 3000 cGy in combination with conventional chemotherapy (11), bolus can reduce permanent alopecia in patients receiving passive scattering proton beam therapy. Another patient population in which superficial dose reduction is important is breast cancer patients with recurrent internal mammary lymph nodes after postoperative radiation. In these patients, proton beam therapy is a good option for re-irradiation which spares the heart and lung from radiation. With bolus, we can also reduce the superficial dose.

The use of multiple beam-angle arrangements is widely adopted to reduce superficial radiation dose. However, it takes more time to treat patients with multiple beams. Another solution is to use a broader snout, but, like using a thicker range compensator, this requires excessive material use and increases collision risk. For small targets, applying bolus is the easiest way to reduce superficial dose.

A previous study evaluated the use of a patient-specific bolus to replace multiple field-specific range compensators during passive scattering proton delivery (12). It showed dosimetric equivalency between the range compensator and bolus plans. Another study found a patient-specific bolus reduced the mean dose to all at-risk organs compared with the snout and nozzle-mounted range shifter in intensity-modulated proton therapy of superficial lesions (13). However, neither study evaluated the superficial dose with bolus.

When the thickness of a range compensator increased, the range of proton beam also increased to cover the same target volume. When a proton beam of higher energy is used, the directional nature of the proton beam is intensified in the forward

direction which can lead to reduced scattering at the snout and aperture (4). Applying of bolus could also reproduce this phenomenon. When we put bolus on the body surface, the range of proton beam needed to be increased to cover the target, thus reducing the scattered protons.

Dose reduction was found to be dependent on range compensator thickness in a previous study which compared a 2 mm-base range compensator with 2 cm-base and 4 cm-base range compensators (4). In our study, the scalp-p dose reduction was more substantial with 2 cm bolus than 1 cm. Future studies should evaluate if there is a ceiling to this effect. However, in practice, it is not easy to apply bolus thicker than 2 cm to the patient due to weight.

In this study, we found that an air gap between bolus and body surface did not affect the superficial dose in the MC simulation, MatriXX, and film, whereas it did in the TPS. The accordance rates (%) on gamma analysis between TPS and MC for criteria of 3% and 3 mm were 93.11%, 95.83%, 98.69%, 90.07%, and 91.83% with no bolus, 1 cm bolus, 2 cm bolus, 1 cm bolus with 1 cm air gap, and 1 cm bolus with 2 cm air gap, respectively. Radiation oncologists should be aware of the limitations of TPS when evaluating plans. It is desirable to reduce the air gap between bolus and the body surface as much as possible to minimize inaccurate TPS dose calculations caused by air gaps. For an irregular body surface, a patient-specific bolus could be made using a 3D printer or moldable bolus. In the current study, we demonstrated that MC simulation is consistent with measured results obtained from MatriXX or film. Therefore, if the proton water equivalent thickness value of a bolus material is known, the dose reduction effect of any kind of bolus can be simulated.

This study has several limitations. First, we could not compare passive scattering to pencil beam scanning (PBS) because MC simulation was only available for passive scattering in our center. However, we observed an excellent dose distribution agreement at the superficial region between TPS calculations and quality assurance measurements for PBS plans. Scattered protons rarely exist in our PBS beam mode because the proton beam is not scattered by nozzle components. If a multileaf collimator or aperture is applied to reduce lateral penumbra in PBS, scattered protons should be considered. Second, we performed MC simulation in only one clinical case. In a future study, we will evaluate more clinical cases and compare passive scattering to PBS in terms of superficial dose received by individual patients. Third, although MC

simulation and measurement showed a definite superficial dose reducing effect with bolus, we need long-term follow-up to determine the clinical impact on patients.

## 5. Conclusion

This study revealed that bolus can reduce the superficial radiation dose and alleviate toxicity in passive scattering proton beam therapy.

## 6. Conflicts of interest

No conflicts of interest.

# References

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Table 1. MatriXX measurement accordance rate (%) on gamma analysis

| | Criteria | | |
|---|---|---|---|
| | 3% and 1 mm | 2% and 1 mm | 1% and 1 mm |
| No bolus vs. 1 cm bolus | 85.70 | 33.64 | 0.00 |
| No bolus vs. 2 cm bolus | 20.15 | 10.80 | 0.00 |
| 1 cm bolus vs. 1 cm bolus with 1 cm air gap | 100.00 | 100.00 | 100.00 |
| 1 cm bolus vs. 1 cm bolus with 2 cm air gap | 100.00 | 100.00 | 97.62 |

**Fig. 1.**

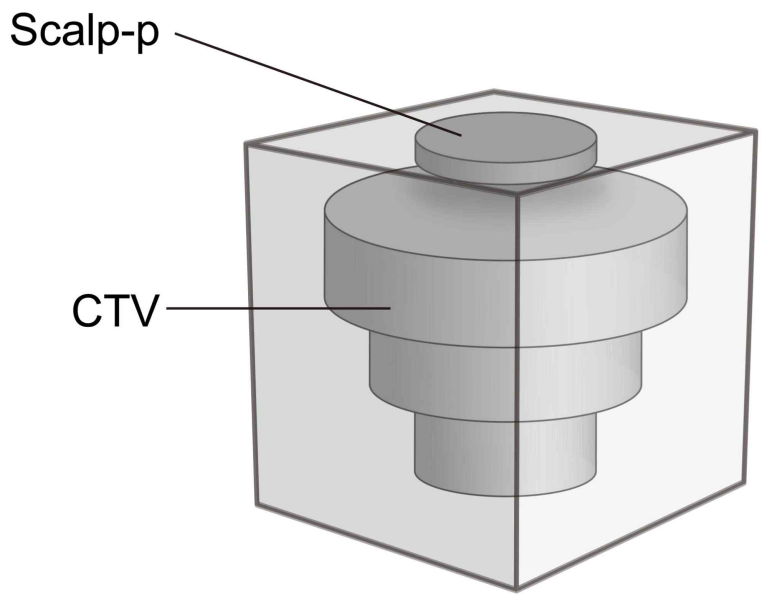



**Fig. 1.** The clinical target volume (CTV) is the shape of an upside-down three-tiered cake with three different radii (4, 3, and 2 cm) and a 2 cm depth for each tier. This CTV was placed at a 1 cm depth from the surface. The scalp-p (dark gray) was defined as the 2 cm radius volume above the CTV with a 5 mm depth from the surface.

**Fig. 2(a)**

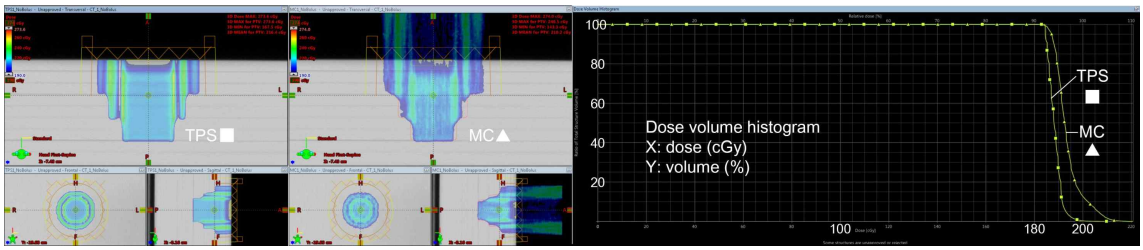



**Fig. 2(b)**

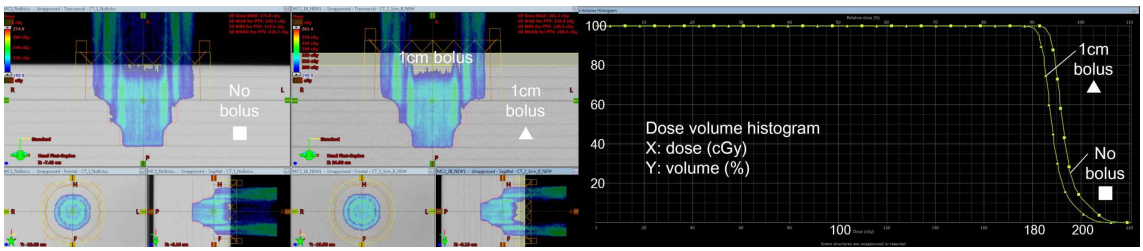



**Fig. 2(c)**

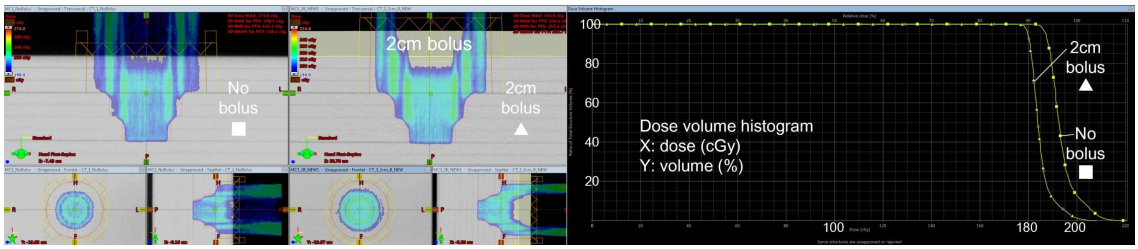



**Fig. 2.** (a) Without bolus, the calculated scalp-p volume receiving 190 cGy was 20% with the treatment planning system (TPS) and 80% with the Monte Carlo (MC) simulation. The dose distribution is presented on the left and dose-volume histogram (DVH) on the right. (b) With 1 cm bolus, the scalp-p volume receiving 190 cGy decreased from 80% to 30%. The dose distribution is presented on the left and DVH on the right. (c) With 2 cm bolus, the scalp-p volume receiving 190 cGy decreased from 80% to 10%. The dose distribution is presented on the left and DVH on the right.

**Fig. 3(a)**

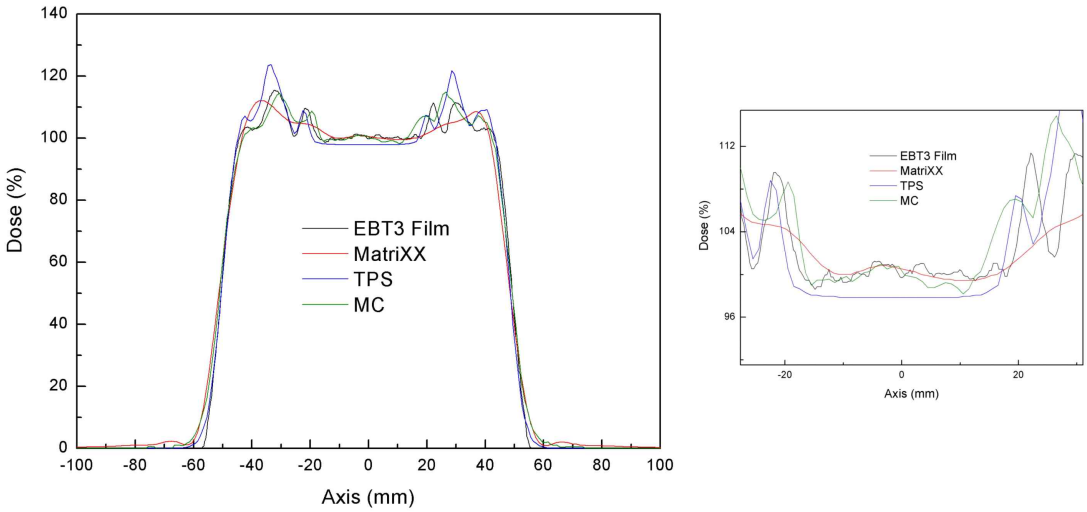



**Fig. 3(b)**

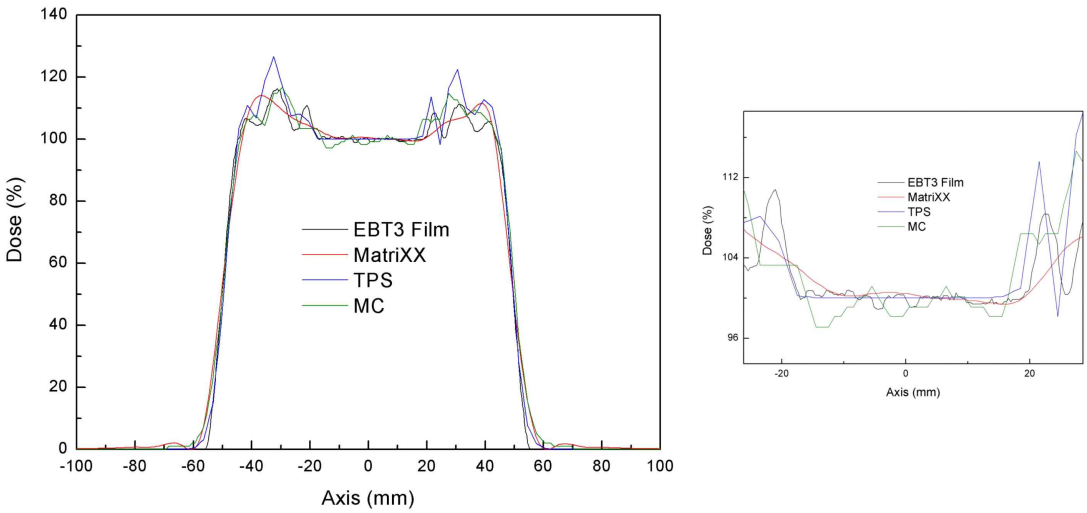



**Fig. 3.** The treatment planning system (TPS) vs. Monte Carlo (MC) simulation vs. MatriXX vs. film scalp-p doses with (a) no bolus, (b) 1 cm bolus.

**Fig. 3(c)**

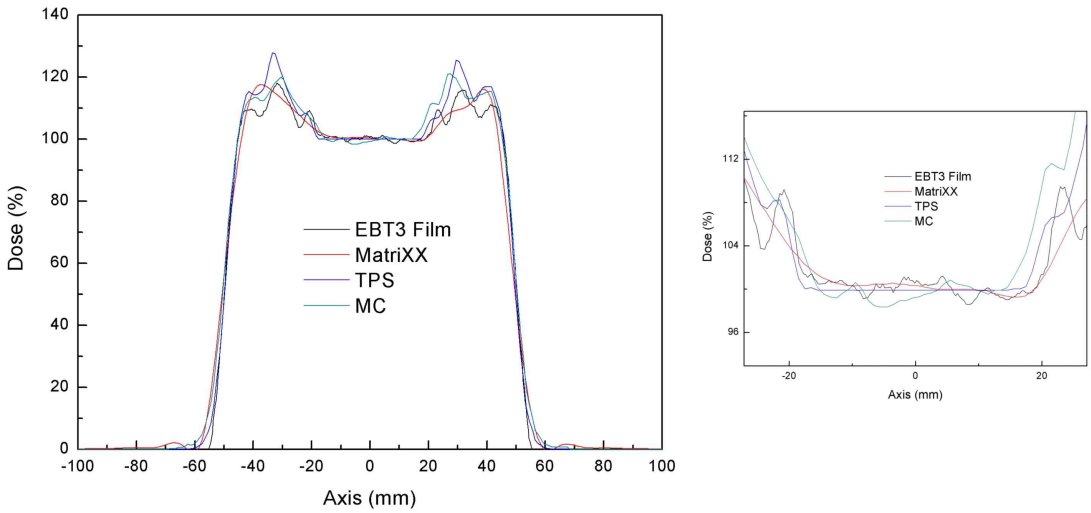



**Fig. 3(d)**

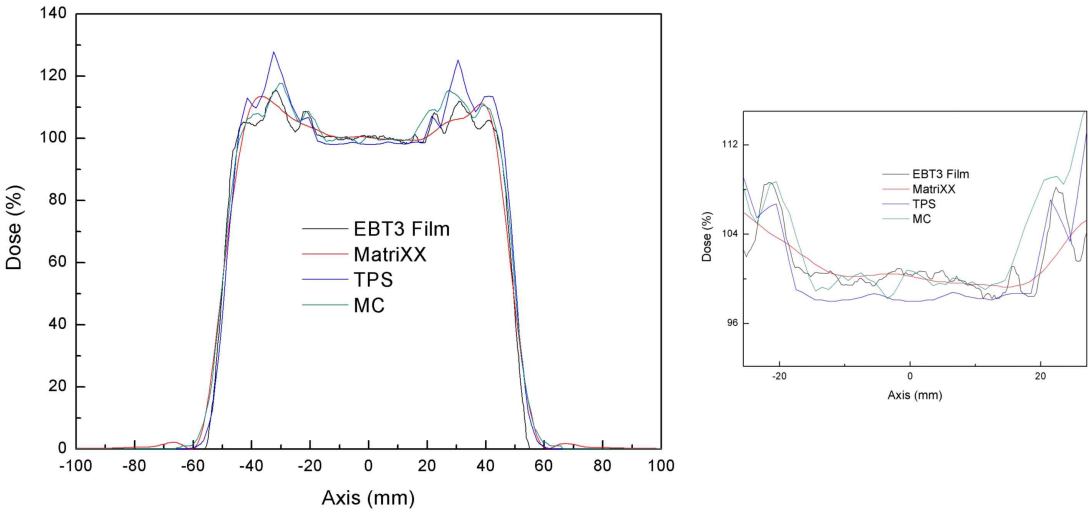



**Fig. 3.** The treatment planning system (TPS) vs. Monte Carlo (MC) simulation vs. MatriXX vs. film scalp-p doses with (c) 2 cm bolus, (d) 1 cm bolus with 1 cm air gap.

**Fig. 3(e)**

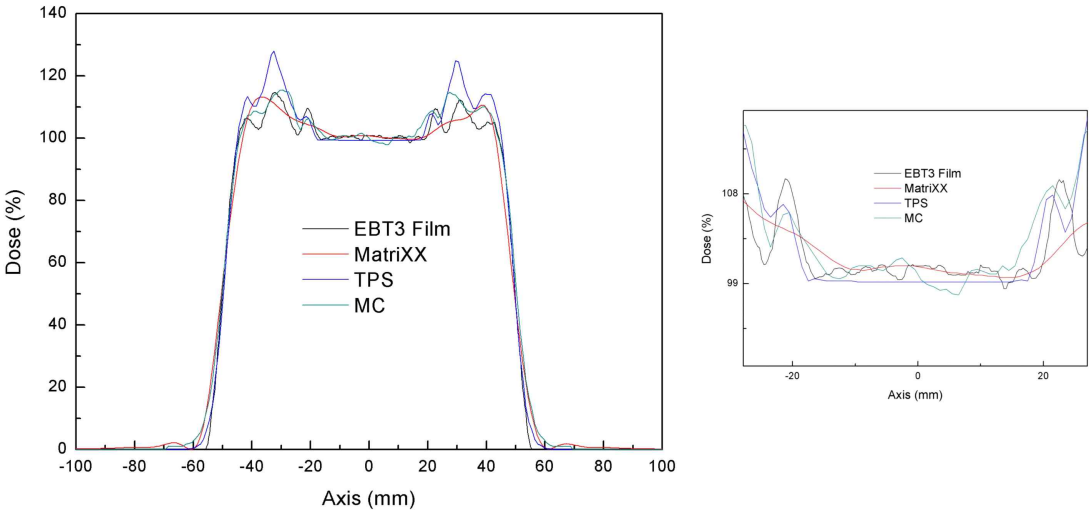



**Fig. 3.** The treatment planning system (TPS) vs. Monte Carlo (MC) simulation vs. MatriXX vs. film scalp-p doses with (e) 1 cm bolus with 2 cm air gap.

**Fig. 4(a)**

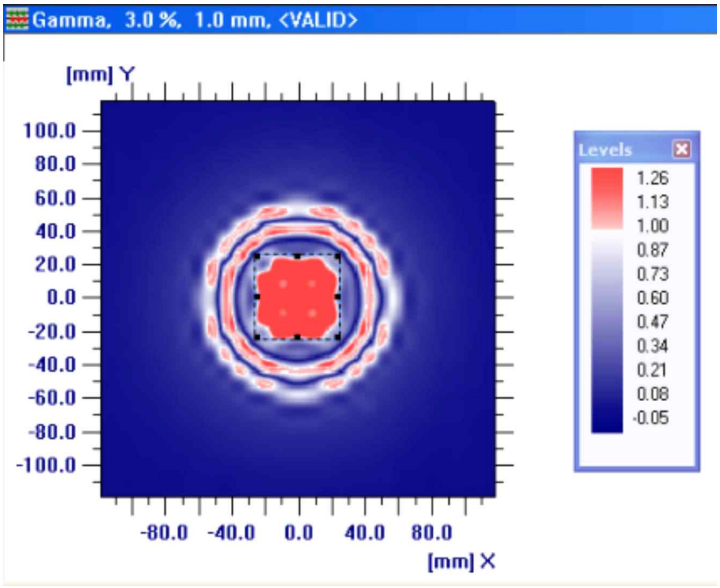



**Fig. 4(b)**

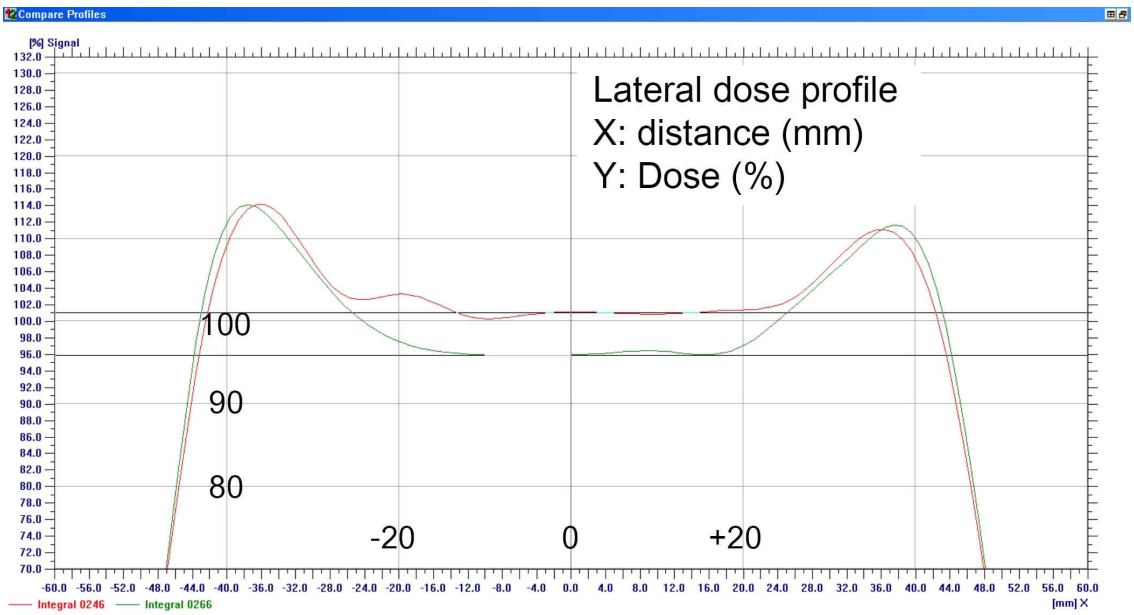



**Fig. 4.** (a) With 2 cm bolus, the accordance rate on gamma analysis was only 20.15% with 3%/1 mm thresholds, compared with no bolus. The red area indicates the area that did not satisfy the criteria. (b) In the lateral dose profile, the relative dose difference between no bolus (red) and 2 cm bolus (green) was 5.2%.

**Fig. 5(a)**

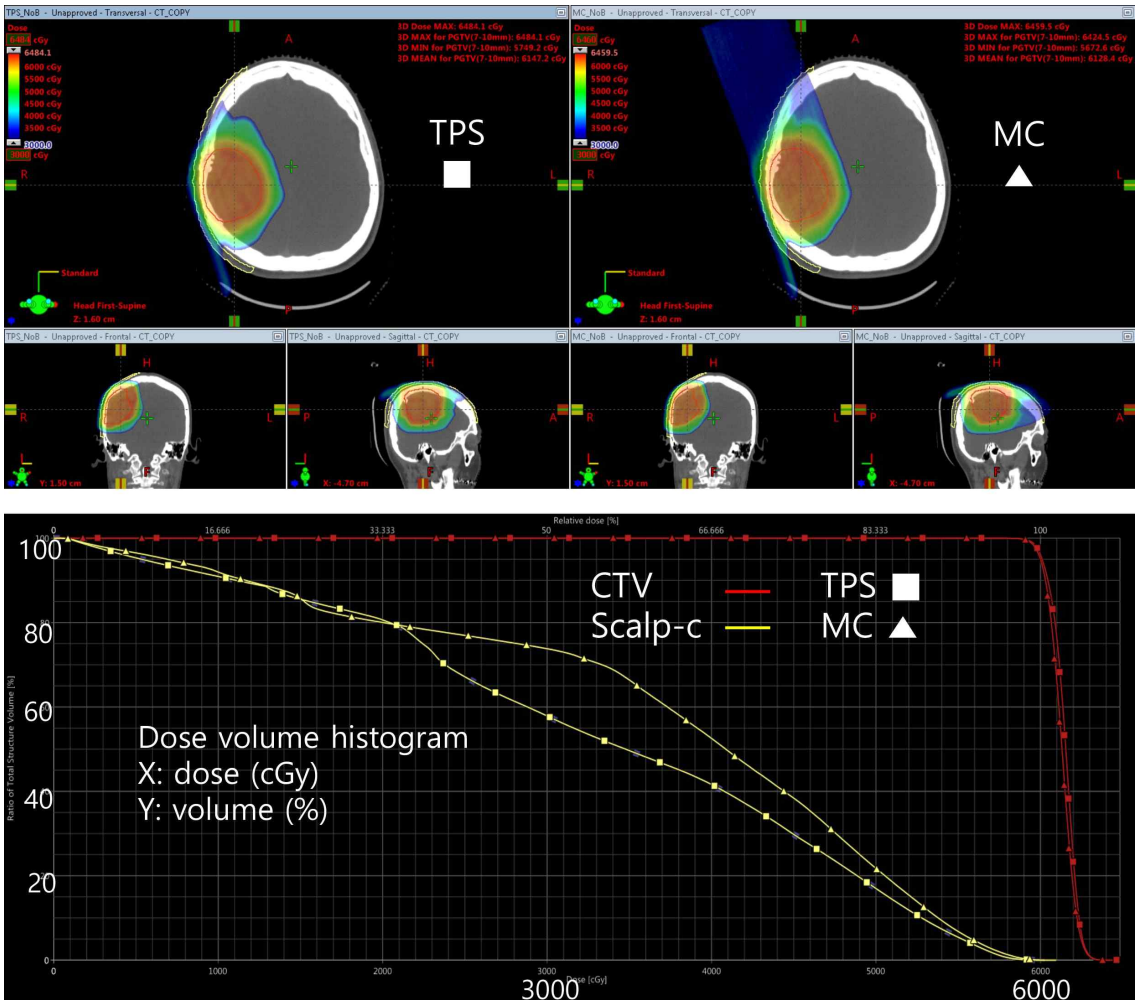



**Fig. 5.** (a) Without bolus, the calculated scalp-c volume receiving 3000 cGy was 58% with the treatment planning system (TPS) and 74% with the Monte Carlo (MC) simulation. The dose distribution is presented on the top and dose-volume histogram (DVH) on the bottom.

**Fig. 5(b)**

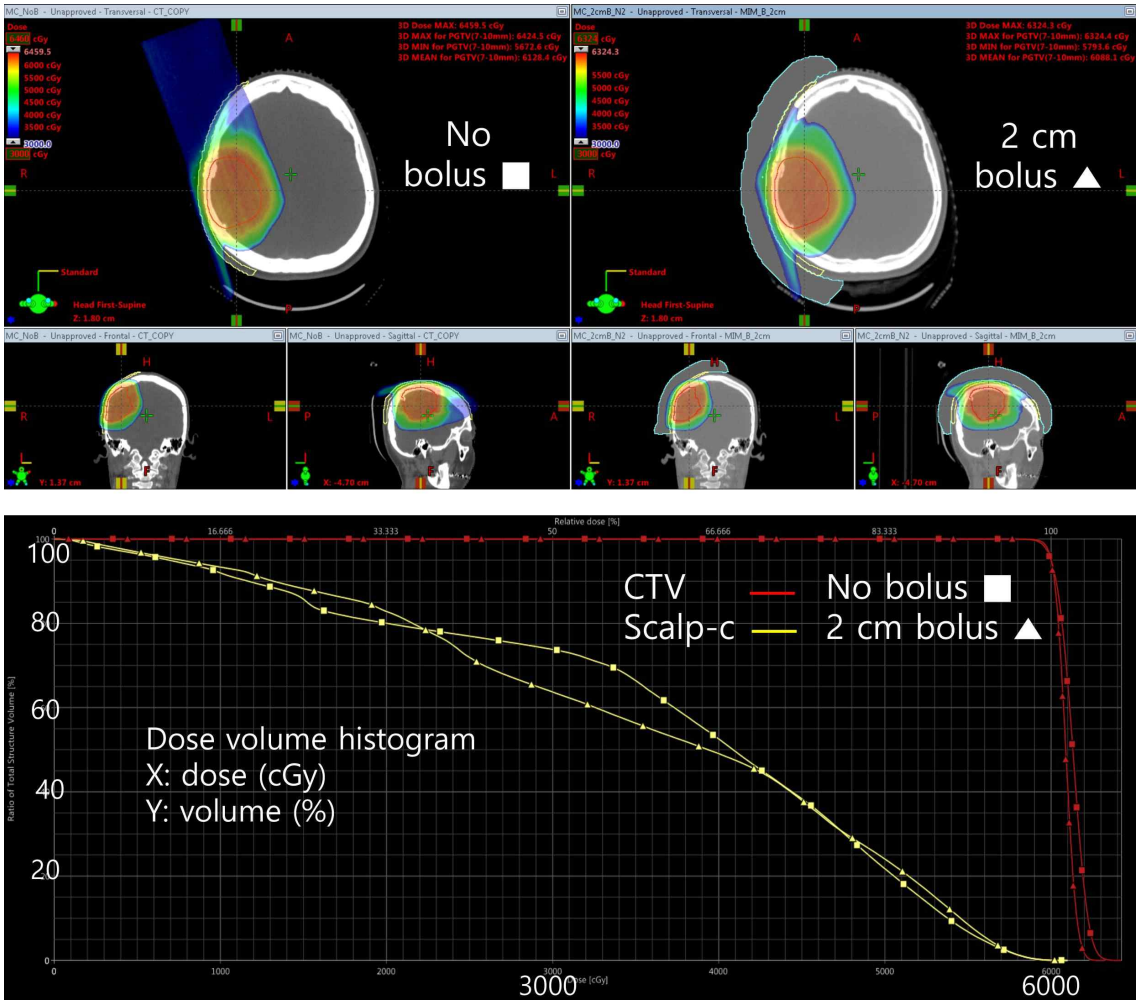
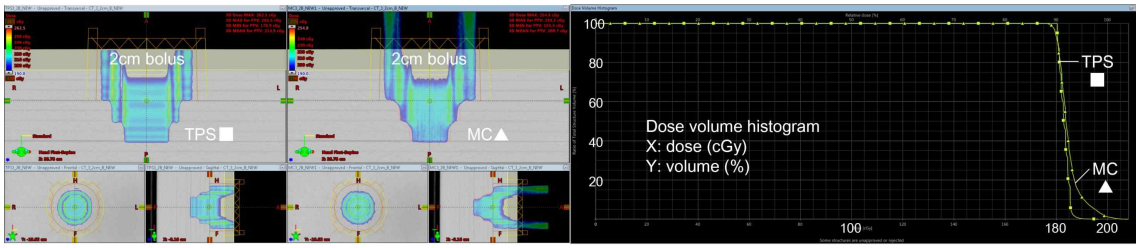


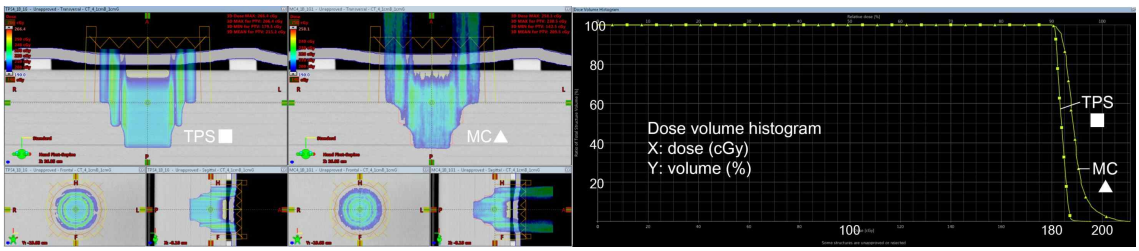

**Fig. 5.** (b) With 2 cm bolus, the scalp-c volume receiving 3000 cGy decreased from 74% to 63%. The dose distribution is presented on the top and DVH on the bottom.

**Supplementary Fig. 1.**

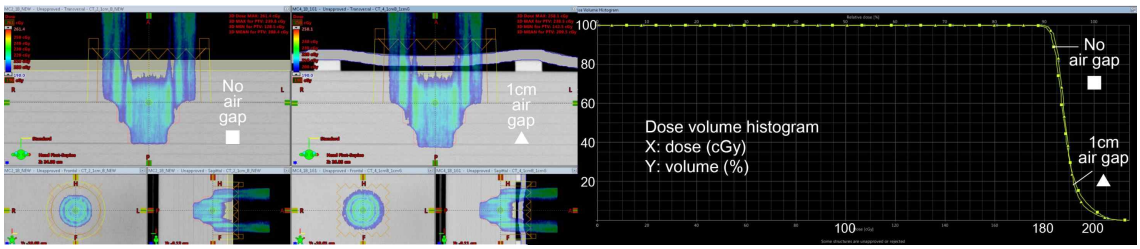



**Supplementary Fig. 1.** With 2 cm bolus, the dose difference between the treatment planning system (TPS) and Monte Carlo (MC) simulation decreased. The dose distribution is presented on the left and dose-volume histogram (DVH) on the right.

**Supplementary Fig. 2**(a)

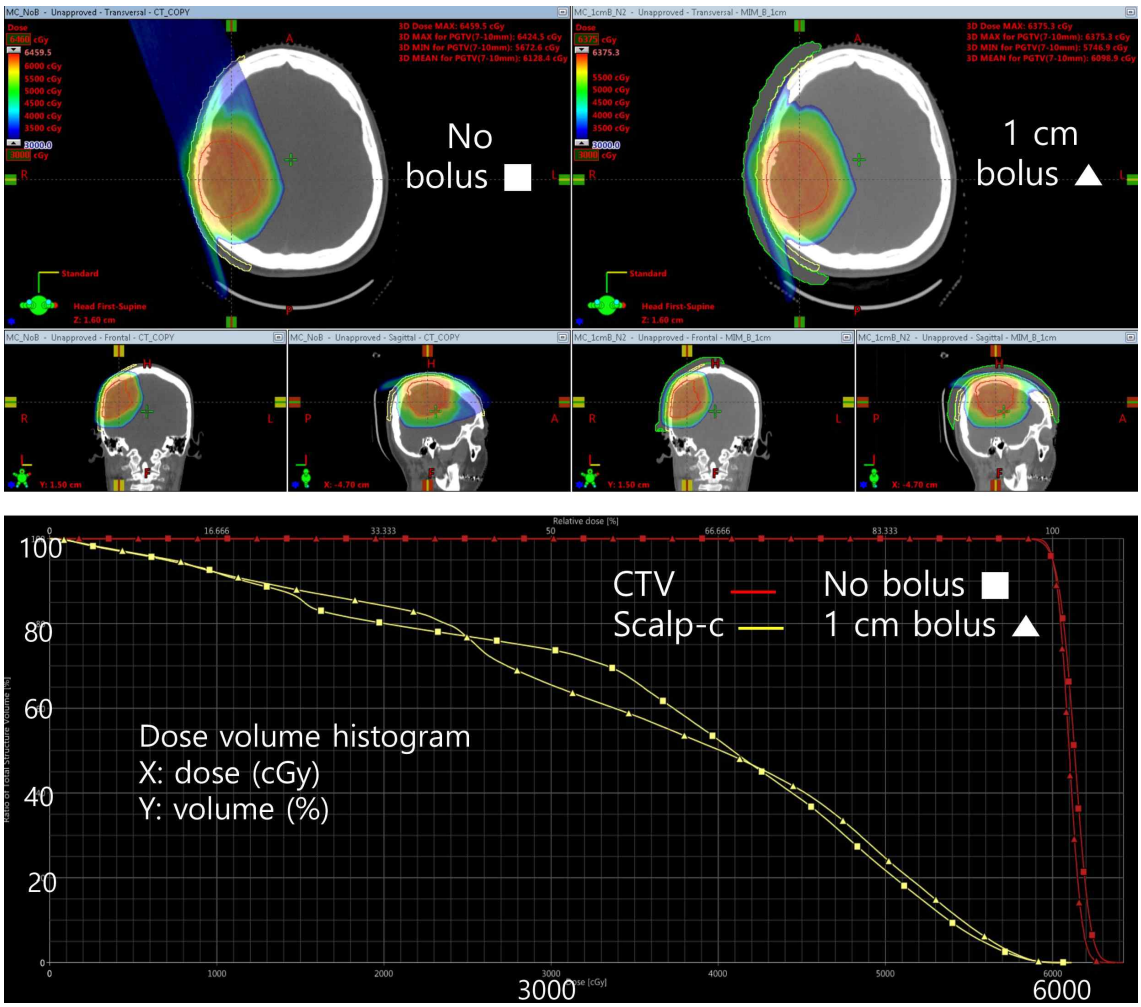



**Supplementary Fig. 2**(b)



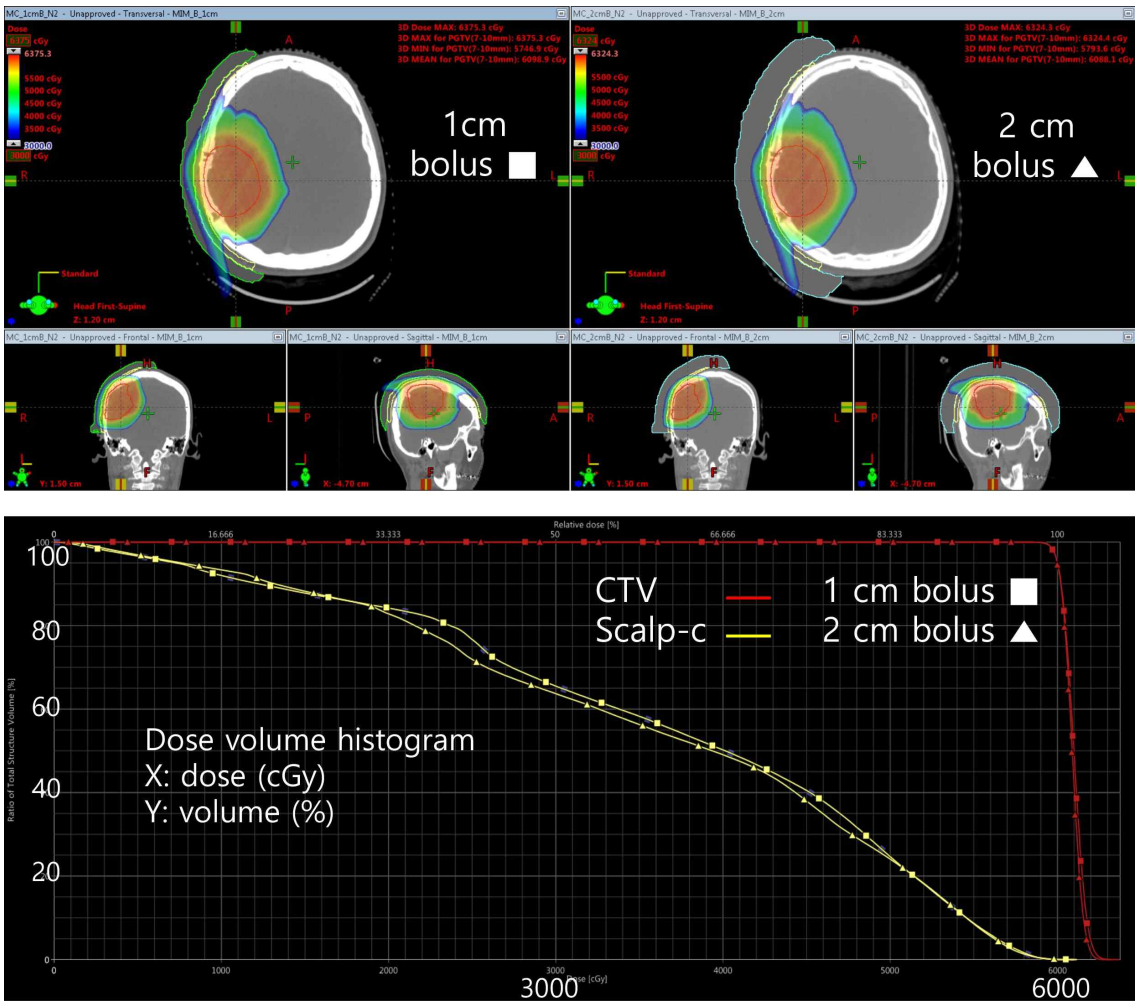

**Supplementary Fig. 2.** (a) With a 1 cm air gap between bolus and solid water phantom, the calculated scalp-p volume receiving 190 cGy was 0% with the treatment planning system (TPS) and 30% with the Monte Carlo (MC) simulation. The dose distribution is presented on the left and dose-volume histogram (DVH) on the right. (b) In the MC simulation, dose reduction by bolus was not compromised by an air gap. There was no difference in the scalp-p dose with or without the air gap in the MC simulation. The dose distribution is presented on the left and DVH on the right.

**Supplementary Fig. 3**(a)



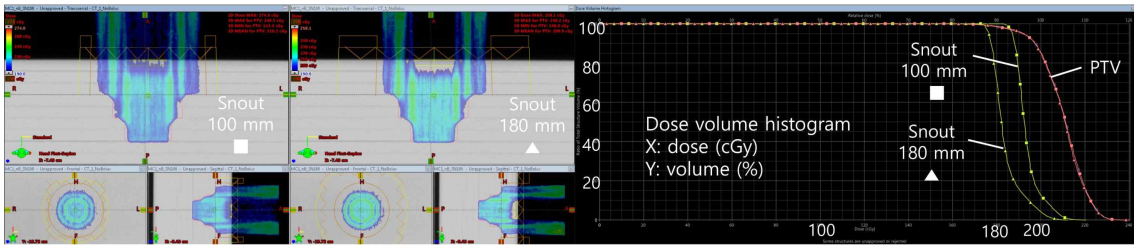

**Supplementary Fig. 3.** (a) With 1 cm bolus, the scalp-c volume receiving 3000 cGy decreased from 74% to 65%. The dose distribution is presented on the top and dose-volume histogram (DVH) on the bottom.

**Supplementary Fig. 3**(b)

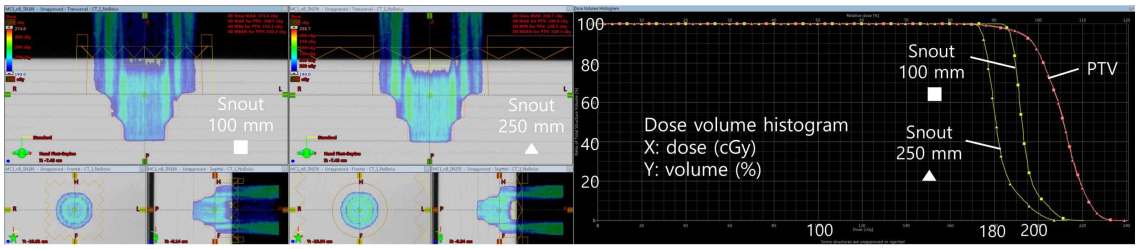



**Supplementary Fig. 3.** (b) The scalp-c dose decreased when bolus thickness increased from 1 to 2 cm.

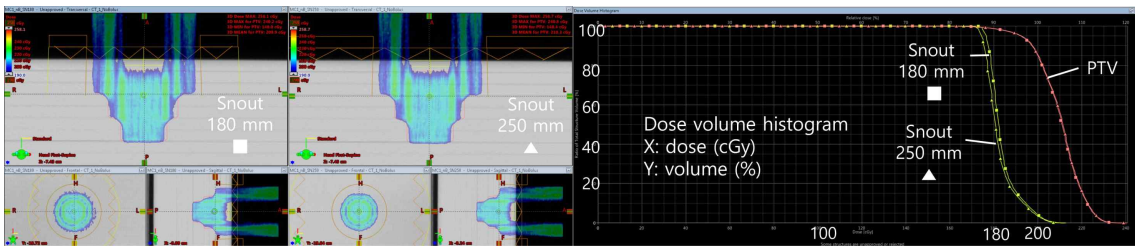
**Supplementary Fig. 4**(a)




**Supplementary Fig. 4**(b)




**Supplementary Fig. 4**(c)




**Supplementary Fig. 4.** (a) The scalp-p volume receiving 190 cGy decreased from 75% with the 100 mm snout to 15% with the 180 mm snout. The dose distribution is presented on the left and DVH on the right. (b)(c) When the snout size increased from 180 mm to 250 mm, the scalp-p dose reduction effect was slightly greater.

# 국문초록

**목적**

수동적 산란(passive scattering) 양성자 치료에서 스나웃(snout)과 애퍼처(aperture)에서 산란된 양성자는 체표면 방사선량을 증가시키지만, 분석 알고리즘에 기반한 치료 계획 시스템에서는 이 부분이 정확히 계산되지 않는다. 이러한 체표면 방사선량의 증가로 인해, 영구적인 탈모증이나 심한 방사선 피부염이 유발될 수 있다. 본 연구에서는 수동적 산란 양성자 치료에서 볼루스(bolus)가 체표면 방사선량에 미치는 영향을 평가하고자 한다.

**방법**

고체 물 팬텀에 임상 표적과 팬텀 두피를 그린 후 치료 계획 시스템을 사용하여 치료 계획을 만들었다. 몬테카를로 시뮬레이션을 통해 독립적으로 선량 분포를 계산하고 이온 챔버 및 방사성 변색 필름으로 실제 선량 분포를 측정하였다. 볼루스가 두피 선량에 미치는 임상적 영향을 평가하기 위해 임상 사례에서도 몬테카를로 시뮬레이션을 사용하여 독립적인 선량 검증을 수행하였다.

**결과**

임상 표적에 200 cGy를 조사했을 때, 볼루스가 없는 고체 물 팬텀에서 190 cGy를 받는 팬텀 두피의 부피는, 치료 계획 시스템에서는 20%였지만 몬테카를로 시뮬레이션에서는 80%였다. 몬테카를로 시뮬레이션에서 2cm 볼루스를 덮으면, 190 cGy를 받는 팬텀 두피의 부피가 80%에서 10%로 감소했다. 측정 결과, 팬텀 두피에 대한 평균 선량은, 2 cm 볼루스를 덮었을 때 5.2% 감소했다. 임상 사례에서 3000 cGy를 받는 임상 두피의 부피는, 2 cm 볼루스를 적용했을 때 74%에서 63%로 감소했다.

**결론**

본 연구는 볼루스가 체표면 방사선량을 줄이고 수동 산란 양성자 치료에서 독성을 완화할 수 있음을 보여주었다.

**주요어 : 양성자 요법, 몬테카를로, 산란 양성자, 볼루스, 두피**

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