Original Article

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Monte Carlo Simulation of the Carbon Beam Nozzle for the Biomedical Research Facility in RAON

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The purpose of the Monte Carlo simulation study was to provide the optimized nozzle design to satisfy the beam conditions for biomedical researches in the Korean heavy-ion accelerator, RAON. The nozzle design was required to produce C^{12} beam satisfying the three conditions; the maximum field size, the dose uniformity and the beam contamination. We employed the GEANT4 toolkit in Monte Carlo simulation to optimize the nozzle design. The beams for biomedical researches were required that the maximum field size should be more than 15×15 cm^2, the dose uniformity was to be less than 3% and the level of beam contamination due to the scattered radiation from collimation systems was less than 5% of total dose. For the field size, we optimized the tilting angle of the circularly rotating beam controlled by a pair of dipole magnets at the most upstream of the user beam line unit and the thickness of the scatter plate located downstream of the dipole magnets. The values of beam scanning angle and the thickness of the scatter plate could be successfully optimized to be 0.5^o and 0.05 cm via this Monte Carlo simulation analysis. For the dose uniformity and the beam contamination, we introduced the new beam configuration technique by the combination of scanning and static beams. With the combination of a central static beam and a circularly rotating beam with the tilting angle of 0.5^o to beam axis, the dose uniformity could be established to be 1.1% in 15×15 cm^2 sized maximum field. For the beam contamination, it was determined by the ratio of the absorbed doses delivered by C^{12} ion and other particles. The level of the beam contamination could be achieved to be less than 2.5% of total dose in the region from 5 cm to 17 cm water equivalent depth in the combined beam configuration. Based on the results, we could establish the optimized nozzle design satisfying the beam conditions which were required for biomedical researches.

Key Words: Accelerator, GEANT4, Heavy ion, Carbon, Nozzle, RAON

Introduction

In the Spring 2008, the team of International Science and Business Belt (ISBB)[1)] was formally organized by the Ministry of Education, Science and Technology, has been examined a validity of Institute for Basic Science (IBS)[2)] and the heavy-ion accelerator for 1 year. As Korean heavy-ion accelerator of the ISBB in Korea, the construction of the rare isotope science was approved in 2009.[3)] Korean heavy-ion accelerator is a particle accelerator of which primary purpose is to elucidate the nuclear force properties in strong interaction to explore the interaction between nucleons forming the nucleus of rare isotopes from basic nuclear physics. In addition, we are able to apply the research to the biomedical science.

As the biomedical researches and experimentations are the one of the major applications of Korean heavy-ion accelerator, it is necessary to construct the beam line to provide a suitable beam. Furthermore, it is necessary to study the beam delivery technique capable of treatment of cancer which is the final

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aim of the biomedical research project using heavy ions in the best way. As the depth dose distribution of the heavy-ion beam in materials presents as the typical form of the Bragg peak, the heavy-ion therapy has the dosimetric benefit in comparison with the dose distribution of conventional x-ray beam.[4] Even, the carbon ion beam has the biological benefit which is measured to be 2～3 of RBE (Relative biological Effectiveness) in the SOBP (Spread Out Bragg Peak) region.[5,6]

The name of the Korean heavy-ion accelerator is called RAON, it is expressed a word meaning “happy” or “joyful”.[7] The Korean heavy-ion accelerator is based on LINAC.[4,8] The preliminary nozzle design of the biomedical research facility in RAON had been the double scattering passive type with 430 MeV/μ of C^{12} beam energy. As the energy in RAON was finally settled to be 310 MeV/μ in 2013, the modification of the nozzle design in Table 1 was required to meet the research beam requirements.[3,9] So, we have performed the Monte Carlo simulation analysis for the new nozzle design with 310 MeV/μ of C^{12} beam energy.

Experiments and Discussion

The previous nozzle design with double scattering mode of beam delivery has been commonly utilized in particle therapy facilities. However, the increase of contamination level and the poor distal/axial penumbras due to scatter are unavoidable and might restrict their application in some clinical situations such as radiotherapies for ocular melanoma cases. As the maximum C^{12} beam energy in RAON was decided to be 310 MeV/μ, the wobbling beam delivery technique becomes feasible to set the projected field size. Since the higher beam energy of C^{12} requires the stronger magnetic field, the wobbling mode with 430 MeV/μ of C^{12} beam energy had been considered to be impossible within the projected research budget. Finally, the semi-wobbling beam method combined with the single scattering and the wobbling mode of beam delivery was introduced for C^{12} beam energy of 310 MeV/μ. The semi-wobbling mode was designed to combine a static beam and a circularly rotating beam with single scatter plate located upstream of dipole magnets. In Monte Carlo simulation, the field size and dose uniformity are optimized by the thickness of scatter plate and the tilting angle of rotating beam. After these optimization process, the weights of the static and rotating beam could be determined. Here, the limit of tilting angel was set to 0.6 degree for a practical reason.

Table 1. Carbon beam characteristics & requirements for the biomedical research project in RAON.

	Previous design	Final design
Beam energy	430 MeV/μ	310 MeV/μ
Beam diameter	3 mm	2.5 mm (1～5 mm)
Beam size	15×15 cm^2 (50%)	15×15 cm^2 (90%)
Dose uncertainty	<5%	<3%
Energy spread	<1%	<1%
Nozzle length	3 m	11 m
Range modulator	Required	Not necessary
Wobbler	Disabled	Enabled
Beam purity	<85%	> 95%

As variable parameters in optimizing processes, we could define the material composition, the thickness, the position of the scatter plate and the tilting angle of scanning beam in Monte Carlo geometry configuration using the GEAN4 toolkit.[10,11] The beams for biomedical researches were required that the field size should be more than 15×15 cm^2, the dose uniformity is to be less than 3% and the level of beam contamination due to the scattered radiation produced at collimation systems was less than 5% of total dose.

The substructures such as the C^{12} ion beam source, tungsten scatter plate, beryllium window, and a lead collimator and a water phantom as shown in Fig. 1 were configured in geometry subroutine. The distance from the C^{12} ion beam source to water surface was set to 11 m. The beryllium window was placed at 10.86 m downstream of beam source. The volume of the beryllium window was set to 1.0×1.0×0.01 m^3. The size of the lead collimator was 1.0×1.0×0.1 m^3 with 18×18 cm^2 of a concentric square hole. The nozzle space situated between downstream source and upstream beryllium window was filled with vacuum and the remaining volume designated as air-filled space except of materialized substructures.

Varying from 0 to 1 mm of scatter plate thickness by 0.1 mm step, the FWHMs of dose profiles at the water surface were obtained to analysis the dependency of the scatter plate thickness. The initial beam radius at the source position was configured to be 2.5 mm without no tilting angle. The Fig. 2 showed the cross sectional dose distribution by changing the

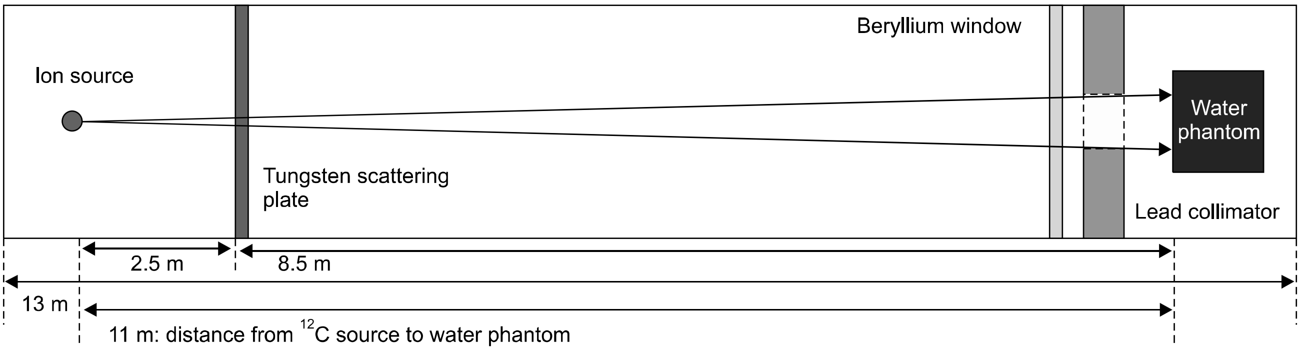

Fig. 1. The schematic diagram of the experimental beam nozzle for GEANT4 simulation.

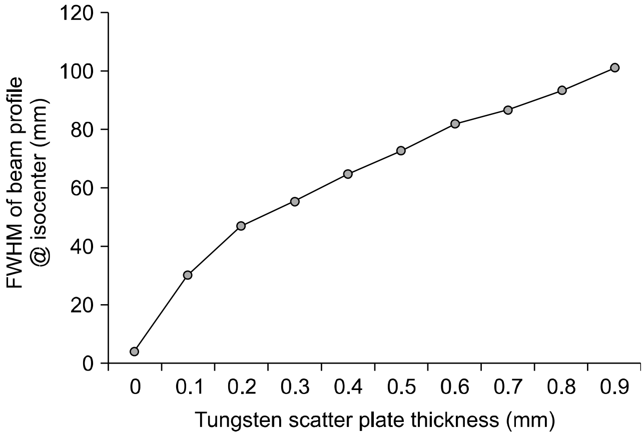

Fig. 2. The full width half maximums of field versus the thicknesses of scatter plate.

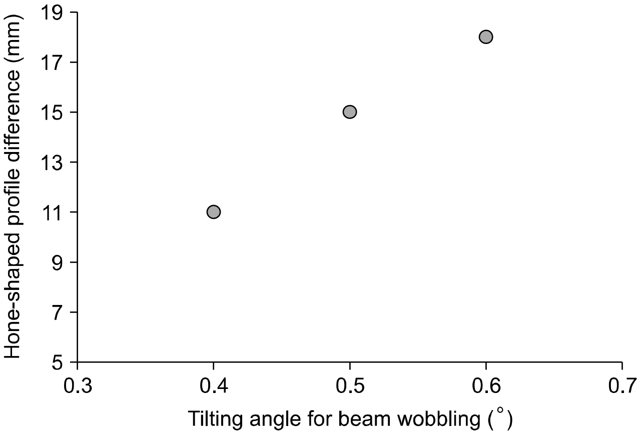

Fig. 3. The distances of hone shapes in each lateral profile according to the various tilting angle for beam wobbling.

thickness of the scatter plate without a lead collimator. Since the optimal FWHM value should be more than the half of required maximum field size in the two sub-beam combination, the minimum thickness of scatter plate would be more than 0.5 mm. Because of the more increasing thickness of scatter plate, the scattering particles in water phantom would be increased. So, the thickness of scatter plate was fixed to 0.5 mm and the lead collimator with an 18 cm×18 cm of the square hole appended at the upstream of water phantom. The symmetric two fold Gaussian shapes of dose profiles could be obtained by a circularly rotating beam with tilting angles. The distance of two maximal dose positions would be more than the required maximum field size. For 15×15 cm^2, the beam polar angle could be 0.5° as shown in Fig. 3.

To minimize the inhomogeneity, the weights of the static and the wobbling beam were optimized. This combinational semi-wobbling technique was described in Fig. 4c. As the profiles of the static beam and the wobbling beam were shown in Fig. 4a and b, the dose distribution combined with optimal beam weights was shown in Fig. 4d in which the uniformity was calculated to be 1.1% For this dose uniformity analysis, 3500 million histories of carbon events were generated for each sub-beam. Using the normalized dose profiles, we figured out 8 times more carbon events were necessary for the rotating beam.

Fig. 5a showed that the Bragg peak of 310 MeV carbon beam was placed in about 170 mm depth of water phantom and in Fig. 5b, depth dose distributions were presented for carbon beams with energies ranged from 160 MeV to 310 MeV. It was possible to increase the width of the SOBP by overlapping different beam energy with calculated weight factors. The C^{12} ion beam from 160 MeV to 310 MeV were delivered

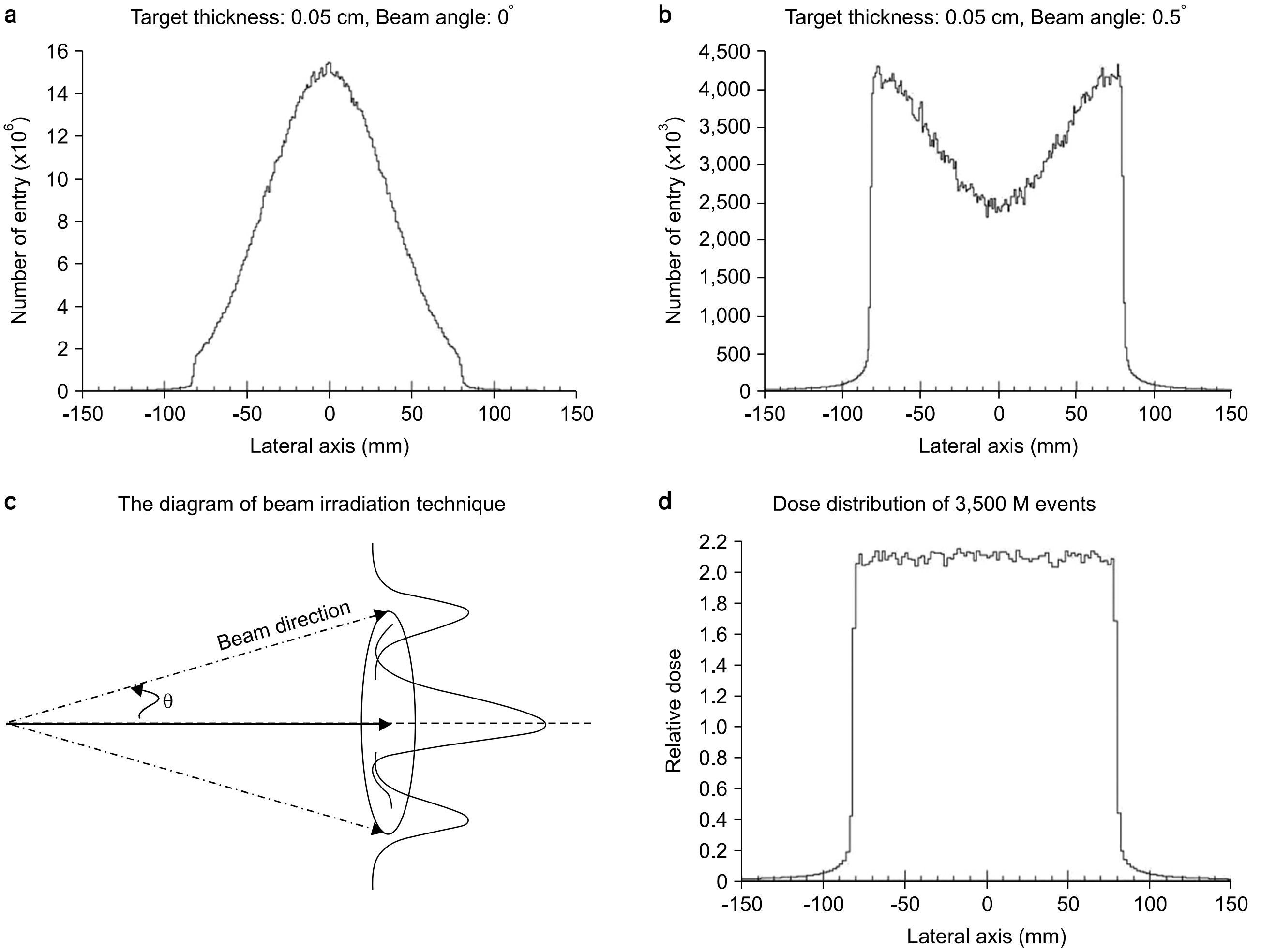

Fig. 4. The normalized lateral dose profiles under conditions with/without the optimized beam tilting angle 0.5° and the diagram of the combined beam delivery: (a) the lateral profile in scatter thickness 0.05 cm and beam tilting angle 0°, (b) the lateral profile in scatter thickness 0.05 cm and beam tilting angle 0.5°, (c) the diagram of the beam combination with a central static beam and a peripheral wobbling beam, and (d) the lateral profile in the combined beam mode for 3500 million MC histories of C^{12}.

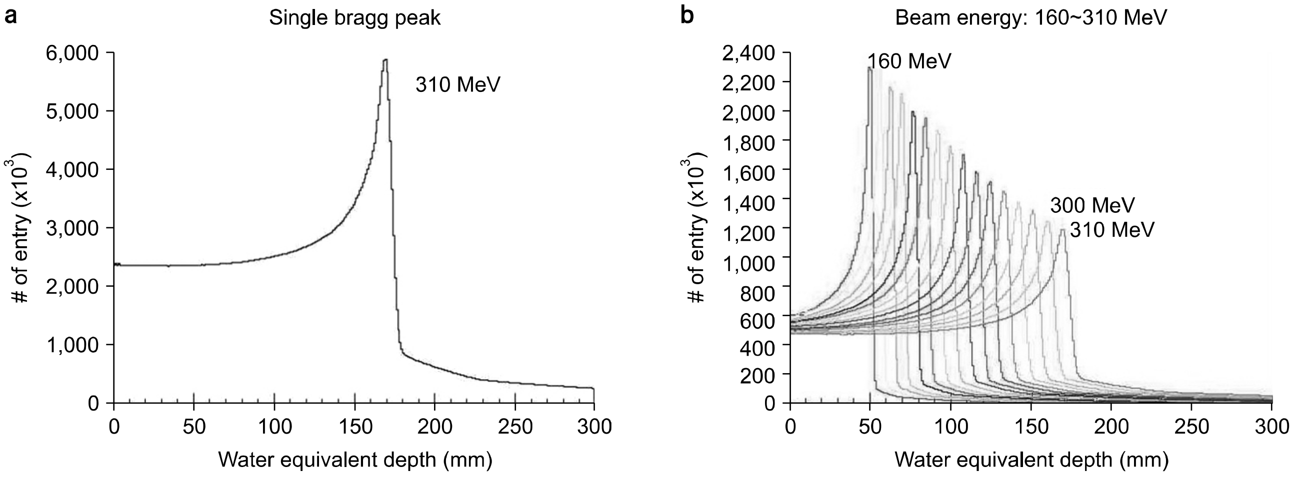

Fig. 5. The Bragg peaks for C^{12} beams with energies ranged from 160 to 310 MeV/u.

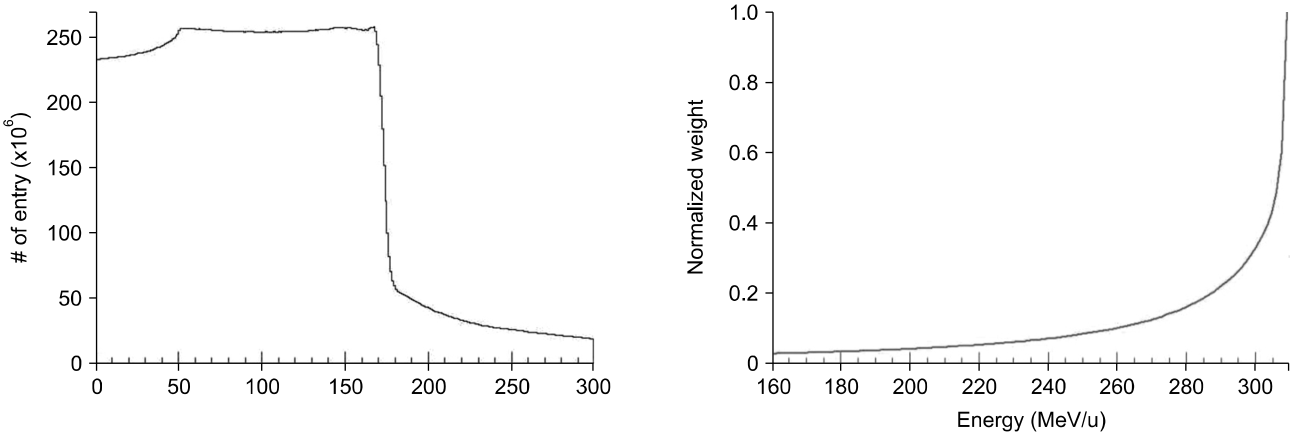

Fig. 6. The C^{12} ion SOBP beam and the corresponding normalized weighting function for each Bragg peaks with C^{12} ion energies ranging from 160 to 310 MeV/u.

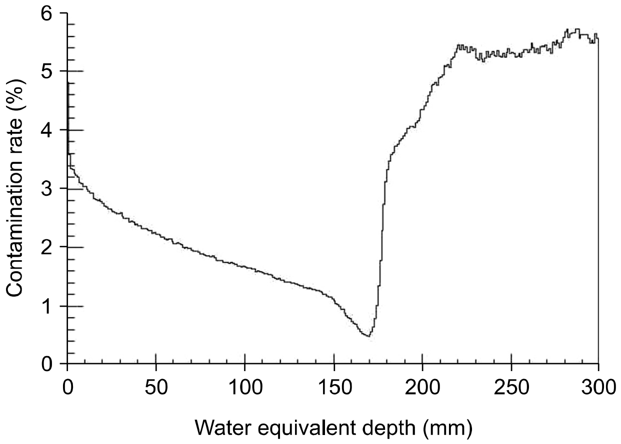

Fig. 7. The percentage of dose delivered by non C^{12} particles tagged at the water phantom surface was interpreted as the beam contamination level.

in water phantom, and the SOBP was maximally extended by using the weighting function. The weight functions of C^{12} ion beams were verified by normalizing to the SOBP as shown in Fig. 6. The particle identifications at the water surface were acquired. The dose from other particles was divided by dose from C^{12} ions to obtain the beam contamination level. Fig. 7 showed that the minimum contamination value of C^{12} beam and maximum contamination value of C^{12} beam were about 0.4% and 5.6%.

Conclusion

In order to find the optimized beam nozzle configuration, the Monte Carlo simulation was performed using the GEANT toolkit. The nozzle design for biomedical researches was optimized to meet the required conditions; the maximum field size of 15×15 cm^2, the beam uniformity within 3%, and the beam contamination less than 5%. The optimal tilting angle of the wobbling beam was 0.5° with the 0.05 cm thickness of the tungsten scatter plate. Using the proposed semi-wobbling beam mode in which a static beam and the wobbling beam were combined, we confirmed the dose uniformity was 1.1% with the wobbling beam weight corresponding to 8 times of the central static one. The flat SOBP region could be formed using the weight function for C^{12} beam energies by 4 MeV step without any ripple filter. Using the depth dose distribution for non C^{12} particles tagged at the water surface, we confirmed the beam contamination level was less than 2% within 5~17 cm of water equivalent depth.

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한국형 중이온 가속기 RAON의 의생물 연구시설 탄소 빔 노즐에 대한 Monte Carlo 시뮬레이션

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본 연구에서 한국형 중이온 가속기 RAON에서의 의생물 실험을 위하여 요구되는 빔 조건을 만족할 수 있도록 Monte Carlo 전산모사를 통한 노즐 설계를 최적화하고자 하였다. 의생명 실험을 위한 빔 조건으로 최대 조사면 크기, 선량균일도 그리고 빔 오염도의 특정 조건을 만족하는 C^{12} 빔 생산이 요구되었다. 이때 최적화된 빔 노즐 설계를 위하여 Monte Carlo 시뮬레이션인 GEANT4 toolkit이 사용되었다. 15×15 cm^2 이상의 빔 조사면 크기와 3% 이내의 선량 균일도 그리고 전체 선량의 5% 보다 낮은 빔 오염도를 기본적인 조건으로 설정 되었다. 조사면 크기는 쌍극자 자석에 의해서 빔의 각도를 기울여 원형으로 회전하면서 쌍극자 자석의 아래쪽에 위치한 산란판의 두께를 조정하여 최적화 하였다. 빔 스캐닝 각도와 산란판의 두께는 Monte Carlo 시뮬레이션 분석에 의해서 각각 0.5°와 0.05 cm로 최적의 값을 나타내었다. 선량균일도와 최대 조사면 크기를 만족하기 위하여 static과 scanning beam을 복합하는 기술을 이용한 새로운 빔 전달 방법을 소개하였다. 중앙 고정용 빔과 빔 축으로부터 0.5° 경사각을 가지고 회전하는 빔과 경사각이 없이 바로 들어오는 빔을 조합하여 선량균일도가 1.1%와 빔 조사면의 최대크기가 15×15 cm^{2}가 되는 것을 확인하였다. 빔 오염도는 C^{12} 이온과 다른 입자들에 의해서 전달된 흡수선량의 비율로 나타내었다. 물등가 깊이(water equivalent depth) 5 cm에서 17 cm 사이에서의 빔 오염도는 전체 선량에서의 2.5% 미만임을 확인하였으며 이와 같은 결과를 바탕으로, 본 연구에서는 의생명 실험을 위하여 요구되는 빔 조건을 만족하는 노즐 구조를 설정할 수 있었다.

중심단어: 가속기, GEANT4, 중이온, 탄소, 노즐, 라온