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Influence of a Localized Transverse Magnetic Field on Dose Distributions of MV Photon Beams in Inhomogeneous Medium

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The purpose of this study is to investigate the effects of the dose distributions caused by a low-strength magnetic field transverse to the incident photon beams in inhomogeneous medium of the body such as the lung. A simple water-air-water phantom was used to evaluate the magnetic field induced dose effect by the field size of the beam and the beam energy. The Gafchromic BET3 self-developing dosimetry film was utilized for all measurements. Our results indicated that a localized magnetic field within the air region offers the capability of producing dose enhancement and dose reduction regions between the proximal and distal interfaces. It was demonstrated that the magnitude of the dose perturbation depends not only on the beam energy, but also on the field size of the beam. It is expected that this magnet technology could be further developed to provide higher dose to the tumor and lower dose to the normal tissue in radiation therapy for lung cancer.

Keywords : MV photon beams, transverse magnetic field, inhomogeneity, permanent magnet

1. Introduction

The effect to improve dose distributions of photon beams has been focused on the application of magnetic fields over the last several decades. Bielajew [1] showed that a 20 T strong longitudinal magnetic field can significantly reduce the penumbra of photon beams. Naqvi [2] and Wadi-Ramahi *et al.* [3] studies the Monte Carlo simulations of the effect of the dose deposition around air cavities irradiated with photon beams. They found that a uniform longitudinal magnetic field of 0.5 T can provide the reduction of the large lateral spread of secondary electrons caused by the presence of air cavities, and the dose enhancement at the distal interface of air cavities. Monte Carlo simulations for the application of a transverse magnetic field to photon beams also have been investigated by several researches. Reiffel *et al.* [4] proposed the use of a strong localized transverse magnetic field with a 24 and 50 MV high-energy photon beam to control the dose distributions. By introducing a specially designed strong transverse magnetic field in or near the target region located at a certain depth, the dose in this region was significantly increased and the dose to surrounding healthy tissue was decreased. Li *et al.* [5] studied the idea of strong transverse magnetic fields from 1 T to 20 T with a variety of high-energy photon beams to enhance dose distributions for radiotherapy. They found that localized regions of large dose enhancement as well as dose reduction in a 15 MV photon beam for the field size of 4×4 cm^2 by applying a 5 T magnetic field. Jette [6] also shows that strong transverse magnetic fields can produce significant dose enhancement and reduction in localized regions under irradiation by very high-energy photon beams. He found that dose enhancement and reduction in localized regions were about 55 % and 30 % for the 30 MV photon beam with a 3 T magnetic field, respectively.

For most of previous studies, meaningful dose enhancements and reductions in a homogenous medium for high-energy photon beams (> 15 MV) were found by

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using strong transverse magnetic fields. Studies of the use of low magnetic field with a low-energy photon beam utilized the longitudinal magnetic field instead of the transverse magnetic field.

The purpose of this study is to present the dose effects induced by a localized transverse magnetic field with low strength in inhomogeneous medium such as the radiation therapy of the lung cancer. Dose distributions in inhomogeneous medium from the different field sizes of the beam and the low-energy photon beams (6 and 10 MV) were also investigated.

2. Materials and Methods

2.1. Measurement setup

In order to apply a low strength magnetic field of 0.5 T, a home-made magnet device manufactured in our previous study was used [7]. The device consists of two parallel neodymium permanent magnets with dimensions of 5 × 5 × 5 cm^3.

A simple water-air-water phantom representing the inhomogeneous medium such a lung was used to investigate the magnetic induced dose effect. As shown in Fig. 1, the water-air-water phantom consists of a 6.8 cm air gap between 3 cm and 5 cm thick water-equivalent material slabs on both the proximal and the distal region to provide sufficient build-up and backscatter. The density of solid water phantom, water-equivalent material, is 1.045 g/cm^3. 6 MV and 10 MV photon beams which widely recommended for beams passing through low-density lung tissue before entering the tumor were used for the investigation [8, 9]. Two permanent magnets placed at a constant distance were located in the air region between water phantoms. Then magnetic field was applied in transverse direction to the incident photon beams.

2.2. Radiochromic EBT3 film calibration

For a film dosimetry, the commercial radiochromic film used in this study was a Gafchromic EBT3 film (Ashland Specialty Ingredients, Bridgewater, NJ, USA) with batch number of 09071704 and sheet dimensions of 20.3 × 25.4 cm^2. The EBT3 film is consisted of an active layer with the thickness of 27 μm and two transparent polyester substrate with a thickness of 120 μm each. For film dosimetry, the films were handled according to the recommendations described in the American Association of Physicists in Medicine (AAPM) Task Group 55 report [10]. A sheet of films were cut into pieces of 5 cm × 5 cm. For irradiation, the film was placed at a 5 cm depth in a solid water phantom with the dimensions of 30 × 30 × 15 cm^3. To provide sufficient backscatter conditions, 10 cm thick solid water phantom was located under the film. The films were irradiated with a 6 MV photon beam on a TrueBeam linear accelerator (Varian Medial Systems, Palo Alto, CA, USA). Irradiations were performed with a field size of 10 × 10 cm^2 and a source-to-surface distance (SSD) of 100 cm. The doses delivered to the pieces of film ranged from 10 to 700 cGy. At least 24 h after irradiations [10, 11], the films were scanned using a flatbed scanner (Epson Expression 10000XL, Seiko Epson Corp., Tokyo, Japan) in transmission scanning mode without color correction. Scanned film images were collected with a resolution of 72 dpi in 16 bits red color channel. The data were saved as TIFF (tagged image file format) files. The ImageJ software (National Institutes of Health, Bethesda, MD, USA) was used to analyze the film with region of interest (ROI) of 5 × 5 pixels in the

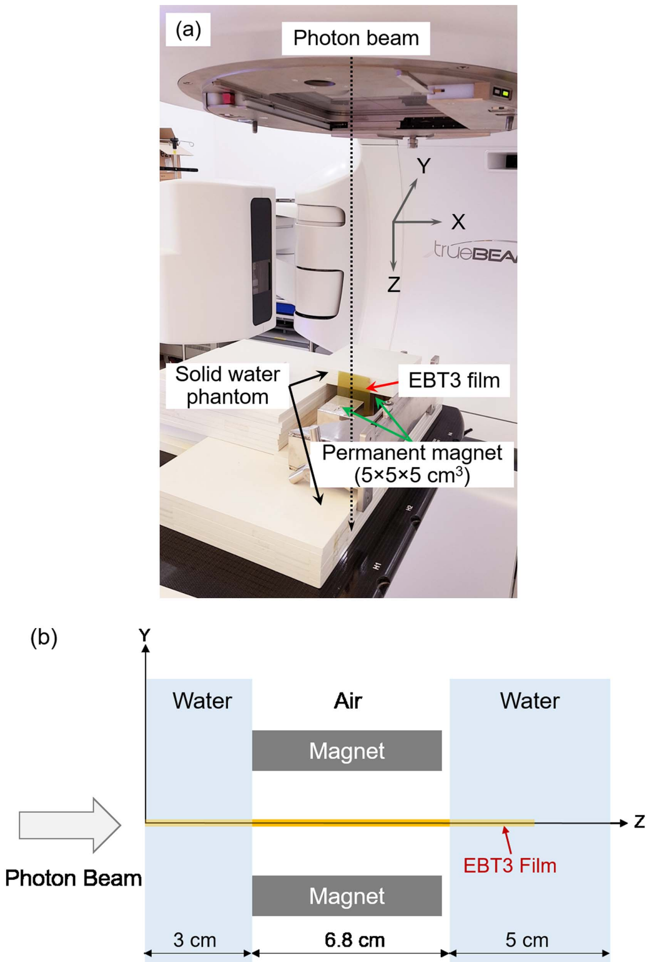

Fig. 1. (Color online) Arrangement of a localized transverse magnetic field for modifying dose distributions along beam axis in z-direction. (a) Photo of the setup showing the direction of the magnetic field and location of EBT3 film. (b) Schematic diagram of the measurement setup at y-z plane.

middle of each film to avoid the edges. The median pixel value (related to intensity of image) obtained from the ROI was then converted to net optical density (NOD) by the following formula:

$$NOD = \log_{10}\left(\frac{I_0}{I}\right) \quad (1)$$

where I_0 and I are the median pixel value for the non-irradiated and irradiated film, respectively.

2.3. Film measurement and analysis

The EBT3 films were cut into pieces of 3 cm × 12.5 cm and 6 cm × 14.5 cm with different field sizes. Each film set cut from a sheet were prepared so that the influence of the dose distributions induced by a low-strength magnetic field transverse to incident beams could be studied. As shown in Fig. 1(a) and (b), the film were inserted in a water-air-water phantom along beam axis in z-direction. The short side of the film was positioned orthogonal to the magnetic field (parallel to the x-axis). The films were then irradiated with 6 and 10 MV photon beams of a TrueBeam linear accelerator. The film measurements were performed for the field sizes of 1.5 × 1.5 and 3.0 ×

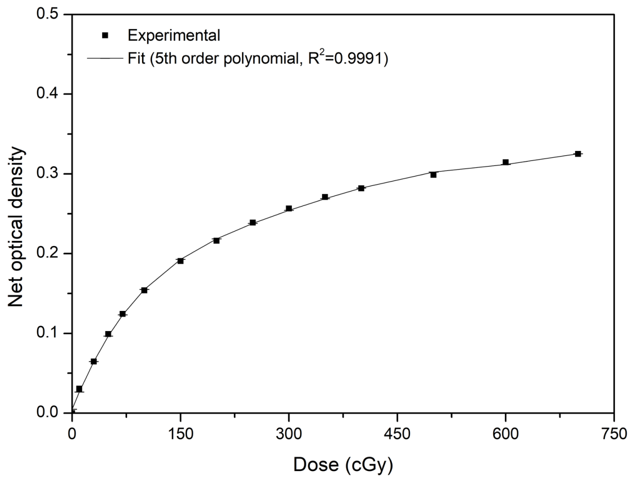

Fig. 2. Dose response curve of EBT3 radiochromic film in red color channel.

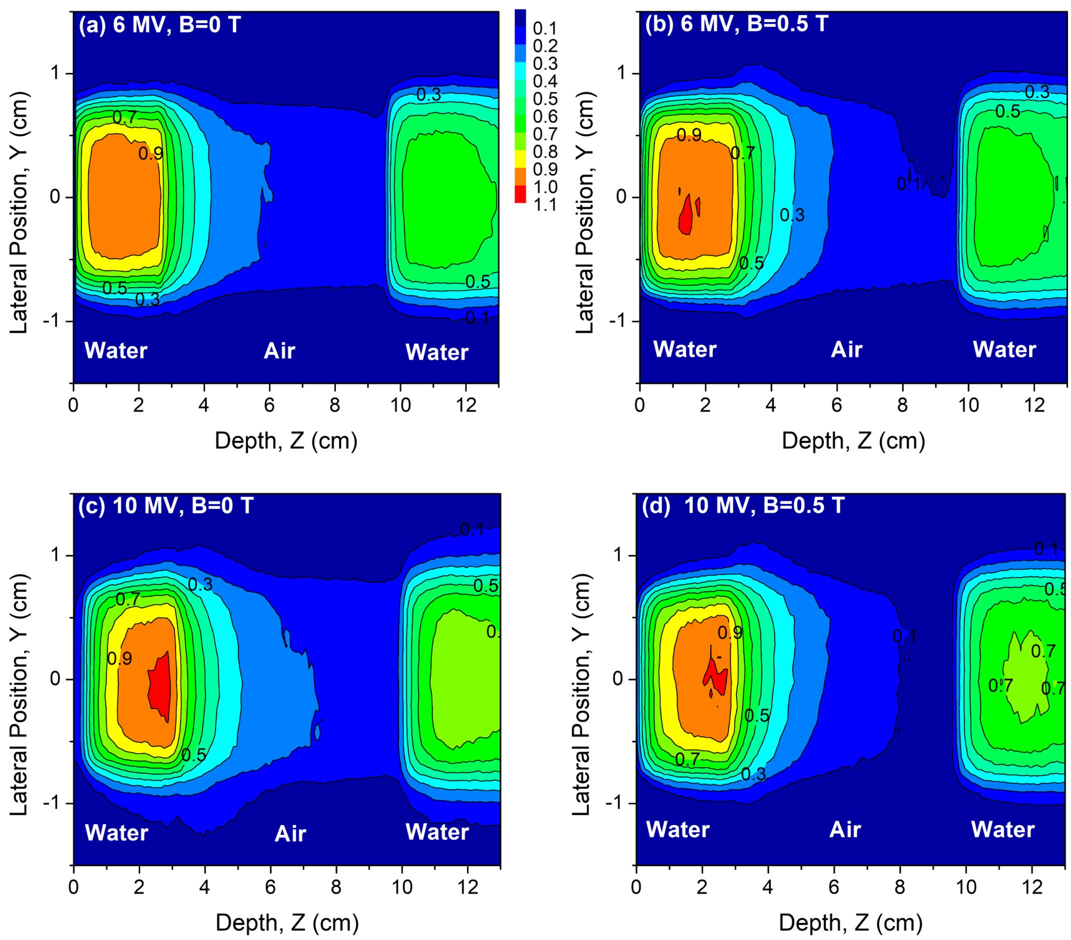

Fig. 3. (Color online) 2-D dose distributions induced by a transverse magnetic field for 6 MV and 10 MV photon beams with the field size of 1.5 × 1.5 cm^2 incident along water-air-water phantom.

3.0 cm^2 at a SSD of 100 cm. After 24 hours from the end of the film exposure, the irradiated films were scanned using an Epson Expression 10000XL flatbed scanner and handled in the same procedure as the film calibration. The images obtained in the red channel of the 48-bit RGB format with the resolution of 72 dpi were imported into the ImageJ software. Consequentially, the measured 2-D dose distributions induced by the magnetic field in inhomogeneous medium were presented for different field sizes of the beam and the photon beams.

3. Results

Dose response curve of EBT3 radiochromic film in transmission scanning mode was obtained as shown in Fig. 2. NOD of each pieces of films were analyzed in the red channel due to a higher sensitivity than other channels (green and blue) up to 10 Gy [12-14]. The curve fitted by a fifth order polynomial coincided with the experimental values within 3 % for dose ranging from 30 to 700 cGy. In low dose regions lower than 300 cGy, the sensitivity of the dose response was greater than that from 300 to 700 cGy.

The magnetic field induced dose distributions of 6 and 10 MV photon beams incident on the water-air-water phantom were shown in Fig. 3 and 4. All iso-dose contour values are normalized to the unity at the depth of maximum dose (d_{max}). The tracks of secondary charged particles produced by photon beams were predominantly affected by a transverse magnetic field applied between 3 and 9.8 cm depths. In the presence of a transverse magnetic field, dose enhancement and dose depression along incident photon beams were clearly distinguished.

The effects of the dose induced by the magnetic field depended on the field size of the beam and the energy of photon beam. For the field size of 1.5 × 1.5 cm^2, the magnitude of the magnetic field induced dose reduction in the air region in front of the distal interface was increased with the energy of the photon beam (Fig. 5(a) and 5(b)). In particular, as the field size increased, the

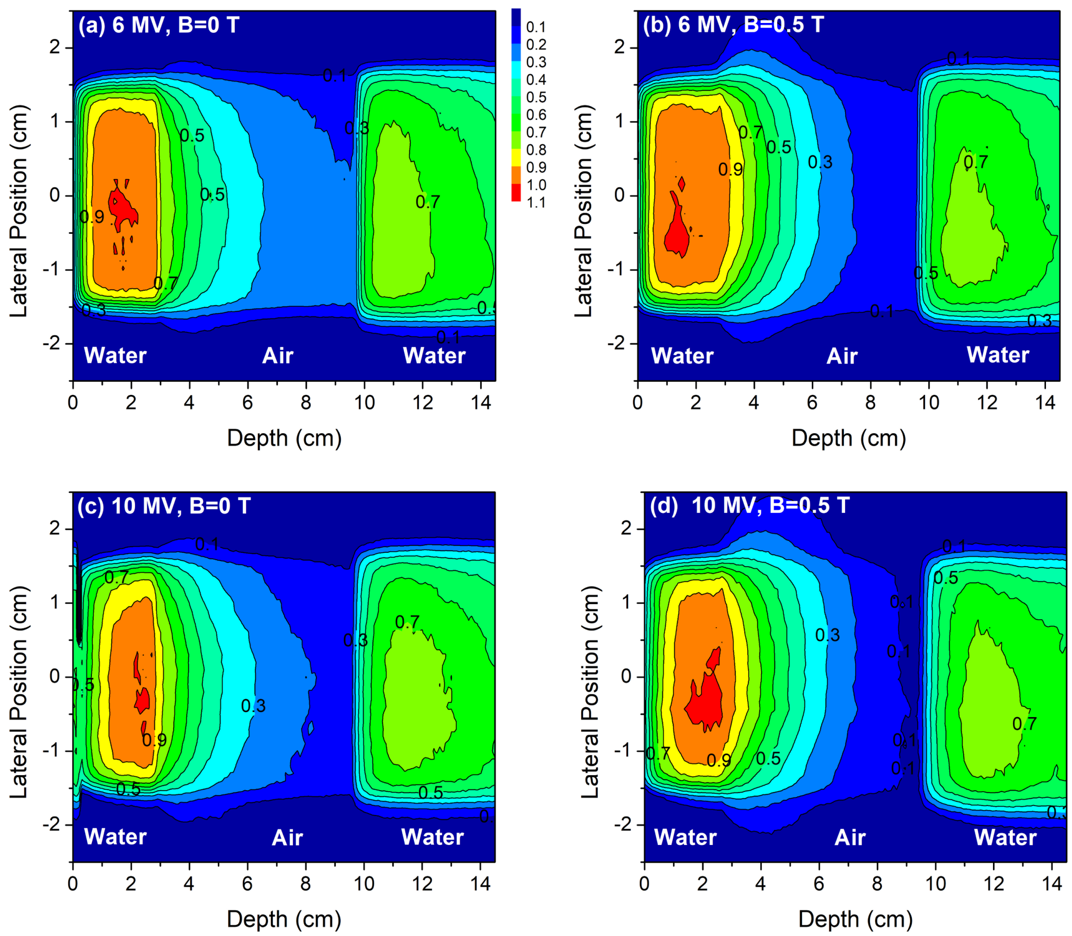

Fig. 4. (Color online) 2-D dose distributions induced by a transverse magnetic field for 6 MV and 10 MV photon beams with the field size of 3 × 3 cm^2 incident along water-air-water phantom.

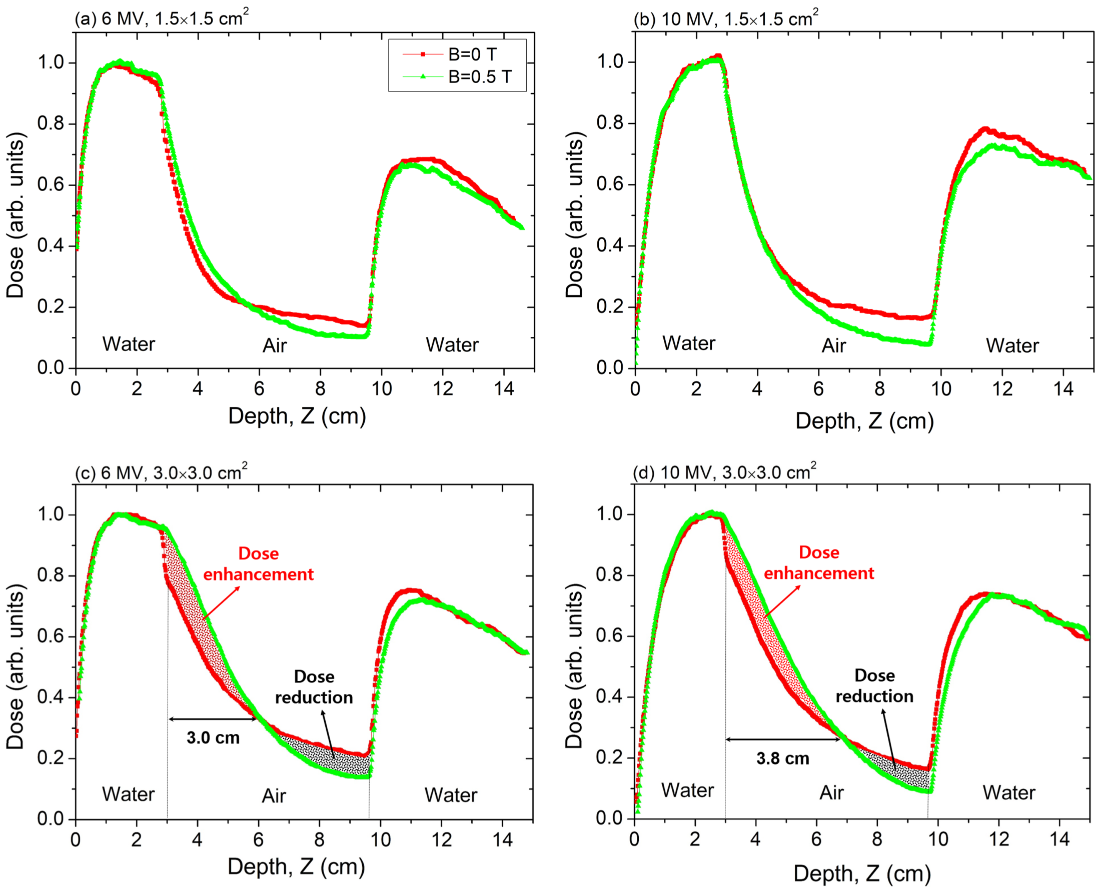

Fig. 5. (Color online) Central axis percent depth doses for indicated beam sizes of 1.5 × 1.5 and 3 × 3 cm^2 with no magnetic field and B = 0.5 T. The curves are normalized to the nominal d_{max}.

dose in behind of the proximal interface was significantly enhanced with depths as shown in Fig. 5(c) and 5(d). For the field size of 3 × 3 cm^2, the magnitudes of the maximum and average dose enhancement were 13.9 % and 8.5 % for 6 MV and 14.6 % and 9.4 % for 10 MV, respectively. The distances of the dose regions enhanced by the magnetic field were 3.0 and 3.8 cm for 6 and 10 MV. In air region in front of distal interface, the magnitudes of the maximum and average dose reduction were 9.0 % and 5.9 % for 6 MV and 11.7 % and 6.1 % for 10 MV, respectively.

4. Discussion

The goal of radiotherapy is to deliver prescribed dose to the tumor while sparing the adjacent normal tissues around it. Intensity-modulated radiation therapy (IMRT) which is widely used in clinical practice has successfully achieved the purpose of radiotherapy due to the development of advanced technology [15-17]. However, unless the energy of photon beams is changed, the photon beams incident in each beam directions cannot be modulated directly. In previous studies by other researchers have reported that an external magnetic field can induce the variation of the dose distribution for the existing photon and electron beams. Those studies have mainly shown that there is the influence of the dose distribution of high energy photon beams by using high strength magnetic fields ranging from 3 to 20 T.

Photon beams itself is not affected by the magnetic field, whereas secondary charged particles produced by photon beams are dominated by the Lorentz force [18, 19]. In this study, assuming a situation similar to radiation therapy for lung cancer, the localized transverse magnetic field with a low strength was applied to modulate mainly scattered secondary electrons entering the proximal air region in water-air-water phantom. Consequently, a noticeable distinction of dose enhancement and dose reduction regions between the proximal and distal interfaces was outstandingly observed. Especially, the dose on the proximal air region significantly increases as the field size of the beam increases due to a large number of scattered electrons prior to entrance in the air as shown in Fig. 5. The electrons produced by the 10 MV photon beam behaves more forwardly in compared to the 6 MV photon beam due to the longer secondary particle track length [2, 20]. Hence the photon beam with higher energy creates a longer region of dose enhancement which is extended substantially beyond the proximal interface (Fig. 5(c) and 5(d)). We also know that the regions of significant dose reduction in the front of the distal interface has been observed along the central axis. This is due to the dis-equilibrium of transient charge particle at the distal end of the magnetic field [21]. As the results of this study, therefore, the low-strength transverse magnetic field applied within the ROI is capable of producing dose enhancement and dose reduction regions along the central axis of the photon beams. This magnetic field induced dose effects could be adjusted by the field size of the beam and the beam energy.

5. Conclusions

In this study, we used the simple water-air-water phantom representing the inhomogeneous medium of the body such as the lung. Our experimental results show that the regions of significant dose enhancement and reduction near the proximal and distal interfaces were clearly achieved by a localized transverse magnetic field of 0.5 T. These magnetic field-induced dose effect can be devised as a potential treatment technique to enhance the dose in the tumor region, and suppress the dose to surrounding health tissue in radiation therapy for lung cancer.

References

[1] A. F. Bielajew, Med. Phys. **20**, 1171 (1993).
[2] S. A. Naqvi, X. A. Li, S. J. Wadi-Ramahi, J. C. Chu, and S. Ye, Med. Phys. **28**, 603 (2001).
[3] S. J. Wadi-Ramahi, S. A. Naqvi, and J. C. Chu, Med. Phys. **28**, 1711 (2001).
[4] L. Reiffel, A. Li, J. Chu, R. W. Wheatley, S. Naqvi, R. Pillsbury, and A. Saxena, Phys. Med. Biol. **45**, N177 (2000).
[5] X. A. Li, L. Reiffel, J. Chu, and S. Naqvi, Med. Phys. **28**, 127 (2001).
[6] D. Jette, Med. Phys. **27**, 2726 (2000).
[7] W. S. Ahn, W. Choi, J. Kwak, Y. R. Ka, C. S. Park, and S. S. Shin, J. Magn. **22**, 709 (2017).
[8] Radiation Therapy Oncology Group. RTOG protocols 0915. Available from: https://www.rtog.org/ClinicalTrials/ProtocolTable.aspx. Accessed on October 2, 2019.
[9] National Comprehensive Cancer Network (NCCN) Clinical Practice Guidelines in Oncology, Non-Small Cell Lung Cancer, version 2.2018 (2018). Available from: https://www2.tri-kobe.org/nccn/guideline/lung/english/non_small.pdf
[10] A. Niroomand-Rad, C. R. Blackwell, B. M. Coursey, K. P. Gall, J. M. Galvin, W. L. McLaughlin, A. S. Meigooni, R. Nath, J. E. Rodgers, and C. G. Soares, Med Phys. **25**, 2093 (1998).
[11] T. Cheung, M. J. Butson, and P. K. Yu, Phys. Med. Biol. **50**, N281 (2005).
[12] D. Lewis, A. Micke, X. Yu, and M. F. Char, Med. Phys. **39**, 6339 (2012).
[13] V. C. Borca, M. Pasquino, G. Russo, P. Grosso, D. Cante, P. Sciacero, G. Girelli, M. R. L. Porta, and S. Tofani, J. Appl. Clin. Med. Phys. **14**, 158 (2013).
[14] S. N. Chen, M. Gauthier, M. Bazalov-Carter, S. Bolanos, S. Glenzer, R. Riquier, G. Revet, P. Antici, A. Morabito, A. Propp. M. Starodubstev, and J. Fuchs, Rev. Sci. Instrum. **87**, 073301 (2016).
[15] T. Bortfeld, Phys. Med. Boil. **51**, R363 (2006).
[16] International Commission on Radiation Units and Measurements. ICRU Report 83: Prescribing, recording, and reporting photon-beam intensity-modulated radiation therapy (IMRT), J. ICRU **10**, (2010).
[17] B. Cho, Radiat. Oncol. J. **36**, 1 (2018).
[18] J. D. Jackson, Classical Electrodynamics, Wiley, New York (1975).
[19] S. Wegener, and S. Weick, and O. A. Sauer, Z. Med. Phys. **29**, 22 (2019).
[20] J. C. H. Chu, L. Reiffel, W. C. His, and V. A. Saxena, Int. J. Cancer. **96**, 131 (2001).
[21] D. Jette, Med. Phys. **27**, 1705 (2000).