Implementation of AAPM's TG-51 Protocol on Co-60 MRI-Guided Radiation Therapy System

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For the ViewRay® system (ViewRay Inc., Cleveland, OH, USA) which is representative of magnetic resonance (MR) guided radiotherapy machine, it is important to evaluate effectiveness of AAPM's TG-51 protocol and the effect of the magnetic field on absolute dosimetry. In order to measure the absolute dose, MR-compatible chamber and water phantom system manufactured in this study were used. The materials of the water phantom system were plastic of polymethyl methacrylate (PMMA) and non-ferrous materials. Due to the inherent feature of the ViewRay®, all Co-60 sources are not located at gantry angle of 0° while being located at gantry angle of 90°. For this reason, absolute dosimetry was performed based on the measurements in solid water phantom (SWP) and water which determine the SWP to water correction factor. For evaluation of output constancy with gantry angle, measurements were made with ionization chamber inserted in cylindrical water-equivalent phantom. For measured doses in water, the values of dose deviation according to a reference dose of 200 cGy for Head 1, Head 2 and Head 3 were −0.27%, −0.45% and −0.22%, respectively. For measured doses in SWP, the values of dose deviation according to a reference dose of 200 cGy for Head 1, Head 2 and Head 3 were −1.91%, −2.07% and −1.84%, respectively. All values of dose measured in SWP tended to be less than those measured in water by −1.63%. With the reference gantry angles of 0° and 90°, the maximum values of deviation for Head 1, Head 2 and Head 3 were 0.48%, 1.06% and 0.40%, respectively. The measurement agreement is within the range of results obtainable for conventional treatment machines. The low strength of the magnetic field does not affect dose measurements. Using the SWP to water correction factor, absolute doses for ViewRay® system can be measured.

Keywords: Absolute dosimetry, AAPM's TG-51 protocol, MRI-guided radiation therapy system

Introduction

Image guided radiation therapy (IGRT) is one of the most cutting-edge radiotherapy technique and several institutions have tried to develop the IGRT system using various image devices in the radiation therapy.[1-8] Among several image devices, magnetic resonance (MR) image has an advantage to distinguish soft tissues without unnecessary radiation exposure in compared with computed tomography (CT) image. With the development of tech-

nology, MR imaging system can be installed in a radiation treatment system and then MR images can be obtained during radiation therapy, which is called MR-IGRT system.[2,9-11] Recently, the most representative MR-IGRT system in the field of radiotherapy is the ViewRay® system (ViewRay Inc., Cleveland, OH, USA) which consists in a MR scanner of 0.35 T static magnetic field for imaging and tri Co-60 sources for treatment.[1,11-13] The total dose rate of the tri Co-60 sources is 550 cGy/min, which is ideal dose rate in radiotherapy planning system (RTP) and the tri Co-60 sources are positioned at 120-degree intervals in a ring type gantry. To minimize geometric penumbra of Co-60 sources, double-focused multi-leaf collimators (MLCs) are used in the ViewRay system®.[1,11-13] The MLC system has a total 60 leaves, 30 leaves on both sides, and the leaf width is 1.05 cm at isocenter. The ViewRay® system has 70 cm of the inner diameter of the ring-type gantry and 105 cm of the source-to-axis distance (SAD).[1,11-13]

After the ViewRay® system was developed, several studies have been steadily reported to clinical application, planning and commissioning of ViewRay® system. Kachani et al.[14] have performed commissioning of the online adaptive radiotherapy using the ViewRay® system. Several planning studies have evaluated static intensity modulated radiation therapy (IMRT) technique from ViewRay® system, compared with volumetric modulated arc therapy (VMAT) and dynamic IMRT from traditional radiotherapy machine in spine, cervix, prostate and lung cancer.[9,15-17] It has been shown that normal tissue sparing of ViewRay® IMRT plan was better than that of VMAT plan in prostate cancer and target margin reduction could be achieved for cervical cancer in compared with VMAT plans. Park et al.[1] have verified the safety of machine, mechanical accuracy, MR imaging system and radiation therapy system performance when they carried out commissioning of the ViewRay® system.

Since the ViewRay® system continues to operate MR imaging system during treatment which is different from traditional radiotherapy machine, absolute dose measurement should be carefully performed for the commissioning and quality assurance (QA). However, there are limits to the absolute dose measurement of ViewRay® system. The magnetic field used in the MR imaging of

the ViewRay® system does not allow the use of electronic devices and chambers containing of ferrous material. For that reason, only MR-compatible chambers should be used for measurement. Furthermore, since one particular Co-60 source ('Head 2') in ring type gantry of ViewRay® system cannot reach the gantry angle of 0° as an inherent feature of the Viewray® system, it is not possible to measure the absolute doses from all sources at the gantry angle of 0° while all Co-60 sources could be positioned at gantry angle of 90°. Finally, absolute dose measurements as suggested by the AAPM's Task Group (TG)-51 protocol[18] for this MR-IGRT system with a static magnetic field of 0.35 T are not well known. For this reason, it is important to evaluate effectiveness of AAPM's TG-51 protocol and the effect of the magnetic field on absolute dosimetry. The aim of the current study is to develop the absolute dosimetry system under static magnetic field and then to validate the absolute dosimetry protocol suggested by the AAPM's TG-51 for ViewRay® system with the absolute dosimetry system developed in this study.

Materials and Methods

1. The design and manufacture of the water phantom system

In order to avoid the effect of the static magnetic field on absolute dosimetry, water phantom system without ferrous materials was manufactured. As shown in Fig. 1, the size of water phantom tank is $40 \times 30 \times 30$ cm^3 and the material of the water phantom tank was plastic of polymethyl methacrylate (PMMA). The water phantom system was designed to move an ionization chamber parallel to axis of beam so that the percentage depth dose (PDD) and point-dose measurements could be performed. A plastic ruler was attached on the water phantom tank in the parallel direction to axis of beam for accurate adjustment of ionization chamber.

Since the static magnetic field could affect the electronic devices, ionization chamber should be positioned manually by the thumbscrew type (shown in Fig. 1(c)), which is not a remote-control moving system like existing water phantom system. The materials of the manual-control
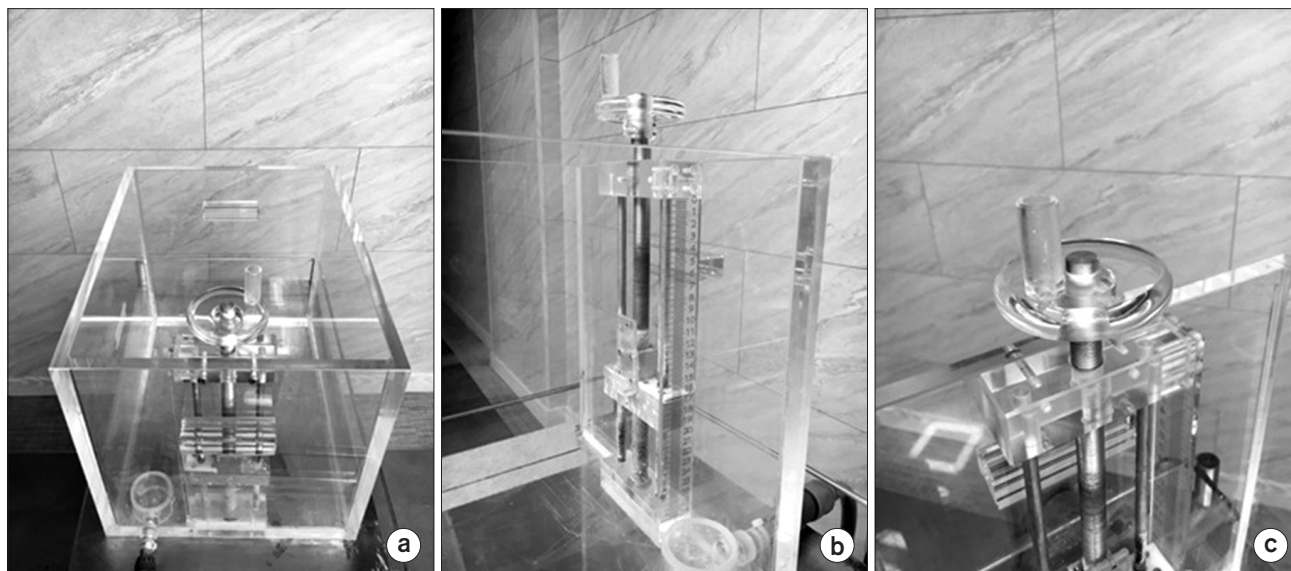
Fig. 1. Water phantom system without ferrous materials was manufactured. Water phantom system consists of (a) water phantom tank, (b) plastic ruler, and (c) thumbscrew type moving system.

moving system were plastic of PMMA and non-ferrous materials.

2. AAPM's TG-51 protocol on Co-60 MRI-guided radiation therapy system

For measurements, a 0.65 cc farmer-type ionization chamber (Exradian A12 Ion Chamber, Standard Imaging Inc., Middleton, WI, USA) in the developed water phantom system was used. The Exradian A12 Ion Chamber is made of conductive plastic material and then could be MR-compatible.[19-21] The ionization chamber was positioned at depth of 5 cm at source-to-surface distance (SSD) of 100 cm. MLC-defined field size was 10.5×10.5 cm^2 at source-to-axis distance (SAD) of 105 cm.

For absolute dosimetry in water, PDDs for all Co-60 sources were measured and then compared to BJR supplement 25.[22] Correction factors (P_{ion}, P_{TP}, P_{elec} and P_{pol}) suggested by AAPM's TG-51 protocol were obtained for Head 1 and Head 3 only which could be set to gantry angle of 0° while Head 2 could not go to gantry angle of 0°. After that, the exposure time was calculated to deliver 200 cGy in the reference point and then, the raw readings were measured by irradiating the beam during the calculated exposure time. Absolute dose values for Head 1 and Head 3 were determined in water using measured raw readings, PDDs and correction factors of AAPM's TG-51 protocol.

To obtain absolute dose for Head 2 in water, solid water phantoms (SWPs) with ionization chamber were stood to be perpendicular to the beam direction when each Co-60 source was positioned at gantry angle of 90°. For the same experimental condition without the gantry angle, the absolute dose values for Head 1 and Head 3 were measured. With these measurements for Head 1 and Head 3 between water and SWP, the SWP to water correction factor was calculated and applied to the measurement for Head 2. The SWP to water correction factors and AAPM's TG-51 protocol correction factors for Head 1 and Head 3 were used for absolute dosimetry for Head 2 which was at gantry angle of 90°.

3. Output constancy with gantry angle

Ring type gantry may have a mechanical uncertainty when gantry rotates and this uncertainty could affect the output of the ViewRay® system. It is important to validate the output constancy with gantry angle for commissioning and absolute dosimetry. For experiments, 0.125 cc cylindrical ionization chamber (Exradian A28 Ion Chamber, Standard Imaging Inc., Middleton, WI, USA)

Table 1. Correction factors of AAPM's TG-51 and absolute dose values in water and solid water phantom (SWP) for Head 1, Head 2, and Head 3. Measurements in water were performed to deliver 200 cGy to reference point when both Head 1 and Head 3 were set to gantry angle of 0°. Measurements in SWP were performed to deliver 200 cGy to reference point when Head 1, Head 2 and Head 3 were set to gantry angle of 90°.

	Correction factor			Output			
	P_{ion}	P_{elec}	P_{pol}	*$D_{w,\,0°}$ (cGy)	†$Dev_{200\,cGy}$ (%)	‡$D_{SWP,\,90°}$ (cGy)	$Dev_{200\,cGy}$ (%)
Head 1	1.001	1.000	0.999	199.5	−0.27	196.2	−1.91
Head 2				§199.1	−0.45	195.9	−2.07
Head 3				199.6	−0.22	196.3	−1.84

*Measured absolute doses in water when each Head was set to gantry of 0°.
†Deviation between measured absolute doses and reference dose of 200 cGy .
‡Measured absolute doses in SWP when each Head was set to gantry of 90°.
§The value of dose for Head 2 was determined from measured absolute doses in solid water phantom using SWP to water correction factor.

inserted in a cylindrical water-equivalent phantom was used. Measurements were performed at gantry angles of 0°, 30°, 60°, 90° and 330° for Head 1, 90°, 270° and 330° for Head 2, and 0°, 45°, 90° and 270° for Head 3. The reference measurements were made at gantry angle of 0° for Head 1 and Head 3, and 90° for Head 2.

Results

1. AAPM's TG−51 protocol on Co−60 MRI−guided radiation therapy system

For absolute dose measurements based on AAPM's TG-51 protocol, correction factors and absolute doses in water and SWP were obtained as shown in Table 1. P_{ion}, P_{elec}, and P_{pol} were 1.001, 1.000, and 0.999, respectively. Measured PDDs for all Co-60 sources agreed with BJR supplement 25 data within 0.3%. For measured doses in water, the values of dose deviation according to a reference dose of 200 cGy for Head 1, Head 2 and Head 3 were −0.27%, −0.45% and −0.22%, respectively. The value of dose for Head 2 in water was not measured with ionization chamber. After measurement in SWP at gantry angle for Head 2 of 90°, this value were determined by multiplying SWP to water correction factor with the value of measured dose in SWP. For measured doses in SWP, the values of dose deviation according to a reference dose of 200 cGy for Head 1, Head 2 and Head 3 were −1.91%, −2.07% and −1.84%, respectively. All values of dose measured in SWP tended to be less than those measured in water by −1.63%.
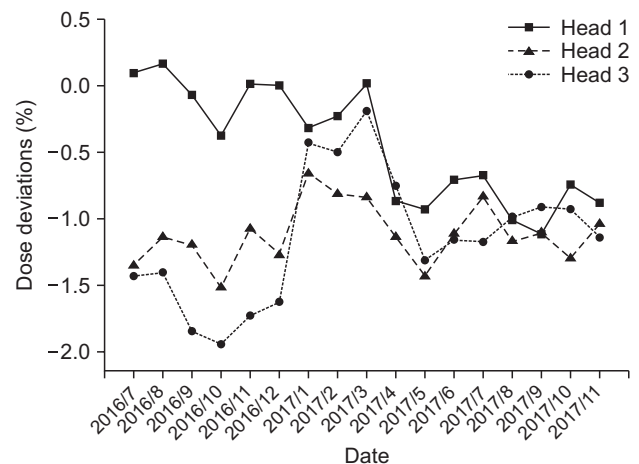
Fig. 2 demonstrates dose deviations between measured

Fig. 2. Dose deviations between measured absolute doses of all Co-60 sources and a reference dose of 100 cGy. After ViewRay® system was commissioned on July 2016, absolute doses were measured for every month.

absolute doses of all Co-60 sources and a reference dose of 100 cGy. After ViewRay® system was commissioned on July 2016, absolute doses were measured for every month. The maximum values of dose deviation for Head 1, Head 2 and Head 3 were −1.11%, −1.51% and −1.94%, respectively. All measurements had a low tendency in dose output. After calibrating ionization chamber and then performing absolute dosimetry on December 2016, dose deviations had decreasing tendency for Head 1 while having increasing tendency for Head 3. The dose deviations for Head 3 did not show noticeable tendency.

2. Output constancy with gantry angle

The output constancy according to gantry angles is

Table 2. Output constancy with gantry angle. The reference measurements were gantry angle of 0° for Head 1 and Head 3, and 90° for Head 2.

Head 1		Head 2		Head 3	
Gantry angle (°)	Deviation (%)	Gantry angle (°)	Deviation (%)	Gantry angle (°)	Deviation (%)
0	0.00	90	0.00	0	0.00
30	0.35	270	0.35	45	0.40
60	0.17	330	1.06	90	0.00
90	−0.44	–	–	270	0.22
330	0.48	–	–	–	–

shown in Table 2. The deviations were determined by comparing measured reading values for certain gantry angles with those for reference gantry angles of 0° and 90°. With the reference angles of 0° and 90°, the maximum values of deviation for Head 1, Head 2 and Head 3 were 0.48%, 1.06% and 0.40%, respectively. The deviation between measured reading values for gantry angles of 0° and 90° were within 0.44%. Since Head 2 cannot placed at gantry angle of 0°, the deviation between measured reading values for 0° and 90° could not obtained.

Discussion

In order to measure the absolute dose under static magnetic field in ViewRay® system, water phantom system was manufactured using non-ferrous materials and AAPM's TG-51 protocol for absolute dosimetry was verified with MR-compatible ionization chamber and the water phantom system. For absolute dosimetry, SWP and SWP to water correction factor were used in this study because Head 2 in ViewRay® system cannot go to gantry angle of 0° which is an inherent limitation in ViewRay® system.[1] As shown in Table 1, measured doses in SWP were lower than those in water. Considering that the values of deviation in output constancy with gantry angles are small, dose difference between water and SWP is caused by due to differences in physical properties. The results of the present study show the similarity to those found in the earlier studies.[23,24] It was demonstrated that ratio of restricted collision stopping powers solid water to air were lower than those for water and this result could affect the values of measured doses.[24] Choi et al.[25] validated the

effectiveness of dose conversion factor between SWP and water for photon and electron beam. With these factors, multi-institutional dosimetry audit was performed, showing a reasonable results and good reproducibility of audit for the external auditing program. SWPs also have different physical properties for each company and each energy range has different interaction with those SWPs. When using other combinations of SWP and energy range as well as that used in this study, different results can be obtained by up to 3%.[26] For this reason, SWP to water correction factors should be determined before applying the measurements.

In the presence of the static magnetic field, track of charged particles can be affected track by Lorentz's force. In the field of radiotherapy, the secondary electrons generated from photon-medium interactions and electron beam travel in a series of arc-shaped trajectories in tissue or water. The return electrons in arc-shaped track cause dose increase at all tissue-air interface which is called the electron return effect (ERE).[27] Several institutions have studied reference dosimetry in magnetic field ranged from 0.35 T to 3.0 T.[26,28,29] It was demonstrated that a chamber response with magnetic field depended on chamber radius, magnetic field strength, orientation of beam, chamber axis and magnetic field direction.[26] In our study, with a low magnetic field of 0.35 T, dose variation with and without magnetic field was less than 0.3% in Y direction (perpendicular to the axis of beam). With respect to MR image quality, the high strength of magnetic field is necessary to improve contrast of the image. Under high magnetic field, ERE can affect the output and treatment quality. For this reason, the correction factor for ERE should be obtained considering the affected elements.

Conclusion

In this study, water phantom system for ViewRay® system was manufactured and AAPM's TG-51 protocol for absolute dosimetry in the presence of static magnetic field was evaluated using MR-compatible ionization chamber. The measurement agreement is within the range of results obtainable for conventional treatment machines. The low strength of the magnetic field does not affect absolute dose

measurements. Using the SWP to water correction factor, absolute doses for ViewRay® system can be measured.

Acknowledgements

Conflicts of Interest

The authors have nothing to disclose.

Availability of Data and Materials

All relevant data are within the paper and its Supporting Information files.

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