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Original article

Evaluation of a magnetic resonance guided linear accelerator for stereotactic radiosurgery treatment

Ning Wen [a,*], Joshua Kim [a], Anthony Doemer [a], Carri Glide-Hurst [a], Indrin J. Chetty [a], Chang Liu [a], Eric Laugeman [a], Ilma Xhaferllari [a], Akila Kumarasiri [a], James Victoria [b], Maria Bellon [b], Steve Kalkanis [c], M. Salim Siddiqui [a], Benjamin Movsas [a]

[a] *Department of Radiation Oncology, Henry Ford Health System, Detroit;* [b] *ViewRay Inc, Mountain View; and* [c] *Department of Neurosurgery, Henry Ford Health System, Detroit, USA*

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ABSTRACT

Introduction: The purpose of this study was to investigate the systematic localization accuracy, treatment planning capability, and delivery accuracy of an integrated magnetic resonance imaging guided Linear Accelerator (MR-Linac) platform for stereotactic radiosurgery.

Materials and methods: The phantom for the end-to-end test comprises three different compartments: a rectangular MR/CT target phantom, a Winston–Lutz cube, and a rectangular MR/CT isocenter phantom. Hidden target tests were performed at gantry angles of 0, 90, 180, and 270 degrees to quantify the systematic accuracy. Five patient plans with a total of eleven lesions were used to evaluate the dosimetric accuracy. Single-isocenter IMRT treatment plans using 10–15 coplanar beams were generated to treat the multiple metastases.

Results: The end-to-end localization accuracy of the system was 1.0 ± 0.1 mm. The conformity index, homogeneity index and gradient index of the plans were 1.26 ± 0.22, 1.22 ± 0.10, and 5.38 ± 1.44, respectively. The average absolute point dose difference between measured and calculated dose was 1.64 ± 1.90%, and the mean percentage of points passing the 3%/1 mm gamma criteria was 96.87%.

Conclusions: Our experience demonstrates that excellent plan quality and delivery accuracy was achievable on the MR-Linac for treating multiple brain metastases with a single isocenter.

Image guidance has been a critical component for target localization in stereotactic radiosurgery via cone beam computed tomography, stereoscopic X-ray imaging, etc. [1,11,25]. However, the technical obstacles in developing an MR-guided radiosurgery system are significant due to the interactions between the magnetic field of an MRI system and the linear accelerator (Linac) system. On the Linac side, many critical components, including the magnetron and port circulator, cannot function properly in the presence of a magnetic field. The magnetic field can also divert both electrons traveling within the beam transport system and secondary electrons generated inside patients [16]. On the MRI side, the high-power radiofrequency energy from the Linac may significantly deteriorate MR image quality [10].

The MRIdian Linac system (ViewRay, Mountain View, CA) is the first MR-Linac system that has received 510(k) clearance from the U.S. Food and Drug Administration. Fig. 1(a) shows the MR-Linac system installed in our institution. The system involves a double-donut superconducting wide bore (70 cm) magnet with 0.345 T field strength and a 6 MV flattening filter free (FFF) Linac as shown in Fig. 1(b). The Linac components are spread among five cylindrical ferromagnetic compartments around a magnetically shielded ring located between the double donuts to avoid magnetic field interference (Fig. 1(c)). The shielding also contains carbon fiber for absorbing radiofrequency energy to avoid MR image quality degradation. The system is equipped with a double-stack, double-focus multi-leaf collimator (MLC), which enables the MLCs to achieve 2 mm spatial resolution (half the MLC leaf width), allowing for good dose conformity of small and complex-shaped tumors in treatment planning.

Stereotactic MR-guided adaptive radiation therapy has been demonstrated to provide an accurate and robust online adaptive solution for SBRT treatment using an MR-guided Co-60 therapy system [3,7,14]. However, due to the limitation of Cobalt source size and MLC leaf resolution, MR-guided stereotactic radiosurgery (MRgSRS) for intracranial treatment is not feasible on the Cobalt unit. The FFF Linac and double stack MLC design enable the possibility to treat small brain metastases and functional abnormalities under MR guidance. In this study, we investigated the systematic

* Corresponding author at: Department of Radiation Oncology, Henry Ford Hospital, 2799 W. Grand Blvd, Detroit, MI 48202, USA.
E-mail address: nwen1@hfhs.org (N. Wen).

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Fig. 1. (a) The MR-Linac system includes a split magnet MRI system, a rotating gantry assembly, and a patient-positioning couch with two in-room couch control panels; (b) a double-donut superconducting wide bore magnet with 0.345 T field strength; (c) the schematic of the Linac components housed in cylindrical ferromagnetic shields.

accuracy of the MRIdian Linac platform and the technical feasibility in treating multiple brain metastases with a shared isocenter. MRgSRS offers potential for an efficient treatment delivery method for treating multiple lesions simultaneously using advanced delivery techniques while the on-board MRI system will allow clinicians to precisely target stereotactic treatments using high spatial resolution 3D imaging for localization and real-time cine planar imaging for monitoring patient motion during treatment.

Methods and materials

Specification of the MR-Linac system

The MR-Linac system comprises a double-donut superconducting wide bore magnet with 0.345 T field strength and a 6 MV Flattening Filter Free (FFF) linear accelerator.

The two halves of the MRI bore are split by a gap of 28 cm, but the pair is mechanically and thermally connected for magnetic field stability through connections at the base of the bore. Each magnet half has ten coil bundles which were optimized to define a homogenous field in the gap. The Siemens MRI system implements true fast imaging with a steady state precession (TrueFisp) pulse sequence for patient positioning and monitoring. Nineteen predefined field of views and resolution combinations are available for patient setup and treatment planning purposes. The 3D image resolution can vary between $1.5 \times 1.5 \times 1.5\ mm^3$ and $1.5 \times 1.5 \times 3.0\ mm^3$ for planning scans. Additionally, real-time planar cine images are acquired continuously during the treatment with $3.5 \times 3.5\ mm^2$ in-plane resolution and 7.0 mm slice thickness either at four frames per second in one sagittal plane or at two frames per second in three consecutive, parallel sagittal planes. Fig. 2 shows the MR images acquired of a healthy volunteer on the MR-Linac using 1.5 mm isotropic voxels and 100 s acquisition time.

The Linac system is equipped with a double-stack, double-focused 138-leaf MLC. The top and bottom layers have 34 and 35 non-ferromagnetic tungsten alloy leaf pairs in each bank, respectively, and they are offset by half of a leaf thickness in the leaf side direction. The physical leaf width is 0.415 cm and the smallest field size achievable is $0.2 \times 0.4\ cm^2$. The system can deliver 3D conformal or step and shoot IMRT plans at a dose rate of 600 cGy/min.

Evaluation of the systematic accuracy

It is essential to quantify the imaging, mechanical, and radiation isocenter stability for the SRS treatments. Multiple approaches have been developed to quantify the radiation isocenter accuracy [4,21,23]. In our study, we developed a phantom for both MR image-based localization and radiation isocenter verification. An end-to-end test simulating the patient treatment workflow was performed to systematically quantify the accuracy of the system.

Description of the end-to-end test phantom

A prototype end-to-end phantom was designed using the compartments from a stereotactic verification phantom (Computerized Imaging Reference Systems, Norfolk, VA) to evaluate the system accuracy. The phantom has three modules as shown in Fig. 3(a): a rectangular MR/CT target phantom containing an irregularly shaped 25 cc volume, a Winston–Lutz cube, and a rectangular MR/CT isocenter phantom containing a ceramic ball bearing (BB). Both rectangular phantoms are filled with distilled water to produce sufficient signal for MR scanning. The 25 cc irregular shape is filled with copper sulfate solution and can be used during the MR/CT fusion of the images for localization. The ceramic fiducial placed in the rectangular MR/CT isocenter phantom is also used to verify the alignment of the phantom, especially in the superior/inferior direction. The cubic phantom in the middle contains a 5 mm diameter tungsten BB at the centroid for the Winston–Lutz test.

The end-to-end test

CT simulation of the end-to-end phantom was performed using a Philips Brilliance Big Bore (Best, Netherlands) CT scanner in helical mode with 0.9 mm slice thickness, $0.5 \times 0.5\ mm^2$ in-plane resolution, and settings of 125 kVp and 1062 mAs. This CT image data set was used as the reference image for image registration (Fig. 3(b)). The 25 cc irregular shape, ceramic BB, and tungsten BB were contoured in the Viewray treatment planning system (ViewRay Inc, Mount View, CA). Treatment isocenter was placed at the center of the tungsten BB in the CT image set. EBT3 Gafchromic films (Ashland ISP Advanced Materials, Wayne, NJ) from a single batch were affixed to all four sides of the central cube phantom (Fig. 3(a)). In the treatment room, the phantom was setup by aligning the wall-mounted lasers to the scribes on the Winston–Lutz cube. Then, the phantom was moved 6 cm inferiorly so that the isocenter was placed at the center of the CT/MR target phantom, which could generate sufficient signal at isocenter to perform MR imaging. Shifts from isocenter of up to 2 cm were also made in the lateral and vertical directions to provide various initial setup conditions. A predefined MR scan with 92 s acquisition time and $1.5 \times 1.5 \times 1.5\ mm^3$ resolution was acquired, and a rigid registration of the MR images to the reference CT images was performed manually as shown in Fig. 3(c). The window and level of the acquired MR images and CT reference images were optimized for visualizing the irregular shape and ceramic BB during fusion. Manual rigid registration was performed to remove the initial lateral, vertical, and inferior shifts. Three degrees of freedom (DoF) couch corrections (translation only) were applied based on the rigid registration results. The four-field Winston–Lutz tests were performed to quan-

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