First MR images obtained during megavoltage photon irradiation from a prototype integrated linac-MR system

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The authors report the first magnetic resonance (MR) images produced by their prototype MR system integrated with a radiation therapy source. The prototype consists of a 6 MV linac mounted onto the open end of a biplanar 0.2 T permanent MR system which has 27.9 cm pole-to-pole opening with flat gradients (40 mT/m) running under a TMX NRC console. The distance from the magnet isocenter to the linac target is 80 cm. The authors’ design has resolved the mutual interferences between the two devices such that the MR magnetic field does not interfere with the trajectory of the electron in the linac waveguide, and the radiofrequency (RF) signals from each system do not interfere with the operation of the other system. Magnetic and RF shielding calculations were performed and confirmed with appropriate measurements. The prototype is currently on a fixed gantry; however, in the very near future, the linac and MR magnet will rotate in unison such that the linac is always aimed through the opening in the biplanar magnet. MR imaging was found to be fully operational during linac irradiation and proven by imaging a phantom with conventional gradient echo sequences. Except for small changes in SNR, MR images produced during irradiation were visually and quantitatively very similar to those taken with the linac turned off. This prototype system provides proof of concept that the design has decreased the mutual interferences sufficiently to allow the development of real-time MR-guided radiotherapy. Low field-strength systems (0.2–0.5 T) have been used clinically as diagnostic tools. The task of the linac-MR system is, however, to provide MR guidance to the radiotherapy beam. Therefore, the 0.2 T field strength would provide adequate image quality for this purpose and, with the addition of fast imaging techniques, has the potential to provide 4D soft-tissue visualization not presently available in image-guided radiotherapy systems. The authors’ initial design incorporates a permanent magnet; however, other types of magnets and field strengths could also be incorporated. Usable MR images were obtained during linac irradiation from the linac-MR prototype. The authors’ prototype design can be used as the functional starting point in developing real-time MR guidance offering soft-tissue contrast that can be coupled with tumor tracking for real-time adaptive radiotherapy. © 2009 American Association of Physicists in Medicine. [DOI: 10.1118/1.3125662]

Key words: real-time MR-guided radiotherapy, linac, MR, image guidance

I. INTRODUCTION

There are proposals for merging megavoltage radiation therapy source with a magnetic resonance imager to allow real-time adaptive radiotherapy. Active groups in this area have discussed integrating a $^{60}$Co source or a linear accelerator (linac) to a magnetic resonance (MR) imaging system. The dose deposition characteristics accounting for the influence of the magnetic field have been studied for each of these proposed geometries. Although several mutual interference issues have prevented the successful integration of these devices in the past, our group at the Cross Cancer Institute reports the design, development, and construction of the first functional linac-MR system that has produced MR images concurrently with megavoltage irradiation. These images, we believe, are the first images produced by an MR system integrated with a radiation therapy source. In this
report, we briefly describe the system and present the results as a proof of concept of the system operation.

II. MATERIALS AND METHODS

Our first prototype system (Fig. 1) is comprised of a 6 MV linac directing radiation beam to the imaging volume through one of the openings of a biplanar Nd$_2$Fe$_{14}$Bpermanent MR magnet system. The magnet has a field strength of 0.2 T and is commercially available from MRI Tech Co. (Winnipeg, MB, Canada). The prototype MR magnet system has a pole-to-pole separation of 27.9 cm, and flat gradient coils are placed on each of the sides of the biplanar poles facing the subject. Linac, magnet structure, and gradient coils rotate in unison within the transverse plane about a single rotational axis. The maximum gradient strengths are specified as 40 mT/m. The MR console is a TMX NRC (National Research Council of Canada, Institute of Biodiagnostics, Winnipeg, MB, Canada). The console software is based on Python programming language (Python Software Foundation, Hampton, NH www.python.org), version 2.3.4, to allow the user full control of development and modification of pulse sequences. Analogic (Analogic Corporation, Peabody, MA) AN8295 gradient coil amplifiers and AN8110 3 kW radiofrequency (RF) power amplifiers are used in the TMX NRC system. The linac components are composed of salvaged parts from a decommissioned magnetron-based Varian 600 c system, which include the straight-through waveguide (without bending magnet). The distance of the linac target to the magnet center is 80 cm. Presently, the MV x-ray beam has primary collimators and the final prototype design will include secondary moving jaws and the multileaf collimator (MLC). A conventional Faraday cage, as is customary for any MR system, surrounds the magnet itself to avoid all RF interferences. Parts of the Faraday cage are visible in Fig. 2. The prototype is currently on a fixed gantry; however, in the future, the linac and MR magnet will rotate in unison such that the linac is always aimed through the opening in the biplanar magnet.

The magnetic field in the accelerating waveguide must be minimized or the electrons will be deflected, preventing them from reaching the end of the accelerating structure and producing x rays. The design goal of magnetic shielding was to achieve a magnetic field of less than 0.5 G (earth’s magnetic-field strength) in and around the accelerating structure while maintaining excellent field homogeneity within the imaging volume. The magnetic field of the MR magnet including magnetic shielding was modeled by using COMSOL MULTIPHYSICS (version 3.4, Comsol, Stockholm, Sweden) and its AC/DC module in conjunction with MATLAB (The MathWorks Inc., Natick, MA) scripts. Multiphysics simulates partial differential equation (PDE)-based problems by using finite element method (FEM) analyses. In our simulations, a 3D model based on the magnetostatics of magnetic materials without electric currents was used.

The 3D simulation geometry is composed of the magnet structure confined in an air-filled cube with a 4 m side, i.e., world box. The world box is required to define the space in which the domain equations are solved and to minimize the computation time. Additional components were placed in the vicinity of the magnet for shielding purposes, i.e., a pair of steel plates and a metal box surrounding the linac and MLC. The main boundary condition required to solve the simulation was along the exterior boundaries of the world box. Specifically, the magnetic field was assumed to be tangential to the box’s walls to resemble the closed loop characteristic of the field lines. The relative permeability curves as a function of magnetic field for the main structures were used in the simulation. Mesh size in FEM for a given component
was selected according to the component size and the desired local resolution. Our mesh size is 0.05 of the size of each structure used in the simulation. We used the FGMRES solver with an algebraic multigrid preconditioner which optimizes the solver for maximum performance with significant reduction in memory usage when applied to large 3D models. The system is set up to stop simulations when the differences between two consecutive iterations is below $10^{-6}$ (this setting is defined as the relative tolerance in the software).

Magnetic-field measurements were obtained with a 3D Hall magnetic-field probe (C050, Senis, GMW Associates, San Carlos, CA) to confirm the efficacy of acceptable shielding that was designed using simulation. A phantom, as shown in its CT image in Fig. 3, was used to test the operation of the linac-MR system. The phantom consists of an acrylic rectangular cube, $15.95 \times 15.95 \times 25.4$ mm$^3$ with holes of diameters of 2.52, 3.45, and 4.78 mm that were drilled parallel to the length (along 25.4 mm) of the rectangular cube. The cube was immersed in a 10 mM solution of CuSO$_4$ within a plastic container with 22.5 mm inner diameter. The container with the cube insert was placed inside an inductively tuned solenoid RF coil with an integrated pin-diode transmit/receive switch.

III. RESULTS AND DISCUSSION

The meshed colorwash resulting from our FEM simulations in Fig. 4 depicts the magnetic field inside and just outside the magnet structure. The vertical shield plates are indicated. The light blue area depicts the extension of the 0.5 G, while the white areas depict less than 0.5 G. As already stated, the objective in this exercise was to shield the waveguide from the magnet so that the waveguide would reside in a field roughly equivalent to that of the earth’s magnetic field, around 0.5 G. This was chosen because linacs operate within the earth’s magnetic field. Items 2 and 3 depict the areas to be occupied by the MLC and the linac waveguide, respectively.

The magnetic fields from the MR system were measured along the central axis of the waveguide with and without shielding and are shown in Fig. 5. The magnetic shielding is placed at about 65 cm from the MR magnet isocenter. It is clear that the magnetic-field within the shielded regions is essentially removed, ensuring that the path of the electron within the waveguide is not influenced by the magnetic field of the MR system.

The linac waveguide was physically attached to the MR magnet of the prototype. An important result is to validate whether the magnetic shielding was appropriate to allow the linac-MR prototype to produce x rays. The linac monitor chambers indicated x-ray production. In addition, survey
meters indicated high levels of radiation around the device and the vault. Computed radiograph (CR) (CR 25, Agfa-Gevaert Group, Belgium) images were taken on the prototype. The images show a central circular area of radiation because the system only contains the primary collimator. A profile through the resultant image is shown in Fig. 6. All these tests confirmed that the linac in our prototype was producing radiation. The complete evaluation of symmetry and flatness will be made after the addition of secondary jaws.

An experiment was performed to validate whether the linac-MR prototype would produce a usable MR image during linac irradiation. If the MR image obtained during linac irradiation is not considerably distorted, compared to the MR image obtained without powering up the linac, then the proof of concept of the design has been achieved.

Multiple MR images were acquired both with beam on and beam off. Signal-to-noise ratios (SNRs) were calculated from images obtained in the area of the phantom that only show the CuSO₄ solution without the insert. The signal is the average of image pixels in a specified region of interest (ROI) within CuSO₄ solution, while the noise is the standard deviation of image pixels in a similar-sized ROI taken outside the signal area. Typical MR images of the phantom (CT image in Fig. 3) are shown in Fig. 7. Figure 7(a) is an image with linac powered on without beam on: SNR=80; Fig. 7(b) is image obtained during the radiation pulse outside acquisition imaging window: SNR=61; and Fig. 7(c) is image obtained during radiation pulse inside acquisition imaging window: SNR=16. All these were obtained with one signal average and 50 MU/min setting of dose rate on the linac. Except for the changes in SNR, there are no significant distortions apparent between the various images of the phantom. This is also true for corresponding slices taken at other locations of the phantom. Profiles measured through the phantom for these images are shown in Fig. 8. We expect to improve the SNR as RF shielding was not fully implemented in this experiment. However, the main concepts for proof of principle have been achieved.

It must be emphasized that the task for the linac-MR system is to provide real-time MR-guided radiotherapy and not to diagnose, and although 0.2 T system may not have the optimum field strength for diagnosis, it has been used as diagnostic tools[6–12] and, with the appropriate fast imaging sequences, could provide the required SNR for radiotherapy guidance. The generic design shows promise and acts as the starting point for developing real-time adaptive radiotherapy coupled with tumor tracking based on soft-tissue visualization provided in MR images. As the generic design matures, the permanent magnet may be replaced by resistive/superconductive magnets with greater field strength.

IV. CONCLUSION

We have obtained usable MR images from our integrated linac-MR prototype during megavoltage irradiation from the linac. This demonstrated that the methods of magnetic shielding of the linac from the MR’s magnetic field and of RF shielding using a Faraday cage are capable of obtaining an MR image during linac irradiation. The design and construction are, of course, being optimized to obtain faster images with sufficient SNR and increase in FOV to allow...
whole body treatment. We are currently investigating phan-
toms to ensure that the magnet and linac isocenters are
aligned.

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