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The Rotating Biplanar Linac–Magnetic Resonance Imaging System

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We have successfully built linac–magnetic resonance imaging (MR) systems based on a linac waveguide placed between open MR planes (perpendicular) or through the central opening of one of the planes (parallel) to improve dosimetric properties. It rotates on a gantry to irradiate at any angle. Irradiation during MR imaging and automatic 2-dimensional MR image–based target tracking and automatic beam steering to the moving target have been demonstrated with our systems. The functioning whole-body system (0.6-T MR and 6-MV linac) has been installed in an existing clinical vault without removing the walls or the ceiling and without the need of a helium exhaust vent.
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Introduction

As discussed in more than 35 of our peer-reviewed articles (http://linacmr.ca/publications.html), we have made progress toward the realization of an innovative clinical linac–magnetic resonance imaging (MR) system, which involves the integration of a linac onto a biplanar rotating MR system shown in the Figure. The main magnet field in a biplaner open magnet goes from one plane to the other (ie, the field vector is perpendicular to the planes). The linac can be placed to irradiate either between the MR's magnet planes or poles or through the central opening of one of the planes. In this way, the corresponding radiation field can be either perpendicular or parallel to the main magnetic field, resulting in different physical or clinical properties. The rotation is required to deliver the radiation beam at a particular angle. The system allows MR during beam on for "live" guidance of the radiation beam.

We have undertaken a 3-phase approach to the development of our linac-MR. Phase I combined a 6-MV linac with a head-sized permanent magnet and demonstrated the feasibility of linac and MR integration, and it was the first to deliver linac radiation during MR acquisition.[1] This allowed us to solve many fundamental scientific and engineering problems that were thought to prohibit both MR-based radiation treatment planning and the integration of a linac and MR into a single system. Phase II interfaced a 6-MV linac with a commercial superconducting whole-body (0.6 T) open-bore magnet to demonstrate the structural and mechanical integrity of the system on a scaled-up rotating gantry. Phase III is our clinical system.

Physics and Engineering Research Development

The following is a brief discussion of our basic physics and engineering development (phases I and II).

MR Simulation and Image Distortions

It is well known that MR images include inherent distortions that must be addressed before their use in radiation therapy planning (also known as simulation). To overcome this, we have developed methods that combine a phantom-based reverse-gradient technique for measurement of gradient nonlinearities and a patient-based phase-difference mapping technique for measurement of magnetic field (B_o) inhomogeneities, susceptibility, and chemical shift distortions. With distortions corrected, we have shown that MRs can be used for treatment planning.[2]

MR Magnet Design

To improve image quality over a larger field of view, we have designed a finite-element analysis technique to optimize the

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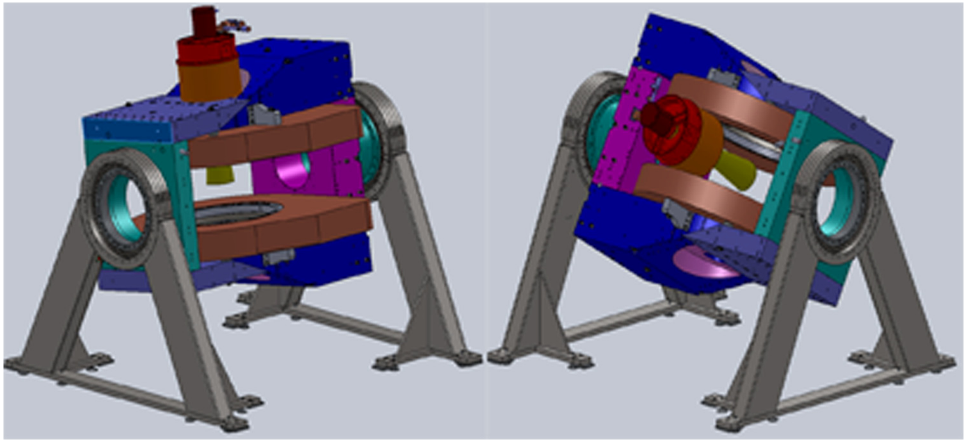

Figure Schematic representation of our currently installed phase II whole-body research system with its designed gantry at the Cross Cancer Institute. This gantry facilitates a 360° rotation of our linac-MR allowing for complex RT treatment plans to be delivered. (Left) Parallel configuration; (right) perpendicular configuration. The linac is 6 MV and the MR is a 0.6-T system with a rectangular opening for the patient (currently, the 60-cm gap is being increased to more than 85 cm) between the 2 poles. RT, radiation therapy. (Color version of figure is available online.)

MR-supporting yoke and pole structure. This further reduces image distortion by improving magnetic field homogeneity. We applied this technique to the Food and Drug Administration–approved superconducting MR to improve its homogeneity for phase III.[3]

Radiofrequency Shielding

MR acquisition relies on measuring the very small radiofrequency (RF) fields generated in the patient. We were the first to quantify the RF noise emanating from the linac and its associated components, which overruns the small patient signal and reduces image quality. We have developed shielding techniques to completely eliminate this unwanted RF noise, thus providing a full recovery of imaging signal-to-noise ratio (SNR).[4]

Radiation-Induced Current

Photon radiation in the therapeutic energy range (MeV) interacts predominantly with electrons in matter. These interactions induce a current in metals, and we quantified its effect in MR coils. We were the first to quantify the image SNR reduction of 15%-18% at 250 MU/min owing to radiation-induced current (RIC), and we have developed methods based on either buildup or image processing in k-space (frequency space of the MR image) to improve SNR and remove RIC effects in our MR images.[5]

Magnetic Shielding

Radiotherapy beams are generated by accelerating electrons within a linac toward a target; subsequent target interactions result in x-ray emission. However, in the presence of magnetic fields, electrons deviate from their straight trajectory according to the Lorentz force. We investigated the effects of MR fringe fields on the linac through generation of benchmarked simulations. Our results showed significant, negative effects on radiation output, and we have developed active- and passive-shielding methods to eliminate these effects and recover full linac functionality.[6,7]

Real-Time Tumor Tracking

Real-time tracking requires execution of specific pulse sequences, postprocessing of raw data, and multileaf collimator (MLC) motion in real time. These processes require a finite amount of time. In our development of tumor tracking, we generated (1) an automatic tumor-contouring algorithm to determine tumor position, (2) a tumor-position prediction algorithm using artificial neural networks, and (3) a tested control system that moves the MLCs in real time to conform to the tumor[8] at the time of irradiation.

Dosimetry in Magnetic Fields

Electrons within the patient gain kinetic energy from the incoming photon radiation. As the electrons travel through the patient, their trajectories are influenced by the MR magnetic field; their direction and the locations at which they deposit energy are changed.[4] We have performed simulations investigating the effect of magnetic fields on patient dosimetry, which may have significant dose increases at the interface of lung and tissue or air and tissue, which must be accounted for.[9,10] To date, no optimization techniques have shown to resolve this issue at the lung-tissue or air-tissue interfaces.

Practical Implementation and Installation

Our system allows configurations where the radiation is either perpendicular or parallel to the MR's main magnetic field. We have shown that the parallel configuration avoids exit skin dose and dosimetric hot spots[9,10] that result from the electronreturn effect that exists within the perpendicular configuration in other systems.

Current installations of MR systems require delivering the magnet in a single piece through an open wall or ceiling and a liquid helium exhaust vent. This would be impractical for existing radiation therapy vaults because of their thick concrete walls and ceilings required for radiation shielding (∼2 m). Our linac-MR integrates a high-temperature superconducting magnet that allows us to overcome these critical issues, as well as facilitates rotating the magnet required in our design. A cryocooler is used to maintain the superconducting temperature without the need for cryogenic liquids. In addition, our system is delivered in parts that are small enough to fit through standard radiotherapy vault entrances and can be reassembled, thus avoiding massive construction costs if walls have to be built after the installation. This installation technique for our linac-MR unit follows the current method of installing medical linacs in pieces within existing vaults. Our phase II system fits within our relatively small vault that is only 5.9 m in depth, 6 m in width, and 3.6 m in height.

Conventional MR simulation, with or without computed tomography simulation, is performed in the pretreatment stage to prepare the treatment plan. Fusion of the pretreatment MR (diagnostic and simulation) images with the at-treatment MR images from the linac-MR system helps the positional setup at and during treatment We believe that our linac-MR is a simple system that allows improved and unique radiation dosimetry because, in addition to the perpendicular configuration that other systems have, it uniquely offers a parallel configuration that eliminates additional exit dose, and running at the optimum magnetic field strength of 0.6 T is, essentially, the only way shown to eliminate the radiation hot spots that occur at lung-tissue interfaces within the lung. In addition, our successful demonstration on our prototype to "on-the-fly" automatically contour, track, and irradiate moving, physical lung-type targets with controlled MLC-motions shows the potential of concurrently seeing, tracking, and irradiating the target with minimal involvement of adjoining health tissues. Furthermore, because our linac-MR uses a high-temperature superconducting magnet, costs of renovation are substantially reduced.

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