

A novel MR-guided radiotherapy system: simulation and experimental validation

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Purpose

MR-guided linear accelerator (linac) technologies are newly emerging as feasible solutions for treatment delivery guidance in radiotherapy. At our institution, a 1.5T MR scanner on rails (IMRIS, Minnetonka, MN) can travel in/out an adjacent 6X TrueBeam linac (Varian Medical Systems, Palo Alto, CA) vault and image in the close proximity of the linac (see Fig. 1). During MR imaging, the linac is in a stand-by mode, with the radiation beam interlocked, and behind RF doors. A modified treatment table (Varian Medical Systems, Palo Alto, CA) transfers the patient between the linac and MR isocenters. The aim of the study was to quantify the magnetic field coupling between the MR fringe field and various ferromagnetic structures present in the linac and patient table assembly. The analysis included numerical simulations as well as experimental measurements.

Methods

The entire MR-linac space was simulated by means of finite element methods in COMSOL Multiphysics (Burlington, MA). All ferromagnetic structural sub-components were identified for the linac (e.g. gantry, bend magnet yoke) and treatment table (e.g. wrists, brakes, main arm). CAD geometries were generated and simplified to allow appropriate meshing with input from the manufacturer (Varian). HB curves for all materials were available from the literature. The 1.5T MR fringe field was available as tabulated data (manufacturer) and from measurements. A realistic coil configuration was generated by using linear optimization techniques[1] to mimic the MR field. Specifically, a coil domain was searched for a global solution representing the most optimal ensemble, given a specific input field map. The coil configuration was then added to COMSOL to generate the MR environment for the simulations. The physics solved the Maxwell equations with boundary conditions in the AC/DC module. The computations included multiple scenarios: variable distance between linac/table and MR and linac gantry rotations. Extensive measurements were also performed to map the magnetic field (Hall probes for low/high fields) at the linac/table and characterize the magnetic pull forces on the various table sub-structures.

Results & Discussion

The main objective for the quantification of the mutual magnetic field decoupling was to find the minimum distance between the MR and linac isocenters for which: a) the fringe field at linac key components (head, waveguide, gun) was negligible to allow the optimal x-ray beam production, b) the magnetic forces at table brakes were well below the limits for the safe operation, and c) the MR field homogeneity inside the imaging volume stayed unperturbed. The optimal iso-to-iso distance was found to be 3.1 m. For this, the maximum fringe field values at the linac head were less than 20 G. The simulation results for the forces and magnetic field mapping at various linac/table locations were in good agreement with the measurements. The MR imaging was fully shimmed for all intended imaging setups in the linac room.

Conclusion

The study confirms the feasibility of the MR-guided linac system. The system is expected a) to provide additional anatomical information, based on MR's excellent soft-tissue contrast, to guide the daily patient setup verification and b) to provide a robust platform for adaptive radiation treatment planning and tumor response assessment.

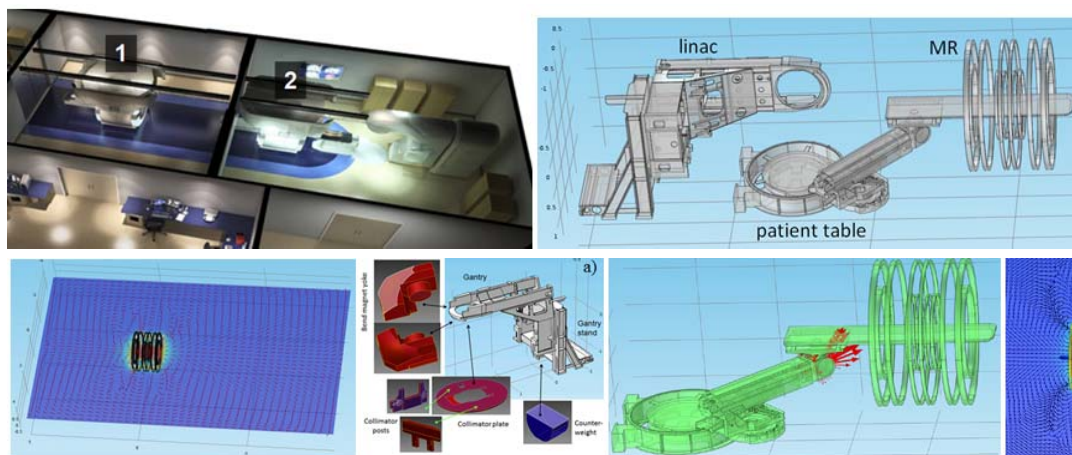


Figure 1: a) MR-guided linac system facility layout: MR at position 1 (MR Sim suite) and 2 (linac vault); b) depiction of the FEM simulation space showing the MR coils, linac and patient table in position at the MR isocenter.

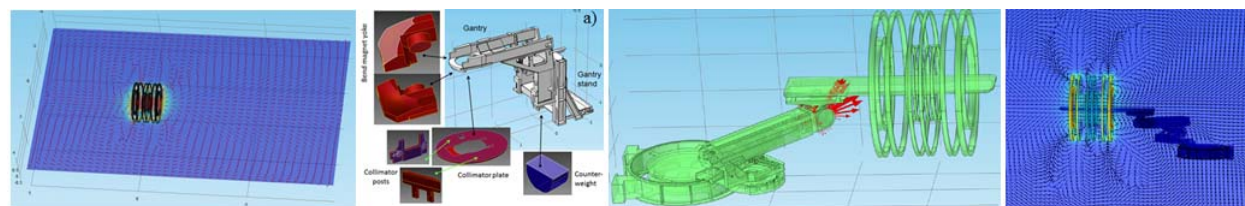


Figure 2. a) Simulated 1.5T MR fringe field using a realistic coil configuration; b) linac CAD geometry including various structural sub-components; c) MR-table assembly example highlighting the computation of magnetic forces on a wrist using the Maxwell stress tensor; d) sample magnetic field map.