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Title

The Australian MRI-Linac Program

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Abstract

The Australian MRI-Linac Program is a $16M government-funded project to advance the science and clinical practice of exquisite real-time anatomic and physiologic adaptive cancer therapy. The centerpiece of the program is a specifically designed 1 Tesla open bore MRI/6MV linac system which is planned for delivery and completion of installation in 2014. Current scientific endeavors include engineering discovery in MRI component design, quantifying MRI and linac interactions and developing image guidance and adaptation strategies.

Body of Manuscript

Introduction

The genesis of the Australian MRI-Linac Program was a $47M Australian Federal Government Health and Hospitals Fund grant to establish the Ingham Institute for Applied Medical Research, of which $7.5M was allocated to a research linear accelerator. Through a series of strategic discussions, acquiring an existing state-of-the-art system was ruled out. We preferred to take a high risk approach, with the vision to create a unique facility that performs world class research with a global impact on the science and clinical practice of radiation oncology. Hence, the Australian MRI-Linac Program was born, based on the synergy between MRI's ability to provide exquisite spatial and temporal images of the tumor and surrounding normal tissue, and adaptive radiotherapy that can precisely account for anatomic changes. An intriguing and largely unexplored question is the capability of MRI to provide physiologic tumor and normal tissue information during and between fractions, such that the most radio-resistant and pre-metastatic regions of the tumor can be targeted with extra radiation dose, and the more sensitive normal tissues can be optimally spared. In this paper we will discuss long and short term research questions, describe our system and outline the scientific endeavors of the Australian MRI-Linac Program.

Research questions

The top-level scientific and clinical questions for MRI-guided radiotherapy that we plan to answer in the long term are:

(1) For each tumor site, what is the expected clinical benefit of real-time anatomic targeting?

(2) What temporally changing cancer physiology is most important for radiation targeting?

(3) What new treatments– oncologic and non-oncologic – are enabled by MRI-guided radiotherapy?

(4) How does real-time MRI-guided radiotherapy interact with concomitant cancer treatments?

The shorter term research questions related to the design and implementation of real-time MRI-Guided radiotherapy include: What are the advantages and disadvantages of the inline (linac aligned with the main magnetic field, B_0) compared with the perpendicular orientation (linac perpendicular to B_0)? If the inline approach is preferable, what are the trade-offs between rotating the system and the patient? If the perpendicular approach is preferable, what are the pros and cons of an open vs. closed bore design? How do the MRI and linac interact with each other? What guidance and adaptation strategies are feasible and optimal?

Key design choices and motivation

The centerpiece of the Australian MRI-Linac Program is a specifically designed 1 Tesla open bore MRI/6MV linac system. The key system components and specifications are shown in Table 1. The MRI-Linac is designed to facilitate the experimental investigation of both the inline and perpendicular orientations (Figure 1). A comparison of the advantages of inline and perpendicular approaches to be experimentally investigated is shown in Table 2. Should the inline approach prove superior, due to the sensitivity of the MRI to motion, the question arises as to whether to rotate the MRI-Linac (more costly and risky) or the patient (less comfortable). Options for rotating the MRI-Linac or the patient, in the horizontal and upright planes for the inline configuration, are shown in Figure 2.

Results and key achievements to date

A challenge of creating an integrated MRI-Linac is that the linac components affect the magnetic field, and the magnetic field affects the linac. To address the problem of the effect of the multileaf collimator (MLC) on the imaging volume homogeneity, a comprehensive finite element modeling study was performed.[1] Key findings of this study were that (1) the MLC does not induce significant field inhomogeneity for source-axis distances of 140cm or more in both inline and perpendicular orientations, (2) the different positions of the MLC leaves during treatment does not induce inhomogeneity sufficient to require dynamic shimming (<5ppm), and (3) the force between the MLC and magnet is manageable (<1500N).[2]

Studies on the effect of the magnet on the linac have focused on the electron gun and skin dose. The magnetic field affects an unshielded electron gun causing current loss in the inline and perpendicular orientations, though the gun is much more sensitive in the perpendicular orientation as the magnetic field accelerates electrons in the gun orthogonally away from the waveguide.[3]

Modifications to the gun can potentially improve the performance. Skin dose for the inline orientation from contamination electrons has been modeled[4-6] and is a concern for inline designs. Potential methods to ameliorate this problem are magnet design, bolus, magnetic scrapers and helium regions above the patient.

Gradient coils for the open bore MRI-Linac system require a bespoke design. The design constraints require strong, linear gradients to be generated over a 30cm diameter of spherical volume (DSV) while preserving the 50 cm patient gap. The designs are based around a method that allow flexible shapes and includes eddy current minimization in the design process.[7, 8] The radiofrequency (RF) system includes a transmitter coil that allows patient access in both orientations and an 8-channel phased array receiver system.

Image guidance and adaptation are additional challenges for MRI-Linacs. We have developed a guidance strategy via the template matching of orthogonal 2D cine MRI with 3D images, where the 2D cine MRI planes intersect the target motion path.[9] The potential for MRI to guide adaptive radiotherapy to account for tumor deformation using a multileaf collimator has been demonstrated.[10]

In order to quantify the patient experience with rotation we have opened and are accruing patients to the ethics-approved clinical study *An investigation into the patient experience of rotation in upright and lying positions* using the Epley Omniax device which is in common use in neurology for the treatment of balance disorders.[11]

The research program has grown from the initial $7.5M investment into a $16M fully Government-funded enterprise with support through 2017.

Conclusions

Real-time MRI-radiotherapy is a potentially disruptive technology to improve cancer and non-oncologic disease outcomes through non-invasive exquisite anatomic and physiologic targeting. The Australian MRI-Linac program, along with other programs around the world, is advancing the science and clinical practice of this exciting new technology.

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Figure legends

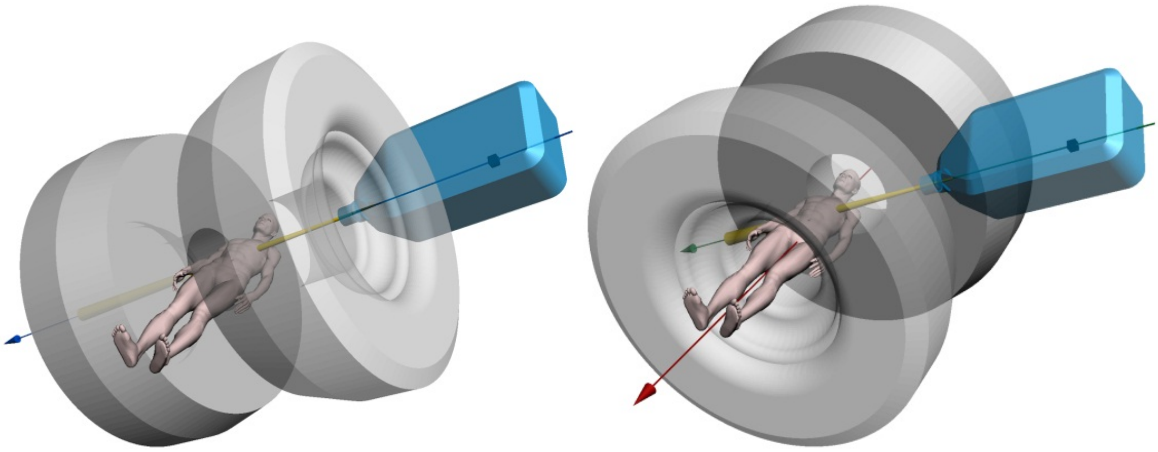

Figure 1. (Left) The inline orientation, i.e. linac aligned with B_0. (Right) The perpendicular orientation, i.e. linac perpendicular to B_0. Both orientations are to be experimentally investigated. From Ref. [3] with permission.

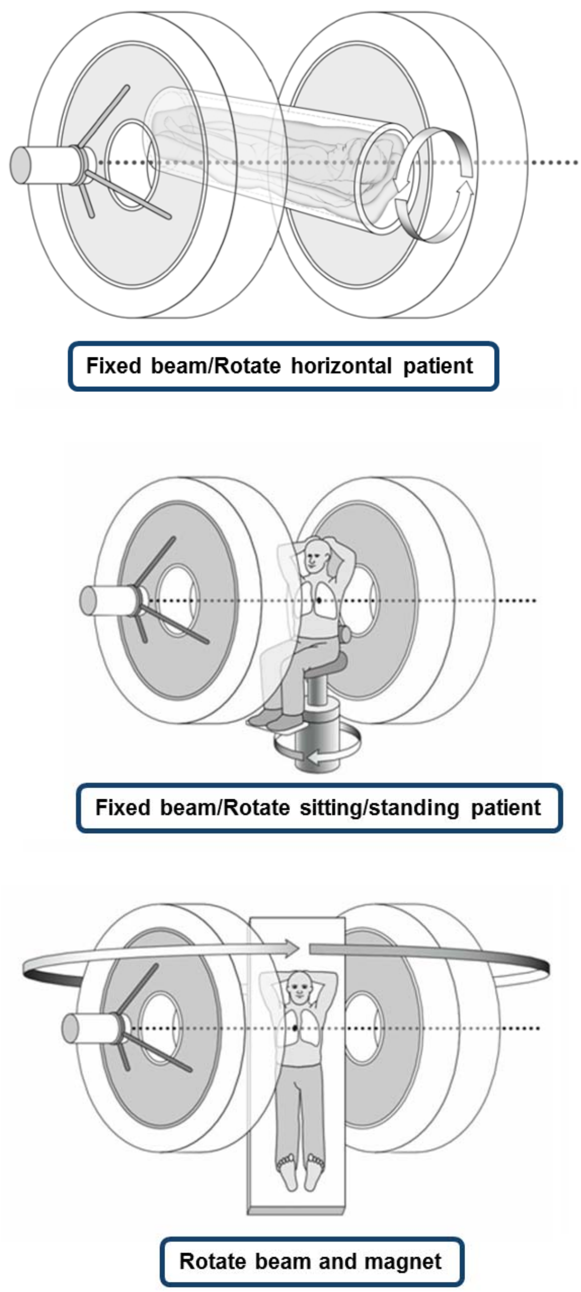

Figure 2. Configuration options for the inline design include rotating the patient in the horizontal plane or upright plane and rotating the beam and magnet.

Table(s)

Table 1. Key components and specifications for the Australian MRI-Linac system.

Component	**Key specifications (Supplier, timeline)**
System bunker	Radiation and magnetic shielding (Crooks construction, complete).
Magnet	1 Tesla open bore magnet, 82 cm diameter bore, 50cm gap, actively shielded with a low field region along B_0 where the linac/MLC will be placed (Agilent, 4/2014).
Spectrometer/Control system	MR imaging subsystem based upon Magnetom Avanto (Siemens, 3/2014).
Gradient coils	High performance split gradient coil, 50cm gap between coils (Tesla, 4/2014).
RF coils	Circularly polarized transmitter coil with an 8-channel receive array (Magnetica, 4/2014).
Linear accelerator	6MV Linatron MP industrial linac (Varian, delivered).
MLC	Millennium 120-leaf allowing real-time control (Varian, delivered).

Table 2. A comparison of the advantages of inline and perpendicular approaches that will be experimentally investigated.

Advantages of inline (Figure 1 left)	Advantages of perpendicular (Figure 1 right)
No beam attenuation and Compton scatter to the patient from irradiation through the Cryostat (if closed bore)	More similar design to mass-produced conventional MRI systems (if closed bore)
Less impact of the B field on electron gun operation	Lower constraints on magnet, gradient coil and RF design resulting in higher potential imaging performance and higher B-field (if closed bore)
Less impact of the B field on waveguide operation	Lower skin dose
Less impact of the B field on electron transport within the patient: sharper penumbra and no electron return effect	No need to rotate magnet or patient
Lower exit dose	
Linac fixed with respect to magnet. This reduces the need to manage eddy currents or dynamic shimming requirements where the linac moves with respect to the magnet	