SEEING TREATING ADAPTING

Cross Cancer Institute MR-Linac: Rotating the Magnet-linac Combo

Real-time MR Guided RT

B.Gino Fallone

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University of Alberta, Edmonton, AB Canada

Linac-MR.ca

Alberta Health Services
Alberta Cancer Board

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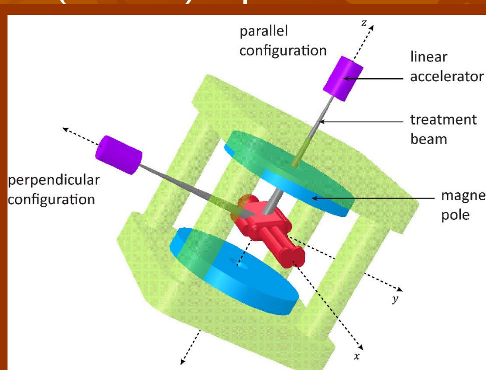
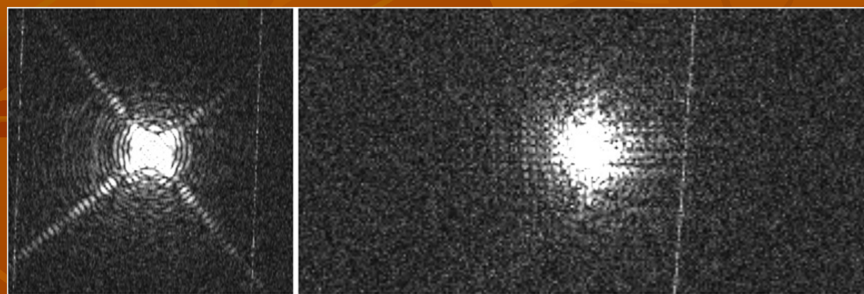
Rotating Bi-Planar linac –MR Cross Cancer Institute

- 6 MV medical linear accelerator (linac).
- Low-field (0.56 T) biplanar MR imager.



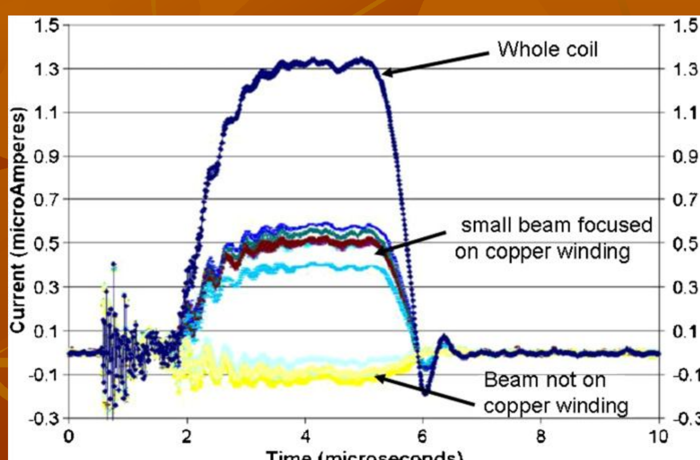
RF Shielding



k-space data of the first (left) and second (right) phantoms taken during linac pulsing while the RF shielding was insufficient. The data illustrate clear 'lines' in the k-space from the RF interference picked up by the MRI coil.

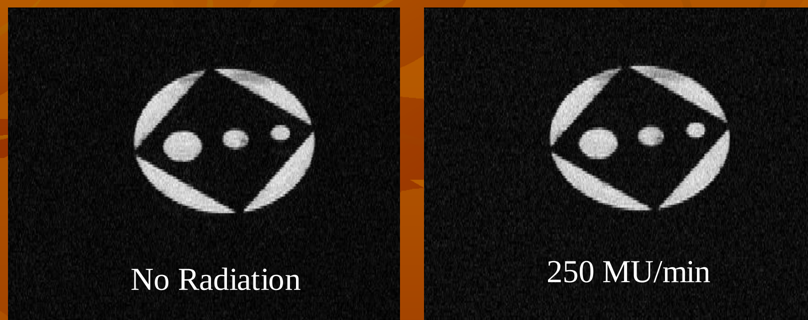
Lamey, Burke, Blosser, Rathee, DeZanche, Fallone, *Radiofrequency shielding for a linac-MRI system*, Phys. Med. Biol., 55(4), pp. 995-1006(2010).

RIC in RF COILs



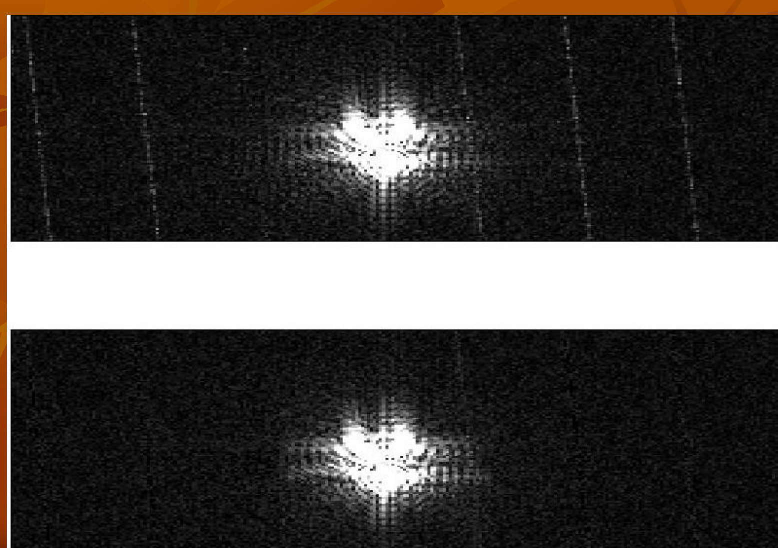
Isolation of copper winding as the source RIC. Magnitude of the RIC pulse is larger when the entire coil length is irradiated compared to only 2.5 cm width.

Linac-MR images

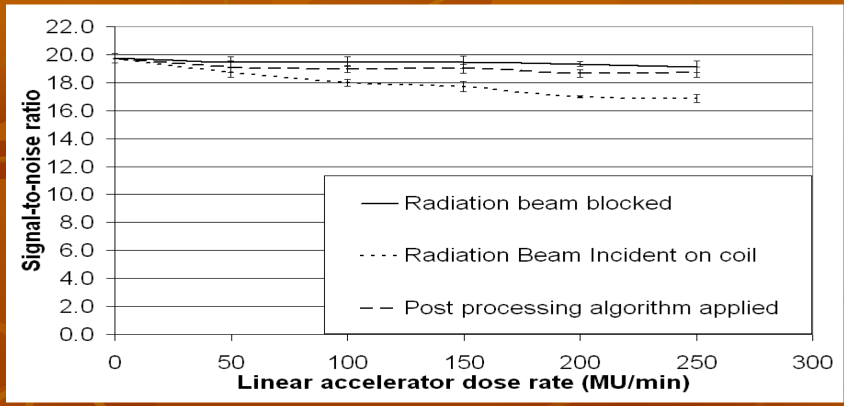


- Linac not producing radiation (left) and with linac producing radiation at 250 MU/min (right).
- RIC not apparent through visual inspection alone

Post-Processing RIC removal



Post-Processing RIC removal



B. Burke*, A. Ghila, B.G. Fallone, S. Rathee, *Radiation induced current in the RF coils of integrated Linac-MR systems: the effect of buildup and magnetic field*, Medical Physics, 39(8), pp.5004-5014 (2012).

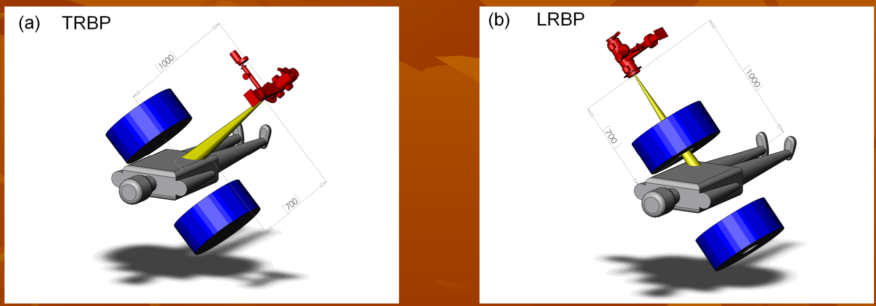
B.Burke*, K. Wachowicz, B.G. Fallone, S. Rathee, *Effect of radiation induced current on the quality of MR images taken with an integrated linac-MR system*, Medical Physics, 39(10), pp. 6139-6147 (2012).

Rotating Biplanar Options

PERPENDICULAR

TRANSVERSE

PARALLEL
LONGITUDINAL
IN-LINE

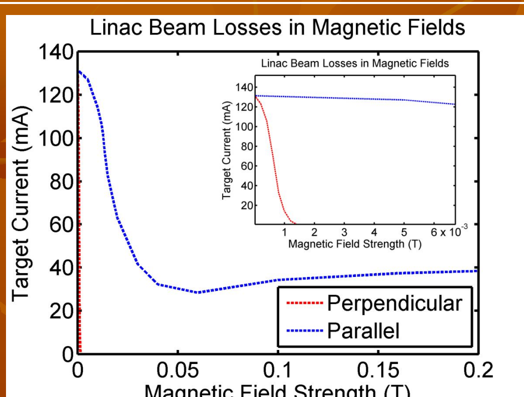


C. Kirkby, B. Murray, S. Rathee, B.G. Fallone. *Lung dosimetry in a linac-MRI radiotherapy unit with longitudinal magneticfield*, Med. Phys. 37(9), 4722-4732 (2010).

Advantage of bi-planar MRI

- Allows PARALLEL in addition to PERPENDICULAR
- **PARALLEL**
  - Simplifies Magnetic Shielding Design
  - NO ELECTRON RETURN EFFECT
  - NO INCREASE in EXIT SURFACE DOSE
- Avoids radiation traversing through MR magnet
- Avoids production of Eddy currents created by linac rotating wrt MRI in cylindrical design

Magnetic shielding

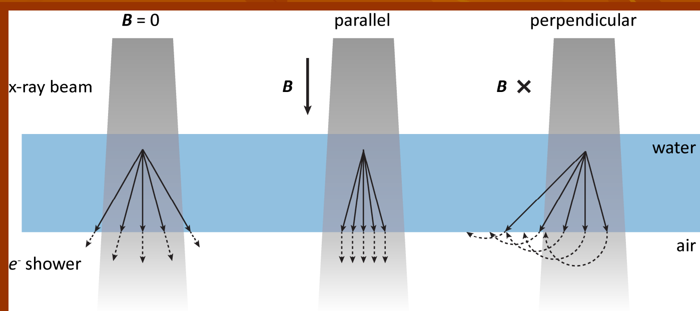


- For 20 % beam loss
  - **Perpendicular ~ 4 G**
  - **Parallel ~ 120 G**
- Parallel at 0.5 T
  - NO shielding required

- **J. St.Aubin, S. Steciw, B.G. Fallone, *Effect of transverse magnetic fields on a simulated in-line 6 MV linac*, PMB, 55(16), 4861-4869 (2010).**
- **J. St-Aubin, S. Steciw, D-M Santos, B.G. Fallone, *Effect of longitudinal magnetic fields on a simulated 6 MV linac*, Med Phys, 37(9), 4916-4923 (2010).**
- **D-M Santos, J. St-Aubin, B.G. Fallone, S. Steciw, *Magnetic shielding investigation for a 6 MV in-line linac in aparallel configuration of a linac-MR system*, Med Phys 39(2): 788-797 (2012).**

Perpendicular vs. Parallel

- In the parallel configuration, the effect of the magnetic field is to somewhat collimate the shower of secondary electrons, thereby reducing the beam penumbra and focusing the dose depositing by a given beam.



5 field Lung Plan
Eclipse TPS

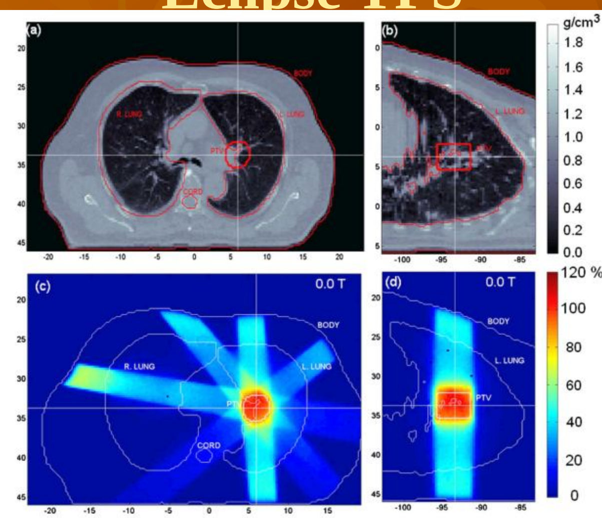
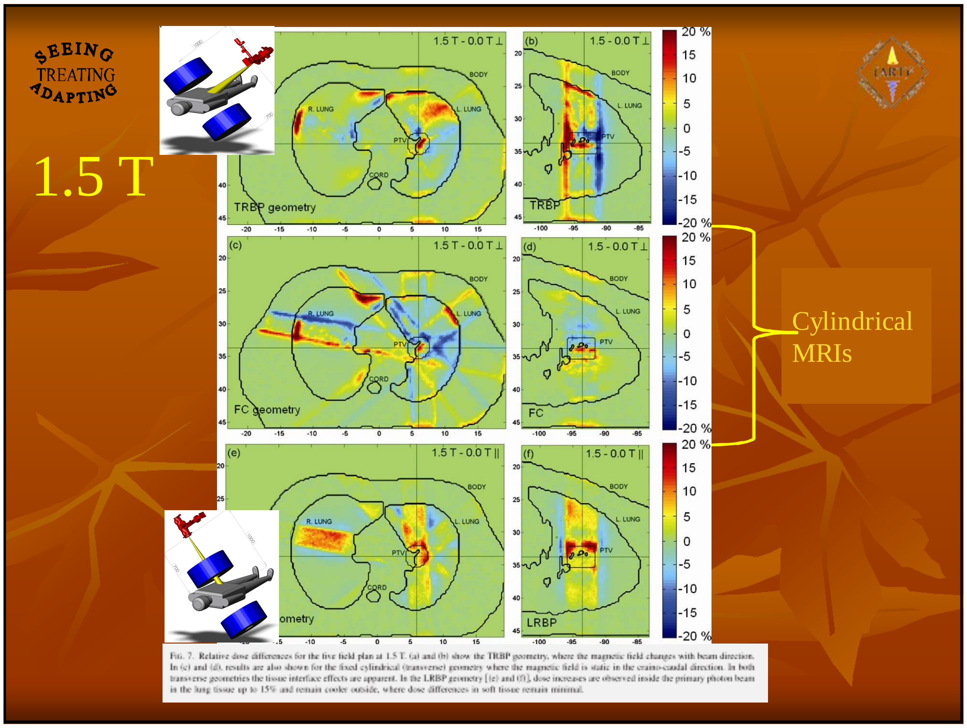
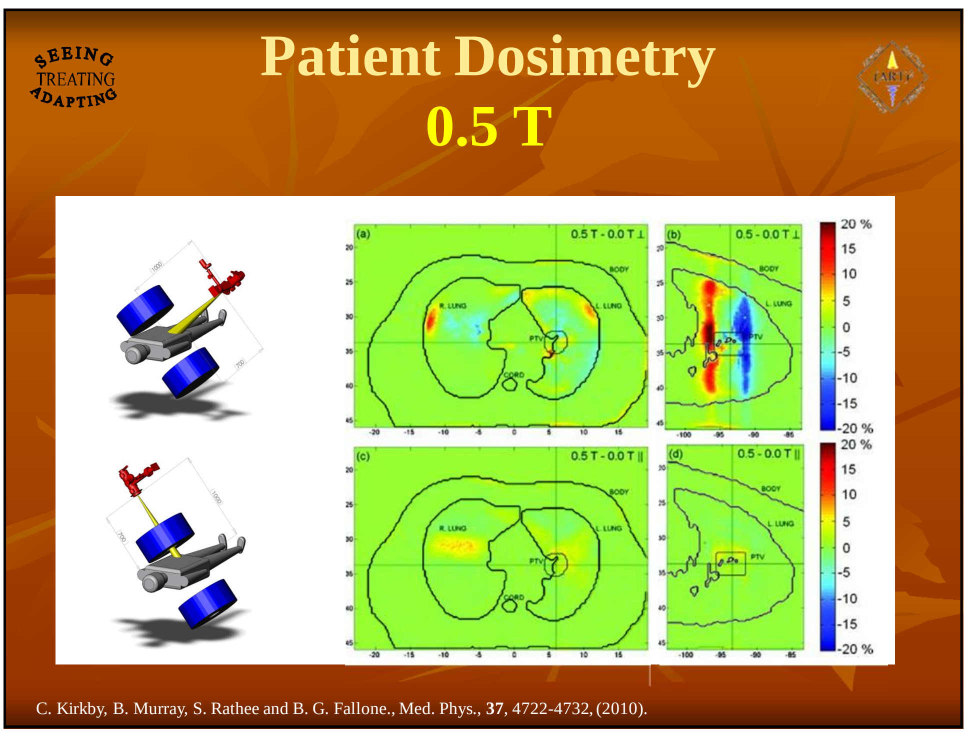
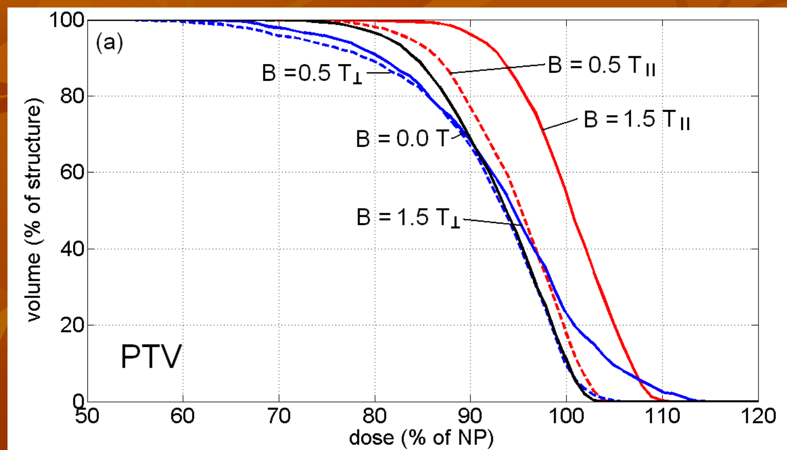


FIG. 3. Physical density maps in axial (a) and sagittal (b) planes through the isocenter, illustrating the variation in density through the anatomy under examination. Structures are superimposed. Also shown are the dose maps, (c) axial and (d) sagittal, normalized to 100% at the isocenter, for the five field plan with zero magnetic field strength.


SEEING
TREATING
ADAPTING
1.5 T
TRBP geometry
TRBP
FC geometry
FC
LRBP
Cylindrical MRIs
FIG. 7. Relative dose differences for the five field plan at 1.5 T. (a) and (b) show the TRBP geometry, where the magnetic field changes with beam direction. In (c) and (d), results are also shown for the fixed cylindrical (transverse) geometry where the magnetic field is static in the cranio-caudal direction. In both transverse geometries the tissue interface effects are apparent. In the LRBP geometry [(e) and (f)], dose increases are observed inside the primary photon beam in the lung tissue up to 15% and remain cooler outside, where dose differences in soft tissue remain minimal.


SEEING
TREATING
ADAPTING
Patient Dosimetry
0.5 T
C. Kirkby, B. Murray, S. Rathee and B. G. Fallone., Med. Phys., 37, 4722-4732, (2010).

Parallel Configuration: Lower penumbra

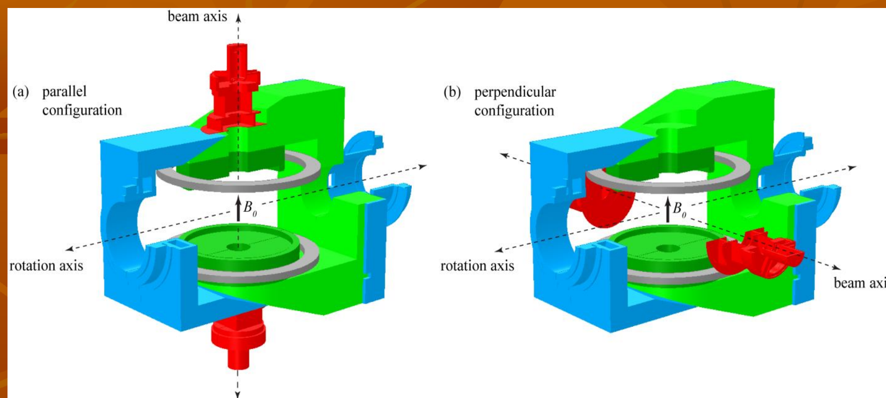


C. Kirkby, B. Murray, S. Rathee, B.G. Fallone. *Lung dosimetry in a linac-MRI radiotherapy unit with longitudinal magneticfield*, Med. Phys. 37(9), 4722-4732 (2010).

SURFACE DOSE

SEEING TREATING ADAPTING

OUR CURRENT SYSTEMS



biplanar magnet assembly
treatment assembly
superconducting coil
gantry support link

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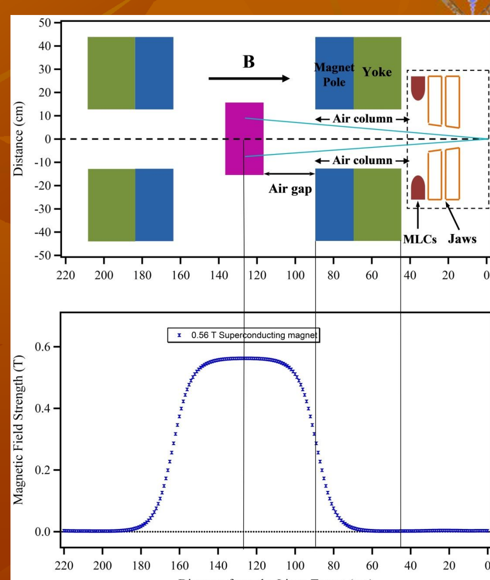
Entrance Surface Dose: Longitudinal

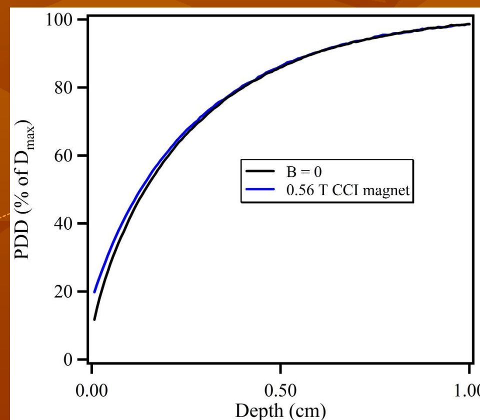
Schematic diagram of the longitudinal linac-MR system with the isocenter at 126 cm.

The CAX magnetic field maps of our realistic 3-D models versus a 1-D model



ENTRANCE SURFACE SKIN DOSE Longitudinal

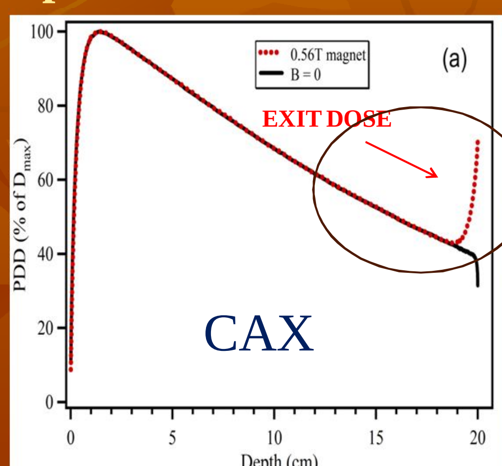
NO SIGNIFICANT INCREASE



A. Keyvanloo*, B. Burke, B. Warkentin, T. Tadic, S. Rathee, C. Kirkby, D.M. Santos, B.G. Fallone, *Skin Dose in Longitudinal and Transverse Linac-MRIs using Monte-Carlo and realistic 3D MRI field models*, Medical Physics, 39(10), pp.6509-6521(2012).

EXIT SURFACE DOSE Perpendicular

SIGNIFICANT INCREASE

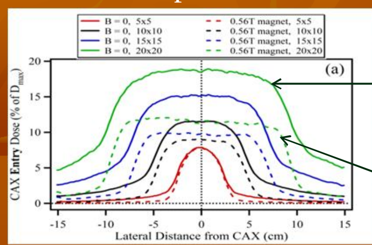


10 x10 cm^2 photon beam; phantom surface at 136 cm from source

PROFILES- Solid lines : NO Bo

Perpendicular

Parallel

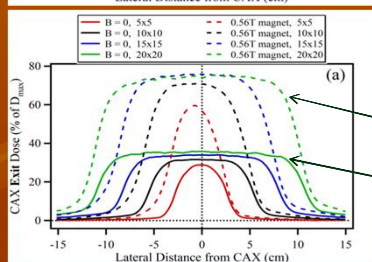


ENTRY

Bo=0

Bo=0.56T

INSIGNICANT INCREASE



EXIT

Bo=0.56T

Bo=0

SAME as Bo=0

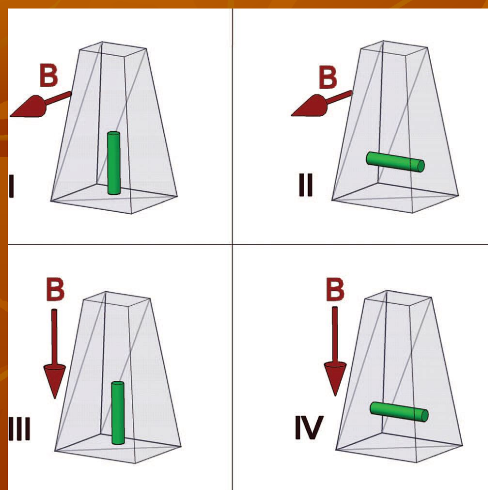
A. Keyvanloo*, B. Burke, B. Warkentin, T. Tadic, S. Rathee, C. Kirkby, D.M. Santos, B.G. Fallone, *Skin Dose in Longitudinal and Transverse Linac-MRIs using Monte-Carlo and realistic 3D MRI field models*, Medical Physics, 39(10), pp.6509-6521(2012).

SUMMARY SURFACE DOSE

	PERPENDICULAR	PARALLEL
ENTRY	DECREASE BY < 1/2	INSIGNICANT INCREASE
EXIT	INCREASE BY > 1/2	SAME as Bo=0

A. Keyvanloo*, B. Burke, B. Warkentin, T. Tadic, S. Rathee, C. Kirkby, D.M. Santos, B.G. Fallone, *Skin Dose in Longitudinal and Transverse Linac-MRIs using Monte-Carlo and realistic 3D MRI field models*, Medical Physics, 39(10), pp.6509-6521(2012).

Calibration: Ion chamber

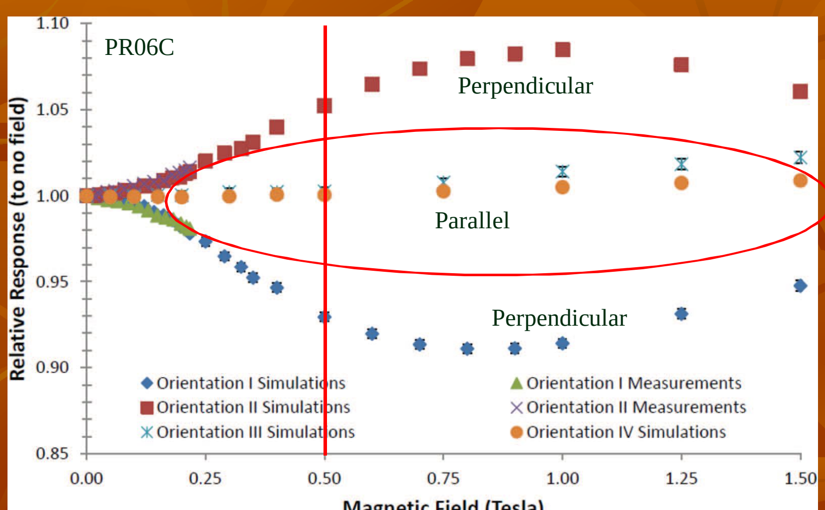


Perpendicular/transverse

Parallel/longitudinal

Arrow: Magnetic field; cylinder: long axis-central
Transparent prism: radiation field

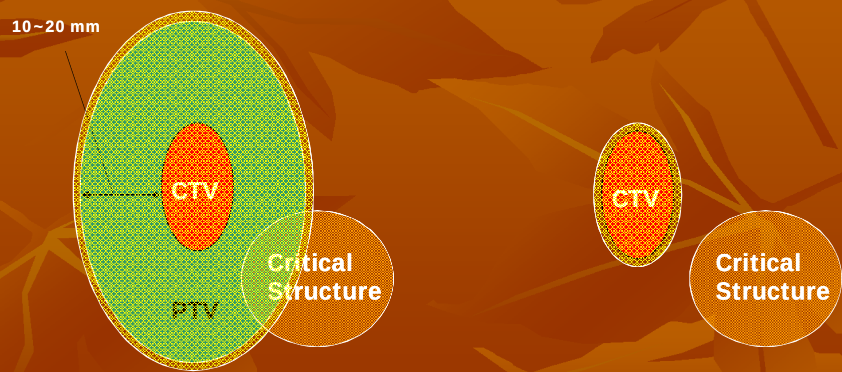
Ion chamber response



M. Reynolds, B.G. Fallone, S. Rathee, *Dose Response of Selected Ion Chambers in Applied Homogeneous Transverse and Longitudinal Magnetic Fields*, Medical Physics, 40(4), 042102(7 pp), (2013).

Real-time Tumour-Tracked Irradiation

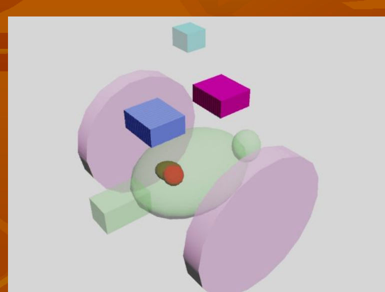
- Minimize PTV margin in dynamic target

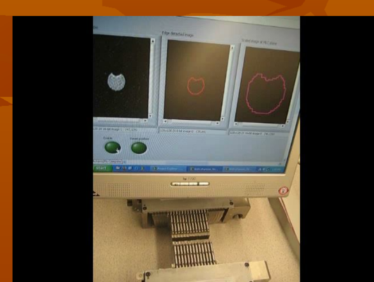


Current State of the art

Real-time MR guided Tumour-Tracked RT

Tumor-Tracked Irradiation: Cross Cancer Institute

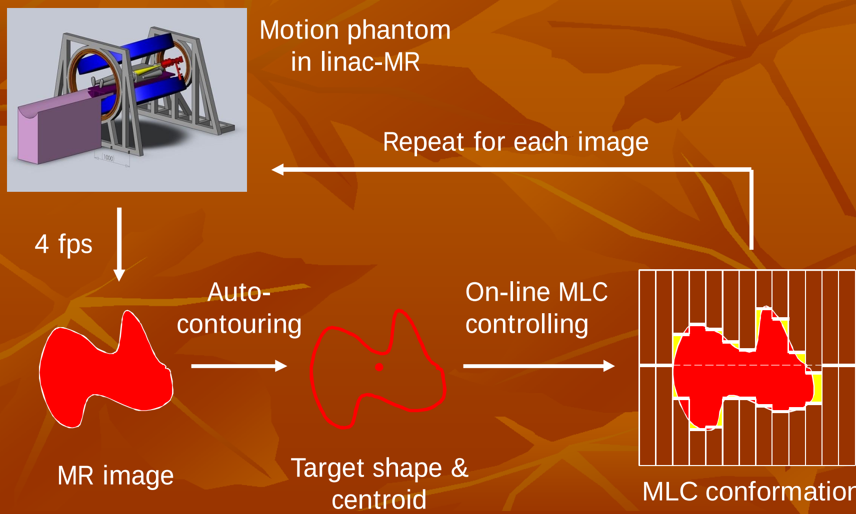




Jun, Mackenzie, Rathee, Fallone, COMP, Vancouver, BC, July 21-24, 2009

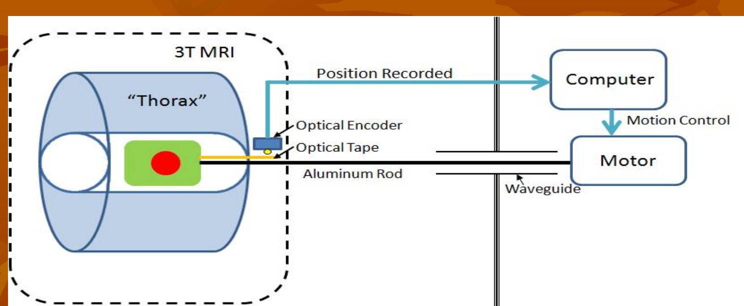
SEEING TREATING ADAPTING

Real-time tumour tracking scheme



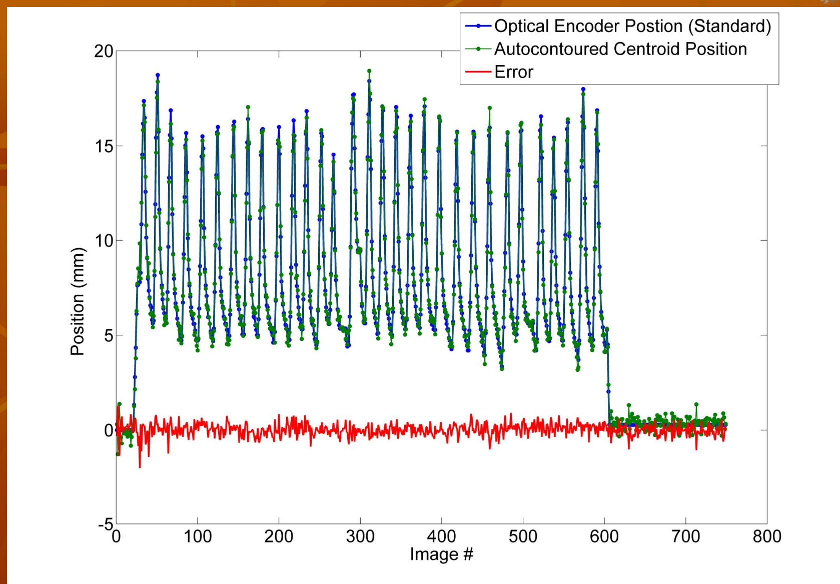
SEEING TREATING ADAPTING

Our Tumour Tracking(Auto contour): Evaluation Experiment



- Lung Phantom is driven in by programmable 1-D motor.
- Optical Encoder independently records position of tumour for comparison

- Realistic tumour movement (inf-sup) as determined through Cyberknife patient data

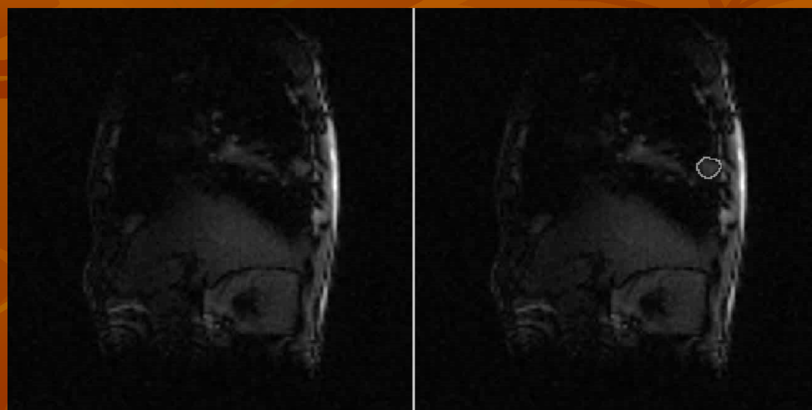


Auto-contouring (3 T images)

Original image

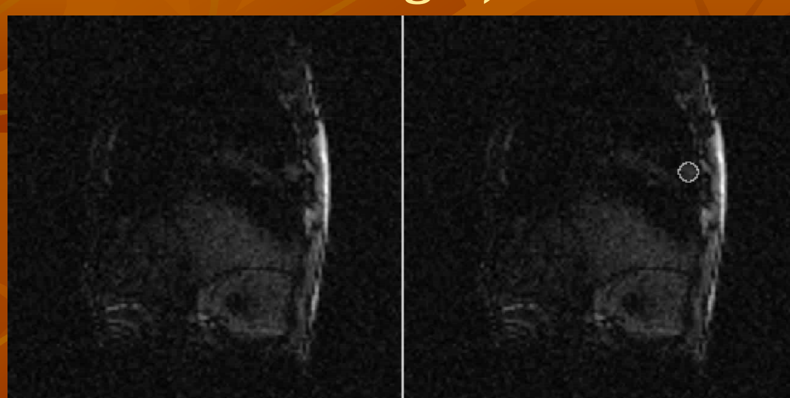
Auto-contoured image

Auto-contouring (Est. 0.5 T images)



Original image Auto-contoured image

Auto-contouring (Est. 0.2 T images)



Original image Auto-contoured image

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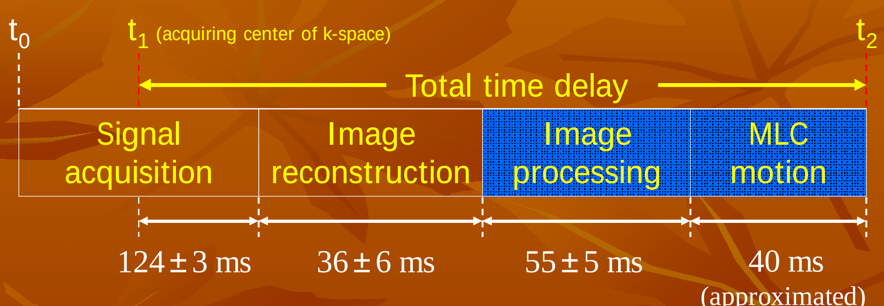
ADAPTING

PREDICTION

SEEING
TREATING
ADAPTING

Measured Time Delay

(Linac-MR System)



- bSSFP (4 fps, 2 mm pixel width, image matrix : 128x96, FOV : 256x192 mm^2)
- Tumour size : 5 cm diameter

Total time delay from imaging to MLC motion completion

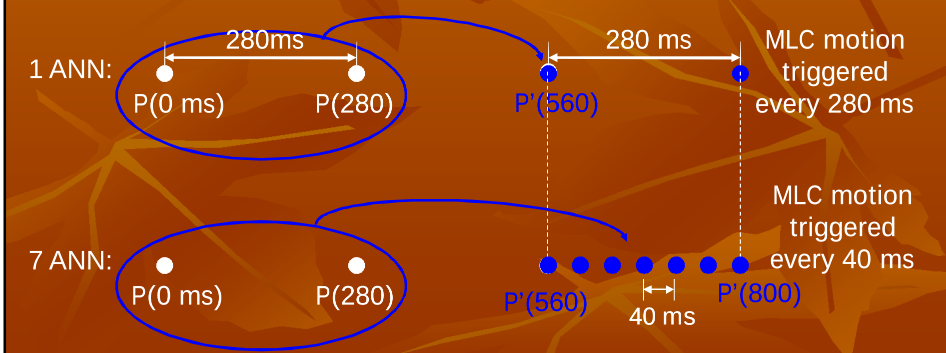
⟶ **241~269 msec**

Solution to tracking failures

- Multiple ANNs & predictions

⟶ More frequent MLC motion triggering

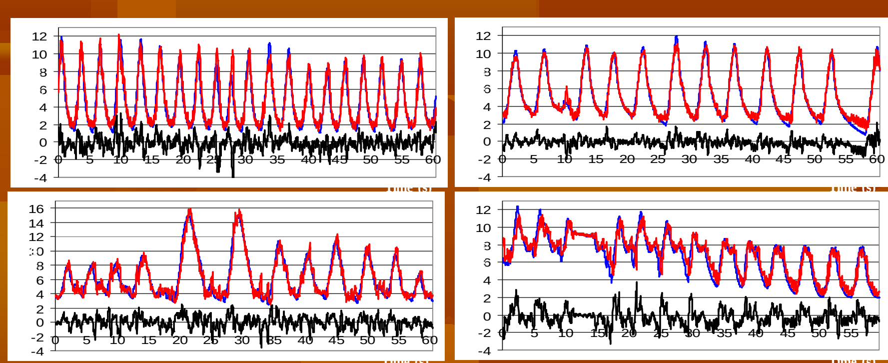
(ex. 1 ANN vs. 7 ANN, imaging at 3.6 fps (every 280 ms)



Motion prediction

Our Algorithm's Prediction-- 1D sup-inf tumour position in 280 ms advance
Tested on 3D tumour motion by Cyberknife: (Suh et al. PMB, 53, 3623-40(2008)

—: Original data —: Prediction —: Error (mm)



J.Yun, M. Mackenzie, S. Rathee, D. Robinson, B.G. Fallone, ***An artificial neural network (ANN) based lung tumor motion predictor for intra-fractional MR tumor tracking,*** **Medical Physics, 39(7), pp. 4423-4433 (2012).**

SEEING TREATING ADAPTING

Demonstration

Tumour-Tracked (2 D imaged) Irradiation

CCI linac-MR Prototype

J. Yun, K.Wachowicz, M. Mackenzie, S. Rathee, D. Robinson, B. Gino Fallone, *First demonstration of intrafractional tumor-tracked irradiation using 2D phantom MR images on a prototype linac-MR*, Medical Physics, 40(5) 051718(12 pp), (2013).

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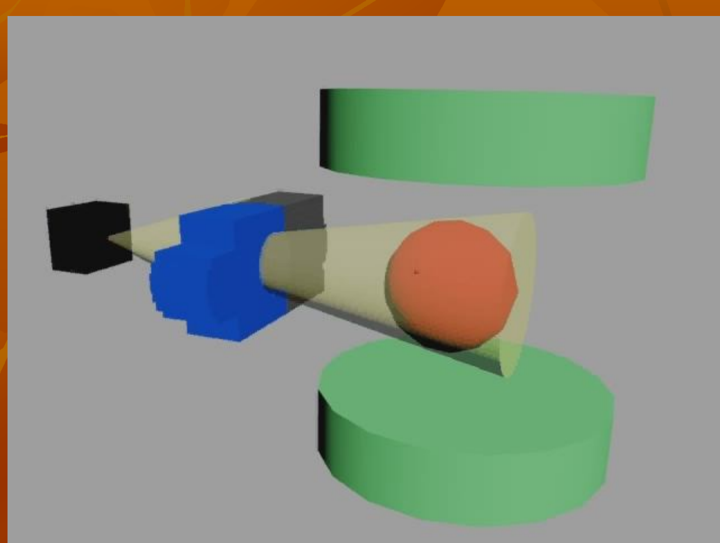
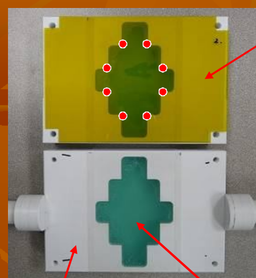
Demonstration of intra-fractional tracking

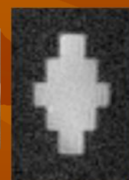


MR compatible motion phantom



Gafchromic film

Assembled phantom



MR image during tracknig

Phantom moving direction

Polystyrene case

Target (porcelain gel + 12 mM $CuSO_4$)

- Phantom motion follows pre-defined 1-D motion pattern during tracking
- To register films to each other, the edges of the phantom (indicated by red dots) are manually marked.

Demonstration of intra-fractional tracked irradiation

- For each motion pattern,
  moving target was irradiated for 2 minutes as follow:

1. Without tracking
   (MLC conformed to initial target position during irradiation)
2. With tracking + without motion prediction
3. With tracking + with motion prediction

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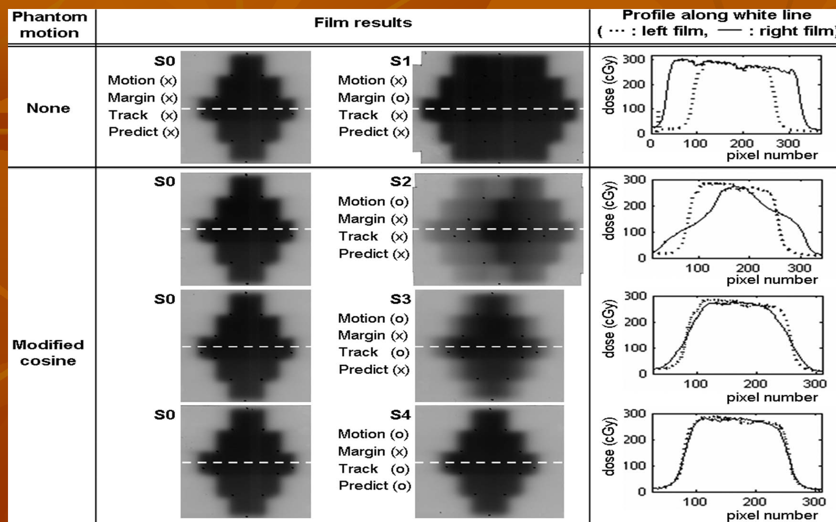
Demonstration of intra-fractional tracking



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Potential Advantages Bi-planar MR Perpendicular

- Bi-planar MR perpendicular
  - Lorentz Force in same direction irrespective of rotation…
    - Potential to preferentially deliver dose towards a region irrespective of rotation angle
  - May have some advantages for some clinical sites

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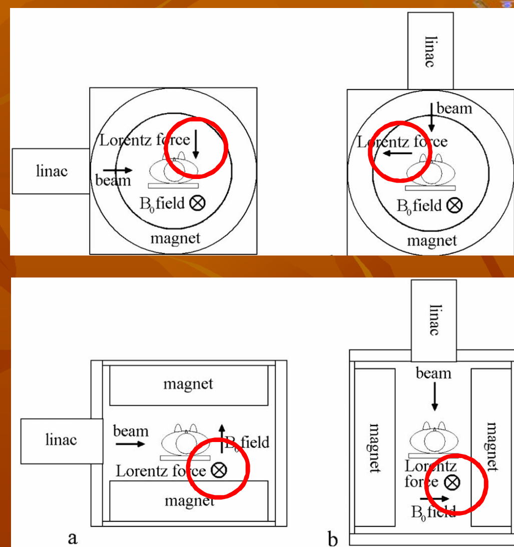
Cylindrical MRI

Bi-Planar MRI (ours)

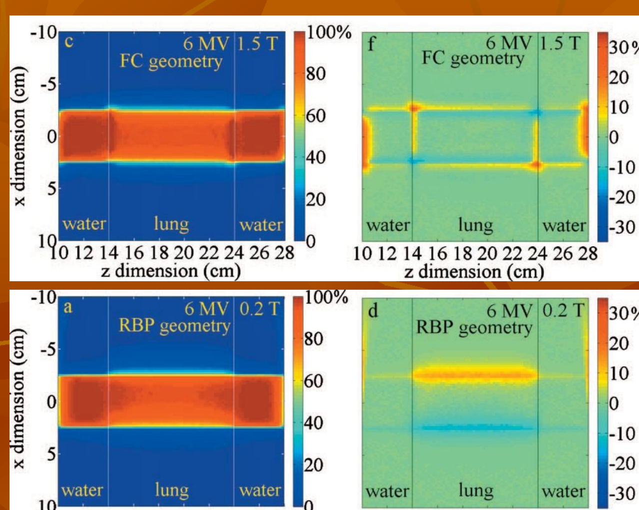


SEEING TREATING ADAPTING

POP FIELDS

Cylindrical MRI

Bi-Planar MRI (ours)



Kirkby, Stanescu, Rathee, Carlone, Murray, Fallone, *Patient dosimetry for hybrid MRI-radiotherapy systems*, Med Phys 36(3), 1019-1027(2008)

Advantages of Real-time MRI-linac

- Margin-reduction, normal-tissue avoidance, , decreased morbidity
- Eliminate set-up & motion uncertainties
- Daily targetting of volume changes & rep. motion
- Monitor tumour-regression
- Tumour-tracking … **Tumour-tracked irradiation**
- Etc.

Clinical Applications Real-time MRI-linac

- Non-small cell lung cancer (NSCLC)
- Hepatobiliary Carcinoma
- Breast Cancer
- Non-Hodgkin's lymphoma of the stomach
- Colorectal Cancer
- Cervical Cancer
- Pediatrics, etc

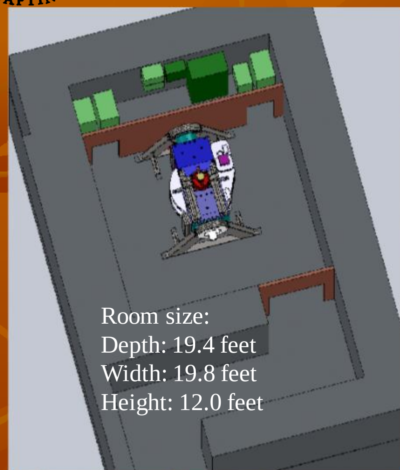
Patient flow

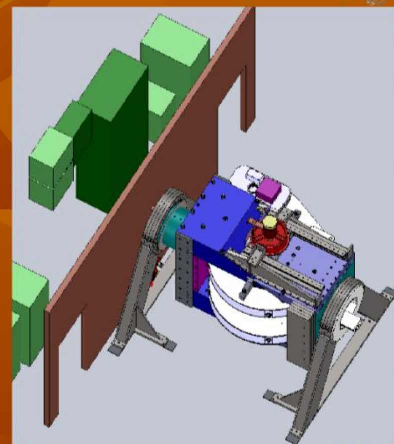
- MR-Simulation & Treatment Planning
- Monitor, verify and treat on MRI-linac hybrid for all fractions

PRESENT INSTALLATION
Cross Cancer Institute
University of Alberta
Edmonton

SEEING TREATING ADAPTING

System Layout at our Hospital





Install Without Need to Remove Wall or Ceiling
No cryogens (helium, nitrogen), no cryogen vent required.

DETERMINE BEST CONFIGURATION FOR EACH DISEASE SITE

SEEING TREATING ADAPTING

The TEAM

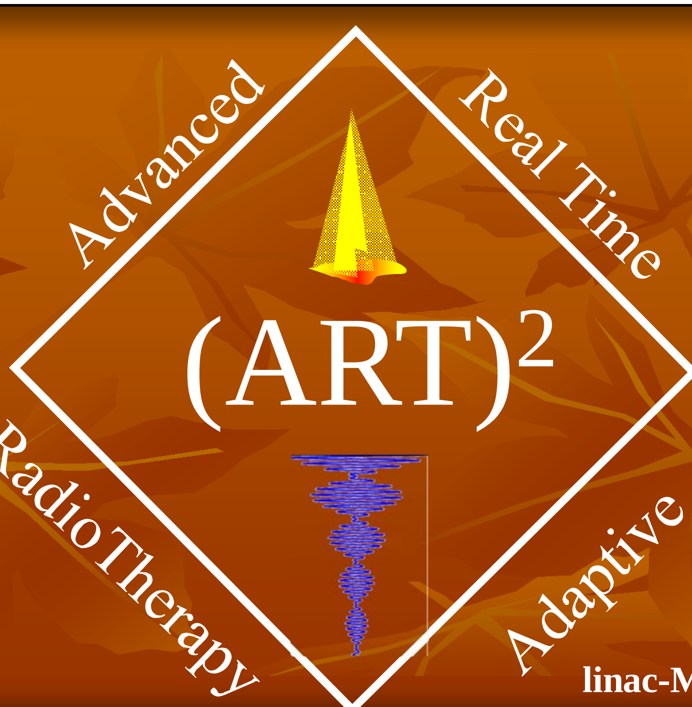
B.G. Fallone, B. Murray, S. Rathee

E.Blosser, S. Steciw, K. Wachowicz, N. deZanche, C. Field
C. Kirkby, M. Mackenzie, D. Robinson, B. Warkentin, J. St-Aubin

B. Burke,, A. Ghila, D. Santos, E. Yip, D. Baillie,
J. Yun, M. Reynolds,
R. Pearcey, R. Urtasan (Radiation Oncologists Leads)

Acknowledgement

- **FUNDED by**
  - **Alberta Cancer Foundation**
  - **Alberta Health Services**
  - **Alberta Innovates: Health Solutions**
  - **Western Economic Diversification, Canada**
  - **Alberta Advanced Education & Technology**
  - **Natural Science & Engineering , Canada (NSERC)**
  - **Canadian Institutes Health Research(CIHR)**



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