ICR The Institute of Cancer Research

The ROYAL MARSDEN
NHS Foundation Trust

MR guided RT

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Making the discoveries that defeat cancer

Workshop on Medical Imaging & Biomedical Engineering, 25-28 July 2018, Ohrid, MK

Disclaimer

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- ICR/RMH has a research agreement with Elekta on MLC tracking
- ICR/RMH is a member of the Elekta Atlantic Research Consortium

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IGRT: Seeing is believing!

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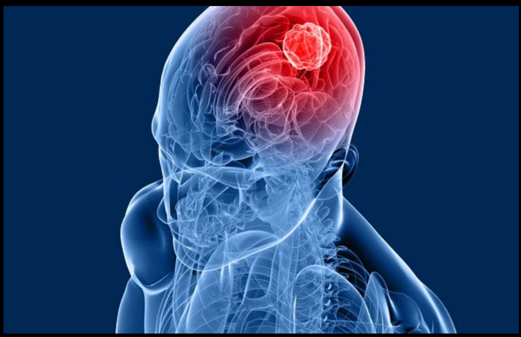
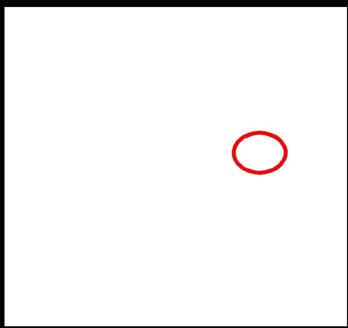
Hitting an invisible target with an invisible beam

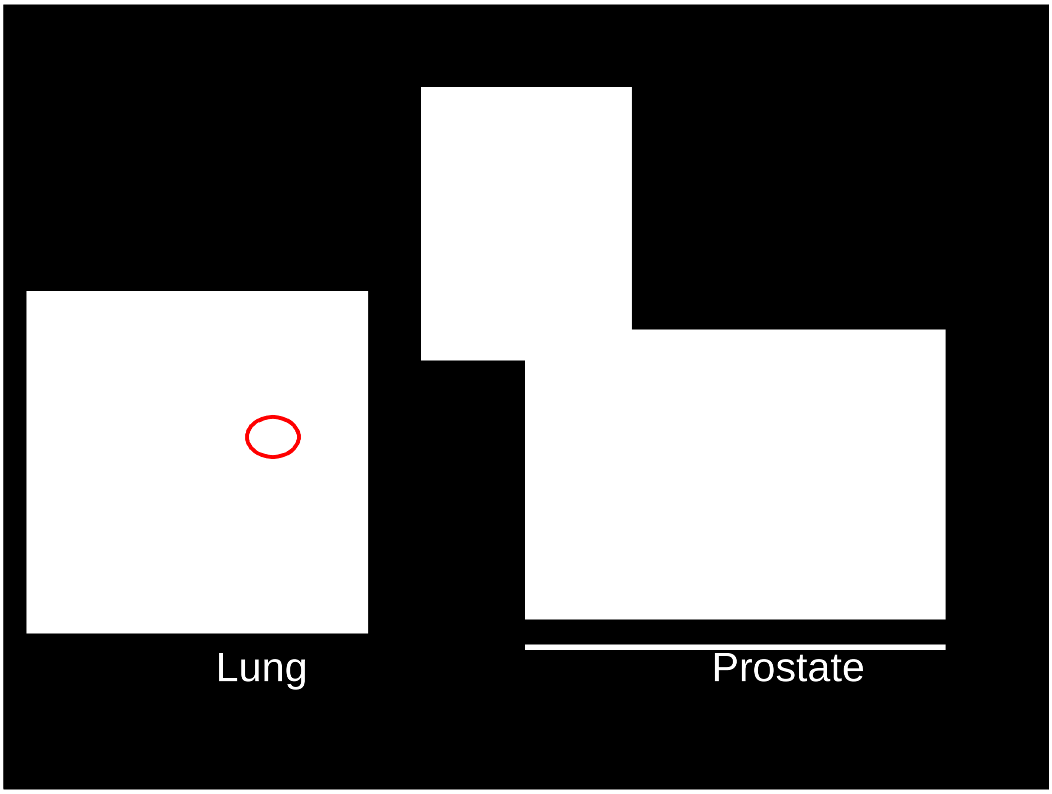


Expectation – diagnostic images



Lung

Prostate



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Problems of x-ray based IGRT

Current status of RT delivery devices

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C-Arm (Standard configuration):

- Multileaf collimators (2.5mm to 10mm leaf width)
- Multiple photon and electron energies
- Flattening filter free photon beams
- kV Cone Beam Computed Tomography
- Support non-coplanar treatments

Varian

Elekta

Sources: Manufactures web site

Problems

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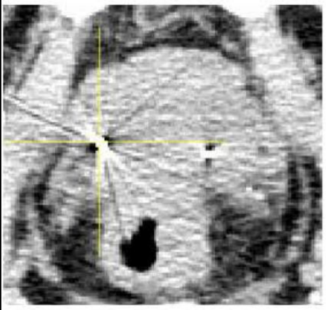
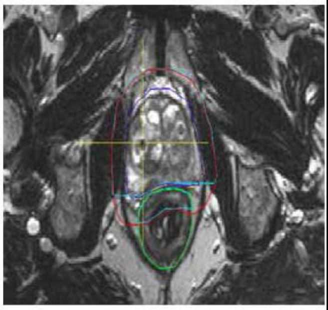
- ❑ Insufficient image quality for in-room imaging
- ❑ Management of intra-fraction organ motion

Why MR – soft tissue visualisation ?





- Lack of soft-tissue contrast
- Radiation dose to acquire image

- Superb tissue contrast
- No radiation dose

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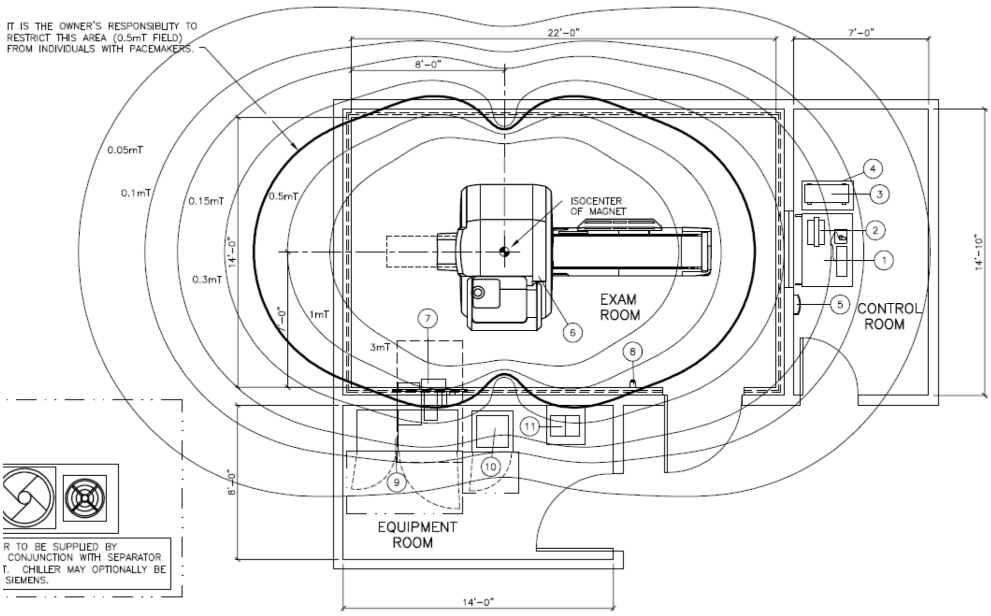
MRgRT: Technical Solutions

In room MRI Guided RT

Reasons for MRIgRT

- MR imaging capabilities
  - No additional imaging dose
  - Improved soft-tissue contrast compared to CT
  - Functional imaging
    - Treatment response monitoring
- Adaptive RT
  - Daily treatment plan adaptation based on MR images
  - Real-time motion monitoring
  - MLC Tracking
  - Online dose reconstruction

Technical Challenge: Magnetic field



From: Siemens Cutsheet 10023 Magnetom

Challenge: fringe fields of the MR scanner

MAGNETIC FRINGE FIELDS

MAGNETIC FIELDS MAY AFFECT THE FUNCTION OF DEVICES IN THE VICINITY OF THE MAGNET. THESE DEVICES MUST BE OUTSIDE CERTAIN MAGNETIC FIELDS. THE DISTANCES LISTED ARE FROM THE MAGNET ISOCENTER AND DO NOT CONSIDER ANY MAGNETIC ROOM SHIELDING.

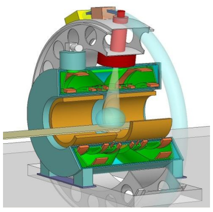
X/Y AND Z AXIS	DEVICES
6'–1" / 9'–2" 3.0mT	SMALL MOTORS, WATCHES, CAMERAS, CREDIT CARDS, MAGNETIC DATA CARRIERS (SHORT–TERM EXPOSURE)
7'–3" / 11'–6" 1.0mT	COMPUTERS, MAGNETIC DISK DRIVES, OSCILLOSCOPES, PROCESSORS
8'–3" / 13'–2" 0.5mT	CARDIAC PACEMAKERS, X–RAY TUBES, INSULIN PUMPS, B/W MONITORS, MAGNETIC DATA CARRIERS (LONG–TERM STORAGE)
9'–9" / 16'–1" 0.2mT	SIEMENS CT SCANNERS
10'–4" / 17'–1" 0.15mT	COLOR MONITORS, SIEMENS LINEAR ACCELERATORS
13'–1" / 22'–3" 0.05mT	X–RAY IMAGE INTENSIFIERS, GAMMA CAMERAS, PET/CYCLOTRON, ELECTRON MICROSCOPES, LINEAR ACCELERATORS

THE OWNER/USER IS TO VERIFY THE LOCATION OF THE 0.5mT FIELD AND ENSURE THAT IT IS MAINTAINED AS A RESTRICTED AREA.

From: Siemens Cutsheet 10023 Magnetom Aera1.5T

IGRT: Magnetic Resonance imaging

Integrated devices



UMC Utrecht ELEKTA/Philips

Elekta MR-Linac is a work in progress and not available for sale or distribution

Sydney (Paul Keall)

Mridian Viewray

Alberta (B. Fallone)

www.viewray.com http://www.inghaminstitute.org.au/Mri-linac.html http://www.mp.med.ualberta.ca/linac-mr/photo_gallery.html

Treatment Devices: Overview

Institution	Radiation Source	B field strength	Magnet Type	Beam-field orientation (with respect to the treatment beam)
Princess Margaret Hospital	Standard Linac	1.5T	Closed	NA
Viewray	^{60}Co, 6MV	0.35T	Split	Perpendicular
Australian MRI-Linac	6MV x-rays	1.0T	Split	Inline and perpendicular
University of Alberta	6MV x-rays	0.2T & 0.5T	Split	Inline and perpendicular
Elekta MR-Linac	7MV x-rays	1.5T	Closed	Perpendicular

Impact of improved image quality

- ❑ Improved Soft tissue contrast
  - ❑ Reduction of geometrical uncertainties → margin reduction
  - ❑ Enabling high precision RT technqiues
  - ❑ Enabling enhanced automation of segmentation and treatment planning
  - ❑ Enabling advanced adaptive dose delivery/planning concepts

Challenges – ‘Dose’ in magnetic fields

Impact on treatment planning

- ❑ Improved Soft tissue contrast
- ❑ Calibration of MR images for dose calculations
- ❑ Influence of the treatment geometry
- ❑ Influence of the magnetic field

Impact on treatment planning

- ❑ Calibration of MR images for dose calculations
  - ❑ Many, many good approaches → MR only
  - ❑ Challenges are tumour site specific
  - ❑ Effects of errors are mostly ‘small’

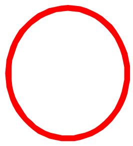
Impact on treatment planning

- ❑ Improved Soft tissue contrast
- ❑ Calibration of MR images for dose calculations
- ❑ Influence of the treatment geometry
- ❑ Influence of the magnetic field

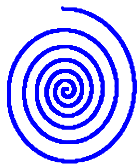
Impact of the electron energy, magnetic field and electron density

E_k kinetic energy (MeV) , electron density —— range (mm)

E_k , B magnetic field (Tesla)



E_k , B magnetic field (Tesla), electron density



Point spread kernels as a function of the magnetic field strength

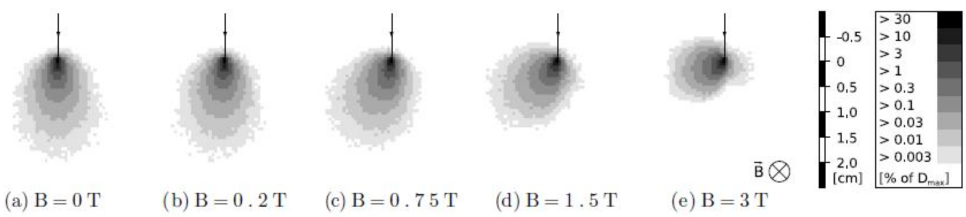


Figure 2. Monte Carlo calculated pointspread kernels for secondary electrons, depending on the magnetic field strength *B*. Logarithmic grey value scaling is used. Primary photons are simulated with a realistic 6 MV linear accelerator energy spectrum.

From Raaymakers et al. PMB 53:909-923(2008)

Electron Return Effect (ERE) at tissue air boundaries

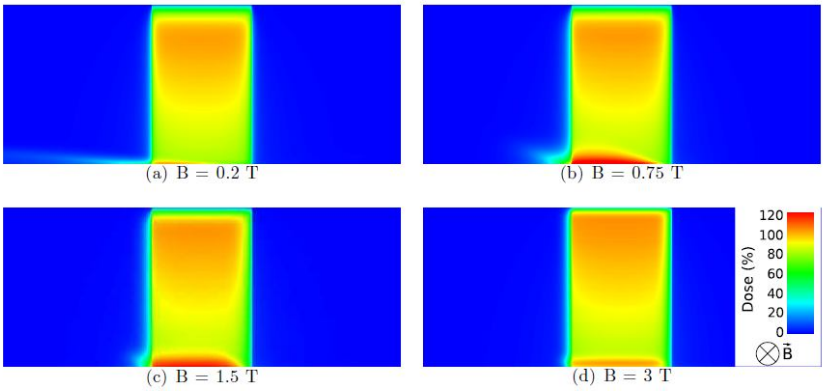


Figure 4. Dose distributions for a 5 × 5 cm^2 6 MV photon beam at the indicated magnetic field strengths.

From Raaymakers et al. PMB 53:909-923(2008)

Treatment planning: ERE at air surfaces

- Increased skin doses for whole breast treatments

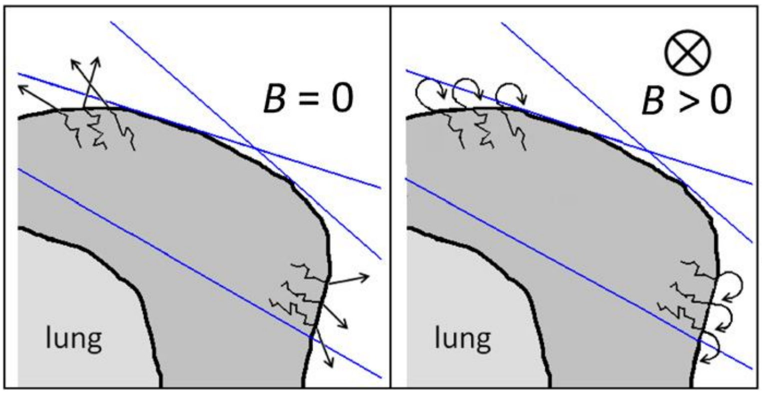


Figure 1. Illustration of the ERE, for left-breast WBI by means of two tangential fields. The edges of the photon beams are depicted by the blue lines. Trajectories of secondary electrons, crossing the skin–air boundary on either exit side of the irradiated breast, are represented by the arrows. The ERE may result in a higher skin dose when comparing the situation of no magnetic field (left) to that of a non-zero magnetic field directed into the plane (right).

From van Heijst *et al.* PMB 58:5917-5930 (2013)

Treatment planning study: Lung

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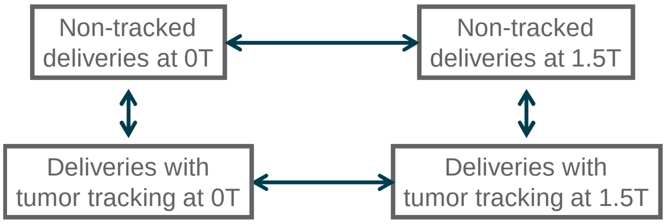
- Planning study using 4DCT scans of 9 stage I NSCLC patients
- Design of 4 SBRT treatment plans per patient:



- Simulation of dose delivery to all 10 4DCT phases
- Deformable dose accumulation
- Comparison of differences in several dose-volume metrics using paired t-test

Treatment planning: NSCLC Stage 1

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- 9 beam IMRT

From Menten *et al.*
Radiother Oncol.
119:461-6 (2016).

Results: effect of 1.5T magnetic field

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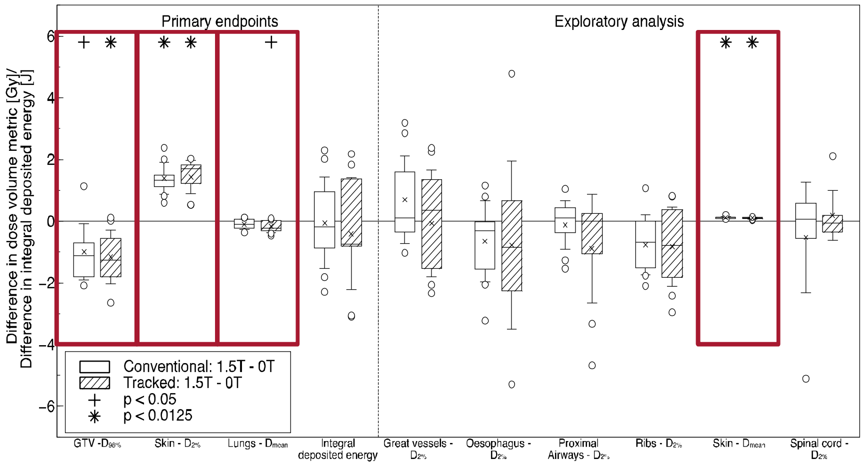

- Slight decrease in dose to the tumor
- Increase in dose at air-tissue interfaces
- All cases fulfilled RTOG 1021 planning constraints

Challenges: Dosimetry in a magnetic field

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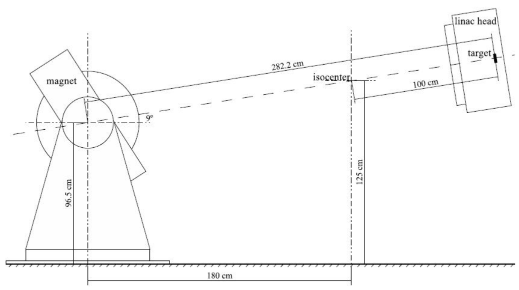

Figure 1. 1.25 T electro magnet positioned next to the Elekta SLi25 linear accelerator.

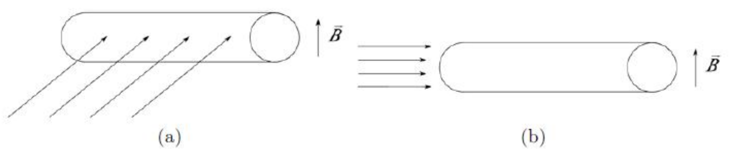

Figure 2. Schematic representation of the geometry set-up of the ionization chamber with respect to the external magnetic field and radiation beam. (a) Configuration I: $B \perp$ beam $\perp$ chamber and (b) configuration II: $B \perp$ beam $\parallel$ chamber.

From Meijsing *et al.* PMB 54:2993-3002 (2009)

Challenges: Dosimetry in a magnetic field

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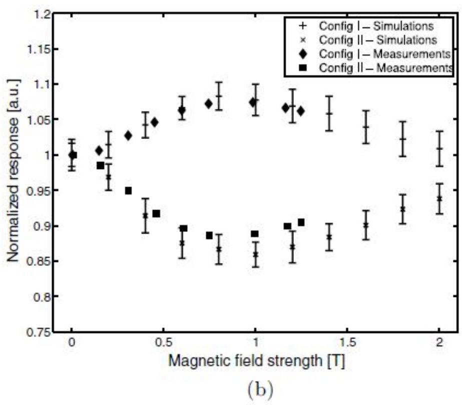

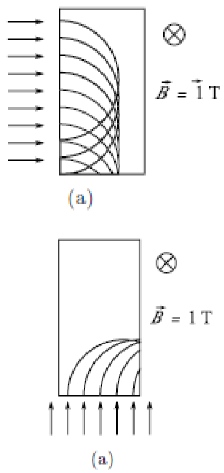

Chamber orientation has an impact on the reading

From Meijsing *et al.* PMB 54:2993-3002 (2009)

Air gap effects

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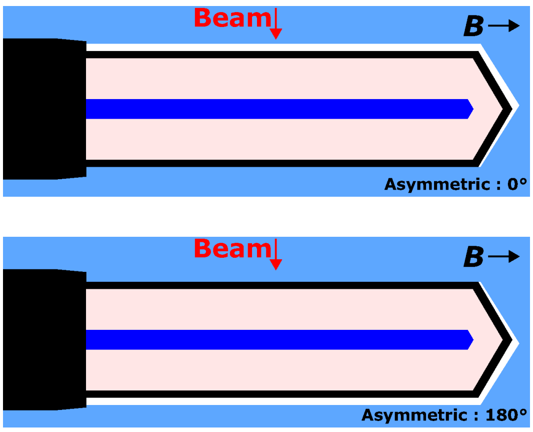
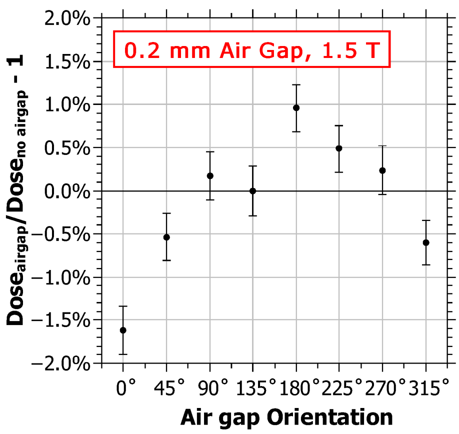
Modeling a sub-millimeter asymmetric air gap around the chamber:





O'Brien and Sawakuchi, Med. Phys. (2017) doi: 10.1002/mp.12290

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Example - MRgRT technology: Elekta MR-Linac at ICR/RMH

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Elekta MR-Linac

7MV FFF Linac

1.5T MRI

In-line linac
143.5cm SAD
57.4cm x 22cm field size
0.71cm leaf width @iso
On-board EPID

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First patient treatment 20th May 2017

University Medical Center Utrecht

From: http://medicalphysicsweb.org/cws/article/research/68865

The MR-Linac facility at RMH/ICR

Elekta MR-Linac @ ICR/RMH: Timeline

Construction completed

03/2016

Gantry delivery

07/05/2016

Magnet delivery

04/06/2016

RF Cage install

11/07/2016

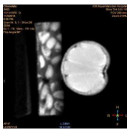
Setting to work

12/09/2016

First beam

03/10/2016

First MRI

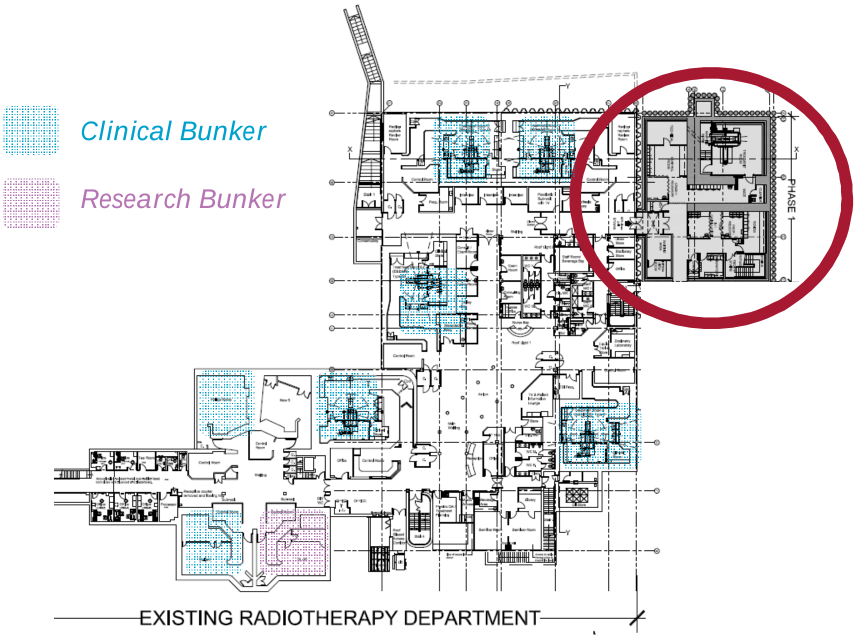


03/11/2016

First human MRI

07/11/2017

Elekta MR-Linac: Facility layout



Elekta MR-Linac: Gantry delivery

07/05/2016

Elekta MR-Linac: Magnet delivery

04/06/2016

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MR Linac: Installation completed

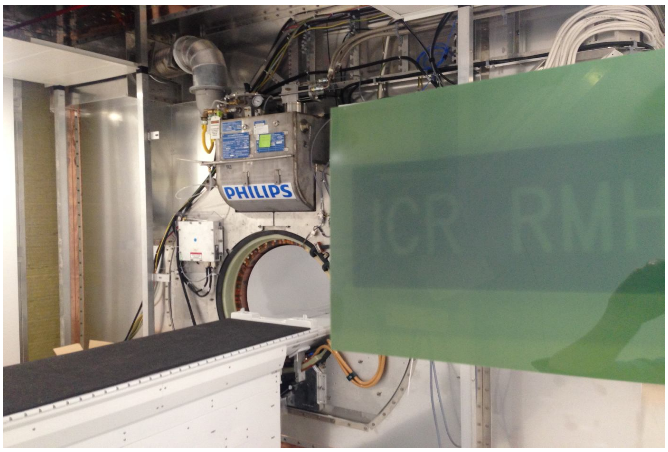
12/09/2016

Royal Visit HRH Prince William, Duke of Cambridge

16/05/2017

First beam, images and data

MR Linac: First beam



03/10/2016

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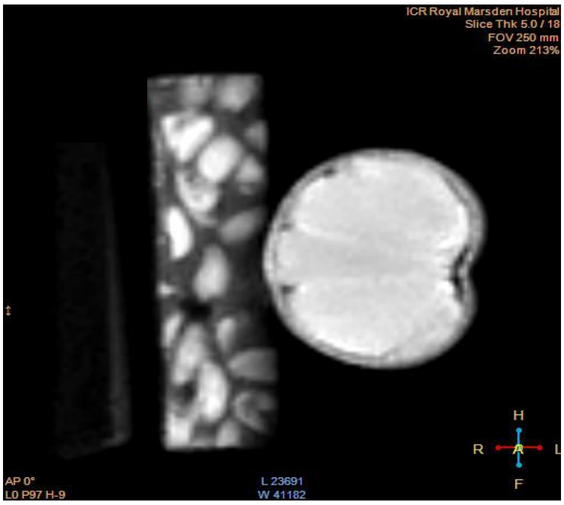
MR Linac: First MR Image



03/11/2016

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MR Linac: First healthy volunteer

https://www.icr.ac.uk/news-archive/mr-linac-first-healthy-volunteer-scanned-in-pioneering-new-radiotherapy-machine

07/11/2017

MR Linac: First healthy volunteer

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T2w TSE (6 min)
1.2x1.2x1.2mm^3

T2w TSE (2 min)
1.5x1.5x2mm^3

07/11/2017

MR Linac: Healthy volunteer

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T2 TSE Multivein (MV) in free breathing showing liver, pancreas, spleen, and bowel (5.5 min)

MR Linac: Healthy volunteer

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Balanced FFE Coronal Views demonstrating liver position in the superior-infererior (head-foot) directions at end exhale (left) and inhale (right) (3 frames / second)

MR Linac: Healthy volunteer

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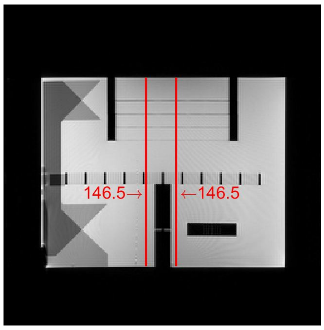
Balanced FFE coronal view
(3 frames / second)

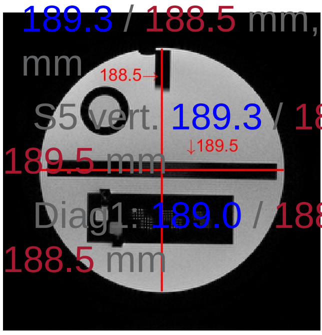
Commissioning of the Elekta MR-Linac

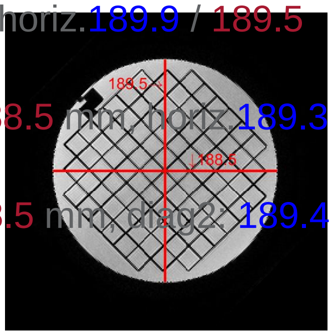
Elekta MR-Linac: MRI Commissioning

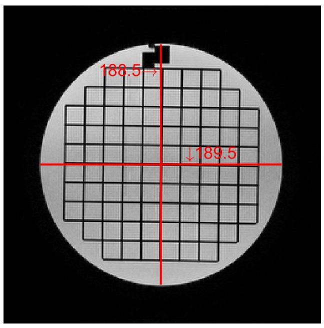
ACR Phantom / Geometric accuracy

- Geometric accuracy within specification (height 148±2 mm, diameter 190±2 mm).
- Localizer: manual 146.3 / automatic 146.5 mm
  S1 vert. 189.3 / 188.5 mm, horiz. 189.9 / 189.5 mm
  S5 vert. 189.3 / 188.5 mm, horiz. 189.3 / 189.5 mm
  Diag1: 189.0 / 188.5 mm, diag2: 189.4 / 188.5 mm









Current status of Elekta MR-Linac @ ICR/RMH

- Linear accelerator performance
- Dosimetry
- Treatment planning studies to evaluate the Electron Return Effect

Elekta MR-Linac: Profile – Left / Right

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FFF beams renormalized following formalism of:

Fogliata, A et al. (2016) Med. Phys., 43: 205:121

Measured:
StarCheck Maxi MR
@ Isocentre
10cm deep RW3

Elekta MR-Linac: Penumbra in water

55

FFF beams renormalized following formalism of:

Fogliata, A et al. (2016) Med. Phys., 43: 205:121

Measured:
StarCheck Maxi MR
@ Isocentre
10cm deep RW3

	L (mm)	R (mm)	S (mm)	I (mm)
Agility FF	8.7	8.6	9.2	9.0
Agility FFF	8.2	8.4	8.3	8.3
MRL FFF	***7.9***	***8.5***	***8.4***	***8.7***

Penumbra width defined as distance from D80 to D20

The Royal Marsden

Starshot Film

Elekta MR-Linac: TPS Commissioning

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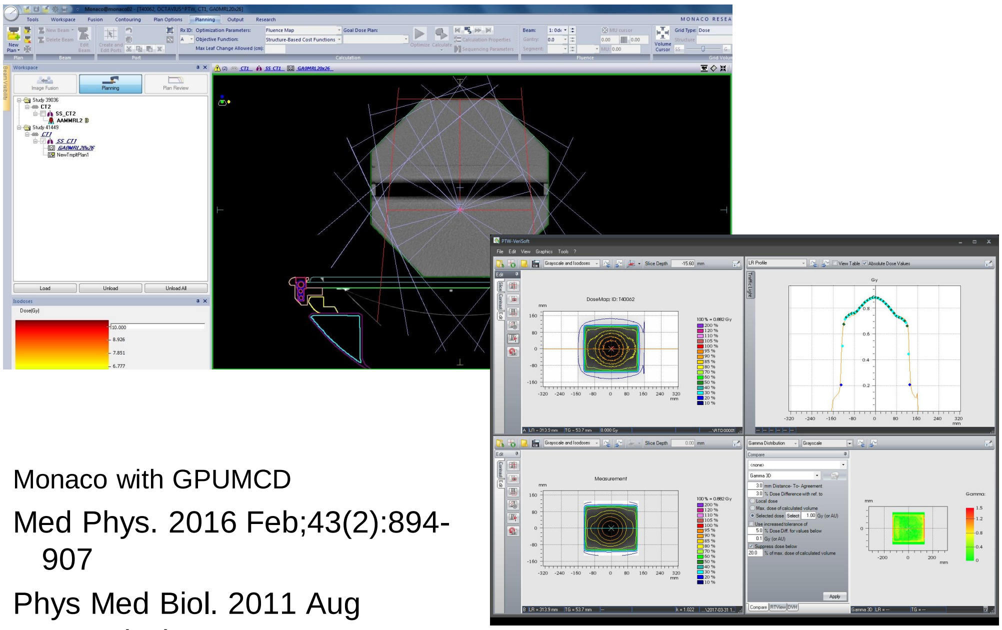


Monaco with GPUMCD

Med Phys. 2016 Feb;43(2):894-907

Phys Med Biol. 2011 Aug 21;56(16):5119-29

The Task: Treating what we see

Patient scheduled for 5-20 minute treatment

- Optimal treatment for the anatomy observed at this time
- Not the anatomy we once have observed
- Original Plan is almost certainly not optimal

Ultrafast treatment planning

The most important aspect is efficient data handling on modern hardware

Ziegenhein et al. **2008** Speed optimized influence matrix processing in inverse treatment planning tools Phys. Med. Biol. 53.

Data transport | Floating point operation

RAM ⟷ CPU cache ⟷ CPU

- 2.62 x 2.62 X 2.62 mm^3 resolution
- 5 x 5 mm^2 beamlets
- > 1400 candidate beams (> 50 GB)

We apply efficient sorting schemes for t

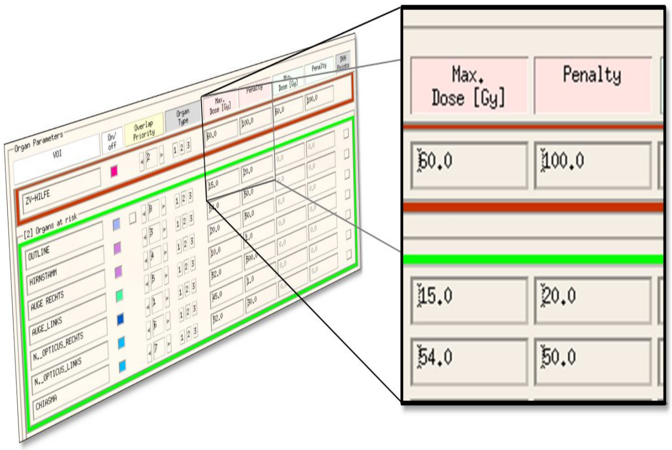
We minimize data transport

We exploit multiple levels of parallelism

→ Full fluence optimization in ~1 sec wi
with 4 CPUs and 128 GB memory (cost ~4500 €)

Conventional IMRT treatment planning

Iterative fluence optimization of an objective function



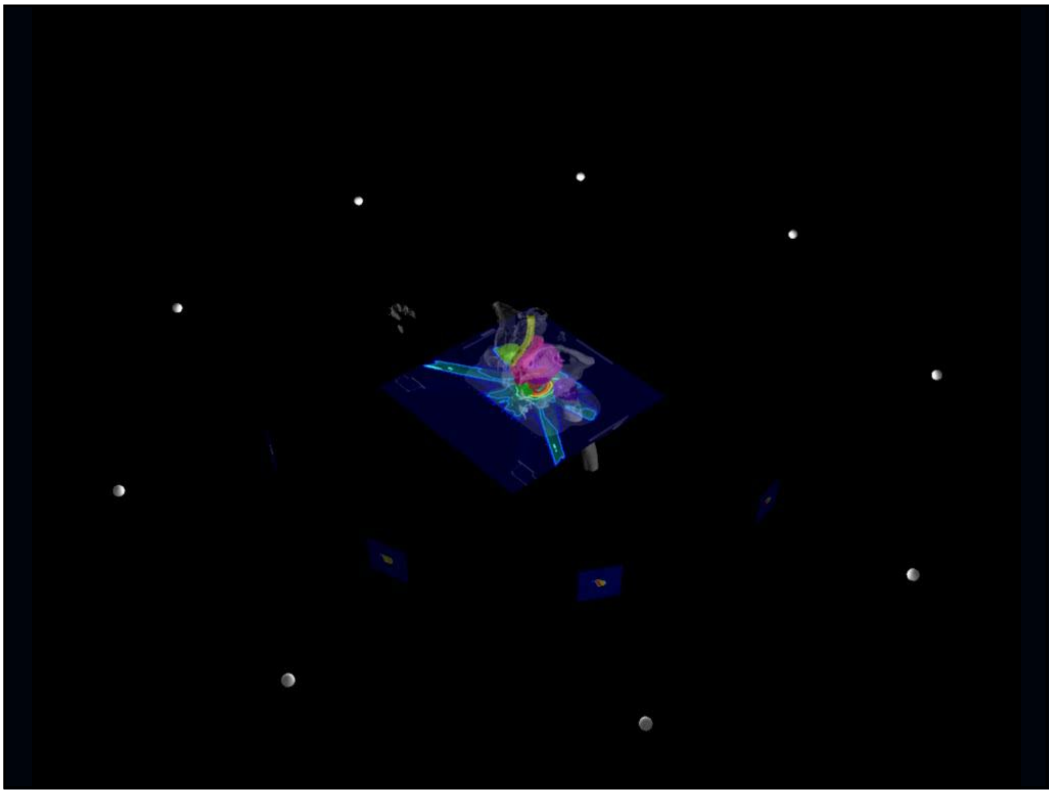
Conventional IMRT treatment planning

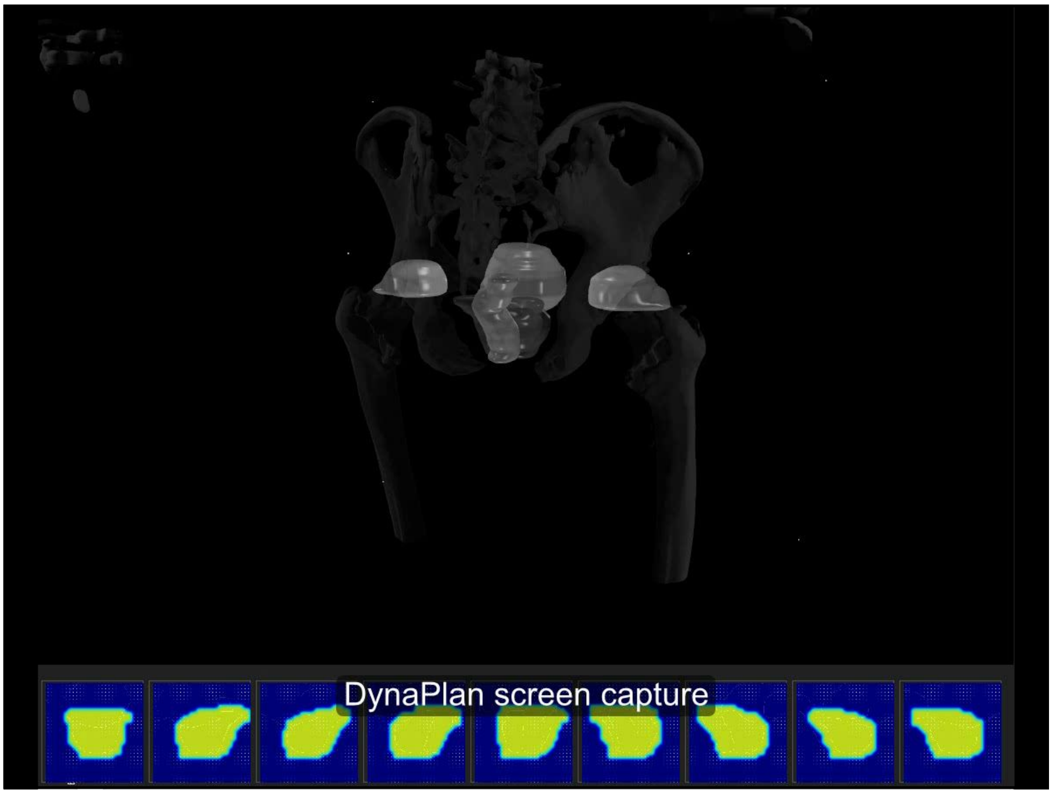
Drawbacks conventional IMRT treatment planning

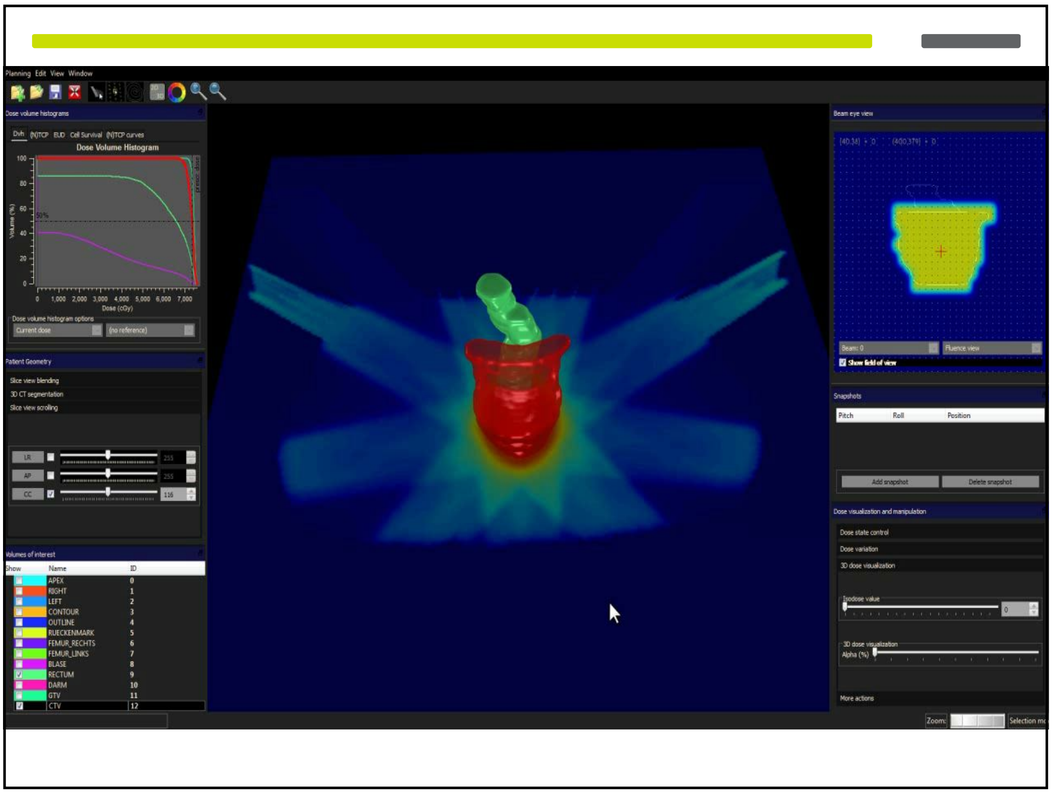
1. Control of local dose features is limited to segmented volumes of interest

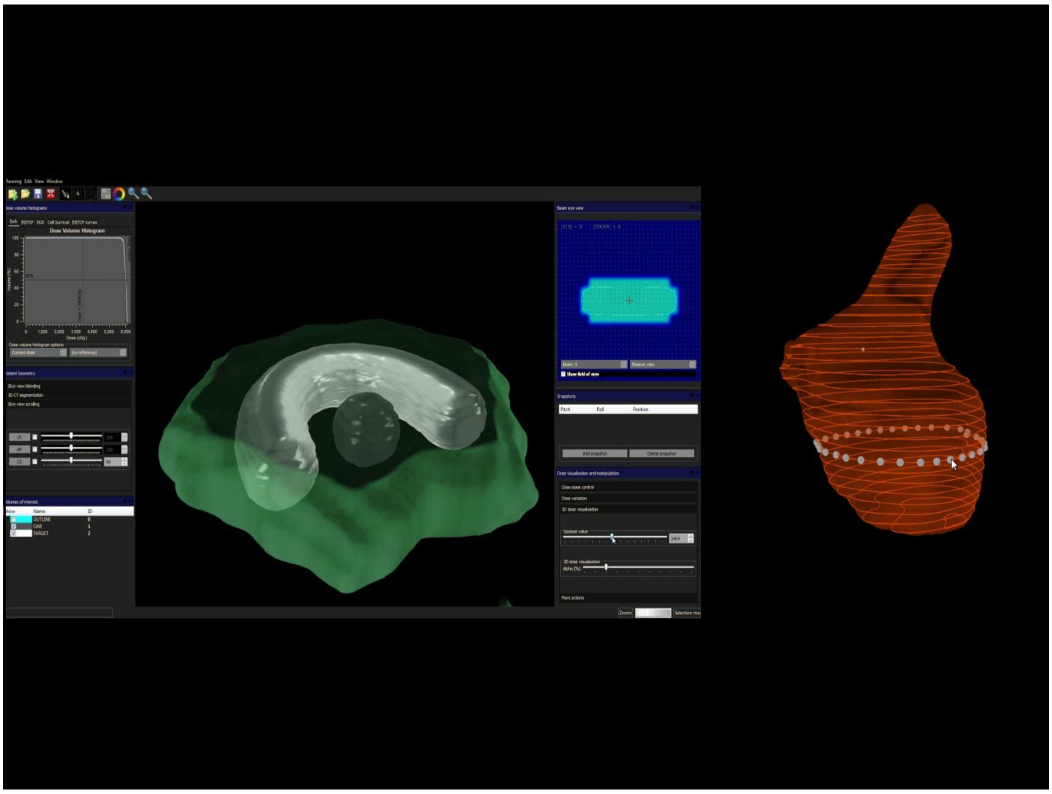
2. No direct mapping between the objective function parameters and the resulting dose distribution

3. Treatment plans are difficult to adapt




DynaPlan screen capture


Planning Edit View Window
Dose volume histograms
Dose Volume Histogram
Volume (%)
Dose (cGy)
Dose volume histogram options
Current dose
(no reference)
Patient Geometry
Slice view blending
3D CT segmentation
Slice view scrolling
LR
AP
CC
Volumes of interest
Show
Name
ID
APEX
RIGHT
LEFT
CONTOUR
OUTLINE
RUECKENMARK
FEMUR_RECHTS
FEMUR_LINKS
BLASE
RECTUM
DARM
GTV
CTV
Beam eye view
Fluence view
Show field of view
Snapshots
Pitch
Roll
Position
Add snapshot
Delete snapshot
Dose visualization and manipulation
Dose state control
Dose variation
3D dose visualization
Isodose value
Alpha (%)
More actions
Zoom:



Improved image quality is 'key' to automate RT procedures