The Need for, and Implementation of, Image-Guidance in Radiation Therapy

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Disclosures

My institution holds Research Agreements with Varian, Elekta, and Philips

I will be discussing devices that are not currently available for sale, and that do not have FDA clearance.
Objectives

- Review the history of IGRT
- Discuss the clinical benefits of IGRT
- Introduce several major advances in IGRT
- Review developments leading to MR-based simulation and planning, and MR-guided radiation therapy
- Describe patient imaging and treatment procedures possible with an MR-guided linac
- Describe recent developments in biology-guided RT
Towards the elimination of invasion

Meanwhile, the practice of surgery itself will continue to change. Prognostication is a hazardous enterprise. But if the past quarter century has brought minimally invasive procedures, the next may bring the elimination of invasion. One feels foolish using terms like nanotechnology — I haven’t the slightest idea what it really means or can do — but scientists are already experimenting with techniques for combining noninvasive ways of seeing into the body through the manipulation of small-scale devices that can be injected or swallowed. Surgical work will probably even become fully automated.
Techniques versus approach

Technical radiation delivery techniques:
- Conventional / Conformal radiotherapy / …
- IMRT / VMAT / Tomotherapy / …
- Cyberknife / Radiosurgery /…
- Protons / Carbon Ions /
- Brachytherapy / …
- etc …

What do we want:
100% cure, 0% toxicity, 100% Quality of Life

Treatment approach: Image Guided RadioTherapy (IGRT)
- spatial control of the dose distribution
- Inhomogeneous dose distribution
- based on the 3D tumor-characteristics
- Individualized treatment

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Results
At TMC review, 25.4% of the patients had noncompliant plans but none in which QARC-recommended changes had been made. At secondary review, 47% of noncompliant plans (12% overall) had deficiencies with a predicted major adverse impact on tumor control. Major deficiencies were unrelated to tumor subsite or to T or N stage (if N+), but were highly correlated with number of patients enrolled at the treatment center (< five patients, 29.8%; ≥ 20 patients, 5.4%; \( P < .001 \)). In patients who received at least 60 Gy, those with major deficiencies in their treatment plans (\( n = 87 \)) had a markedly inferior outcome compared with those whose treatment was initially protocol compliant (\( n = 502 \)): −2 years overall survival, 50% v 70%; hazard ratio (HR), 1.99; \( P < .001 \); and 2 years freedom from locoregional failure, 54% v 78%; HR, 2.37; \( P < .001 \), respectively.
Why do we need image-guided RT?

Dosimetric Effect of Organ Variability

Original Plan

Original Plan on New CT

CT scan a week later

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Slide courtesy L. Court
Why do we need image-guided RT?

Rectal diameter at simulation

de Crevoisier et al, IJROBP 62 (4): 965-973, 2005

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Why do we need image-guided RT?

Local and locoregional failure-free survival rates

Patients receiving IGRT were more likely to receive a higher tumor dose.

Increasing Treatments with Higher Conformality Requires Better Targeting

Improved imaging allows for better tumor delineation for RT planning
Image-Guided RT

- Not a new idea
- Benefits of imaging patient in treatment position
- Position can be assessed at time of beam-on
- Real-time corrections can be made
- Margins can be reduced
From 2D to 3D, 4D, IMRT and IGRT

Courtesy P. Balter
Common IGRT technologies

- 2D projection x-rays (kV or MV)
- CT (cone-beam) (kV or MV)
- Ultrasound
- Surface imaging
- Implanted marker

Kamino et al, IJROBP, 66, 271, 2006
Novalis Exactrac: 2D/3D
CT-guided Radiation Therapy

G. Ibbott, ICMP, Bangkok, 2016
Breakthrough: CT-linac

Changing concepts:

History
- Fractionated
- Homogeneous dose
- Dose prescription ICRU
- Radioresistant tumors
- Etc

Tendency
- Hypofractionated
- Inhomogeneous dose / stereotaxy
- Maximum dose less important, if safe
- Probably do not exist (e.g. kidney)

This makes Image Guided Radiotherapy a real alternative for surgery

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Respiratory Motion and its effect on dose – example planned on 3DCT evaluated on 4DCT
Current Status of IGRT

- kv imaging widely used but relies on bony landmarks or fiducials
- CBCT IGRT has transformed RT practice and perception. Its potential may not have been fully exploited
- However, several issues remain ...
  - Inadequate soft tissue visualization
    o particularly in abdomen and pelvic anatomy
  - Lack of functional information
    - CT cannot reveal tissue characteristics
  - Intrafraction motion
    - Long acquisition time of CBCT largely limits it to pre-treatment or periodic imaging

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Clinical benefits of MRI-based IGRT

Soft-tissue visualization
• Difficult-to-image targets and critical structures become ‘easy’
• Improved ability to adapt treatment
• Ability to see the tumor not just the organ - GTV boost

Real-time 2D and 3D imaging
• Imaging simultaneous with irradiation
• Gating and tracking without surrogates

No imaging dose
• Freedom to image at any time

Quantitative imaging
• Tumor treatment response assessment (inter- and intra-fractions)
What does MR bring to IGRT?

- ‘Real time’ no radiation dose imaging
- Simultaneous with irradiation
- Soft tissue visualization
- Many targets and structures become easier to visualize
- Improved ability to adapt treatment
- Ability to see the tumor not just the organ
  - Prostate, brain, liver, etc,
- Potential for functional and molecular imaging
- Therefore addressing the two remaining IGRT problems
Improved Anatomical Imaging:
Better Soft Tissue Contrast for Target Delineation

Better soft tissue contrast helps us delineate tumor and lymph nodes and normal structures in H&N
The heterogeneity of functional indices across pixels within a histologically defined, Gleason grade 4 + 3 tumor in the right lobe of the prostate

For radiation oncologists, *spatial* dose/response data is what separates us from other cancer paradigms.
4D-MRI: Volume Delineation of Moving Target in Abdomen

Courtesy of Jing Cai, PhD

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Special Precautions Required

• Radiation Oncology staff are generally not familiar with safety precautions required for working with 1.5 T magnet
• Develop safety zones
• Staff must have appropriate training to enter successive zones
• Must consider both MR safety and radiation safety concerns
PMH - MR on Rails

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ViewRay MR-Cobalt Unit

Images courtesy of ViewRay
http://www.viewray.com/
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Philips/Elekta Solution for MR-IGRT

**Purpose**

Treat the patient while simultaneously imaging with a ‘conventional’ 1.5T diagnostic MRI

**How**

1. Mount the Linac on a rotatable gantry around the MRI magnet
   
   _The radiation isocenter is at the centre of the MRI imaging volume_

2. Modify the Linac to make it compatible with the MR environment

3. Modify the MRI system
   
   _Minimize material in the beam path_

   _Minimize magnetic field at the Linac_
Atlantic delivers high quality volumetric images

Example volunteer images

T2w 3D TSE
0.7 x 0.7 x 1 mm³
Imaging time 2 min 12s

T2w 3D TSE
Voxel size 1.5 x 1.5 x 2 mm³
Imaging time 4 min 10 s

Images courtesy of Philips

MR-Linac is a research programme. It is not available for sale and its future availability cannot be guaranteed.
Atlantic can image and detect the target in real time simultaneous with irradiation

- Localization results for Kidney
- Alternating axial, coronal and sagittal slices
- Acquired and processed in 200 ms
MR-Simulation and Treatment Planning

MR segmentation - Lund Univ has developed automatic tools

Synthetic CT from MR images

Use for treatment planning

Generate sDRR for image guidance
Clinical Workflow for Daily Adaptive Treatment

Patient arrives for daily treatment, position on table

Conduct daily 3D image acquisition

Register daily images with reference plan, edit contours

Create daily adapted treatment plan

Perform QA of daily plan

Perform fast imaging to monitor motion

Gate delivery or track motion with MLC

Perform functional imaging

Begin treatment delivery

Complete treatment delivery
Preclinical study of the effect of a magnetic field on cell survival

• Objective: To study whether magnetic fields affect the dose response cells irradiated in culture

• Past work:
  – Cells plated and exposed to magnetic field or sham exposure - demonstrated no change in plating efficiency
  – Cells irradiated to identical dose/fractionation with prototype MR Linac and with conventional linac - demonstrated no change in survival

• Ongoing work:
  – Animals will be irradiated under identical conditions with and without magnetic field to confirm cell results
MRL Radiation Biology Study

MRI - Linac radiation effect (MRL vs. Linac)

In vitro (Funded by Elekta)

Manuscript submitted

MRI-Linac radiation effect (MRL vs. Linac)

In vivo (Funded by Elekta)

In vivo experiments set up and Xenograft models

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Emission-Guided Radiation Therapy
Emission-Guided Radiation Therapy

Courtesy RefleXion Medical
MRI’s role is growing in Radiation Oncology

Expansion to Treatment Time imaging

Diagnosis Staging → Simulation → Treatment Planning → Tx Delivery On-Line Adaption & Tx Assessment → Off-line Response Assessment

MR Scanner
MR Scanner w/ MR-RT Oncology Configuration
Treatment Planning S/W with MR support
MRI Guided Radiation therapy
MR Scanner Sequences and Post-processing S/W

MR Images courtesy of Philips

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Thank you for your attention!

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