RECENT ADVANCES IN LINEAR ACCELERATORS

DR. UPASNA SAXENA
CONSULTANT RADIATION ONCOLOGIST
MR LINEAR ACCELERATOR
• Magnetic Resonance Simulation (MR-Sim) is a diagnostic magnetic resonance imaging (MRI) platform that has been adapted to optimize radiotherapy treatment planning by making a hybrid of CT scan and MRI
• It allow for online real time MR imaging for high-precision adaptive radiotherapy. ²,³
• The term used for it is MR guided radiotherapy [MRgRT]
• MR-linac systems offer real-time tumour tracking and beam gating. ⁴
• The first MR-Sim was approved by Health Canada in 2010, ⁴² and the first MR-linac system was approved by Health Canada in 2017. ⁴³
• MR linac is a hybrid device with a linear accelerator to deliver radiotherapy and a MRI scanner\textsuperscript{21} [somewhat like the CBCT acquisition in other linacs \textsuperscript{22}]

• Combined use of MR Sim and MR Linac holds promise for better delineation and accurate delivery
• MR-Sim is a diagnostic MRI like the CT sim that helps in contouring targets and OARs for radiotherapy planning.¹
• MR Sim may or may not be used for planning purpose with a MR Linac
• MR CT coregistration for contouring can cause errors of 1-2mm¹⁷ which can be minimized by using MR Sim instead of diagnostic MRI coregistration
• MR Sim has a MR only workflow for contouring and planning, the electron density for planning is less reliable in MRI though
• MR Sim has features like
  • coil bridges to prevent deformation of the patient’s body contour⁶
  • MRI compatible mobilization devices to minimize patient movement¹³
  • rigid flat table top¹³
  • laser positioning system⁷
  • wider bore⁷
  • patient imaged in treatment (as opposed to imaging) position⁷
  • dedicated scan protocols.³⁵,⁷
Radiation with linear accelerator involves generating a radiation plan for a volume to account for target and OAR motion. There is no real time confirmation of the movement.\textsuperscript{20}

It's essential to have immobilization devices that permits placement of MRI coils close to the area to be scanned.

MR-linac uses fast dynamic MR sequences for tumour tracking and real-time motion monitoring.\textsuperscript{11} MR guided Real-time adaptive radiotherapy, accounts for natural body movement to improve coverage and reduce OAR dose.\textsuperscript{20}
Benefits from MR Linac

- While MRI is superior in imaging of soft tissue [target and OAR]
- Has no burden of escalating radiation dose by multiple imaging
- It will enable dose escalation
- It will enable margin reduction
- That will translate to higher cure rates and less toxicity for patients.¹
- It may enable the assessment of response [by imaging] before or during the early phases of treatment which may be clinically useful,⁴¹ for plan adaptation or changing treatment objective³⁵
- A study examined and found no significant differences in mean lung density changes for patients who had lung stereotactic ablative radiotherapy using a MR-linac versus a linear accelerator delivery system.²⁵
- Evidence from a study found that patients of pancreatic cancer treated with dose-escalated MR-linac demonstrated improved overall survival and freedom from local failure.⁵¹ Stereotactic MRI-guided On-table Adaptive Radiation Therapy (SMART) study has been launched in 2019 for pancreatic cancer.
- Similar study for prostatic cancer, concluded that MR-linac was feasible and well-tolerated.⁵²
- Multiple studies are ongoing for technical feasibility and assessment of outcomes for different sites using MRgRT
COST CONCERNS WITH MR Linacs

• Its anticipated that by the next decade it will be standard practice to use MR Linac \(^{21,39}\)
• Concerns are it comes along with longer time of image acquisition and higher cost of installation
• The equipement and installation cost ranges from 8.5-10 million dollars for the Elekta MR Linac Unity, 8-10 million dollars for ViewRay MRIIdian
• It’s a challenge to the value based system
• Other cost factors would be
  – Vault construction – lesser for MRIIdian system due to ‘split magnet’ design
  – Additional staff – radiation oncologist, medical physicist, radiotherapy technician, medical radiotherapy technologist
SAFETY CONCERNS

• There are safety issues related to the projectile capabilities of metallic objects in the strong magnetic field

• It’s needed to screen patients for contraindications such as aneurysm clips, cardiac bypass surgery, some heart valves, embedded wires, stimulators, batteries, implanted electrodes, shunts, pumps, pacemakers, and some penile implants.¹⁷

• Even non-magnetic metallic implants may cause artefacts in the MR images, such as signal loss, intense areas of signal accumulation, and distortion in areas near the implant.³⁵

• The loud knocking noise can be a deterrent and need ear protection and can cause peripheral nerve stimulation

• The thermal effects of radiofrequency used can cause heating of the body
TECHNICAL CHALLENGES IN IMPLEMENTATION

• Assessment and resolution of technical factors regarding electron density assessment, contour generation, planning, verification and adaptation
• Newer quality assurance needing training of physicist
• Training for RTT as MR is new for them
• Selection of people for the work and conducting training will be a pre-requisite
• Areas of MRgRT-related focused training include:40,63
  • New treatment planning systems
  • MR safety, patient screening
  • MR-based anatomy — image assessment on MRI versus cone beam CT versus CT
  • MR image quality, formation, scan optimization and interpretation
  • Multimodality image registration
  • Contour/modify organs at risk for adaptive radiotherapy
  • Adaptive radiotherapy strategies and methodologies
  • Novel radiotherapy delivery techniques
  • Daily/weekly quality assurance and quality control requirements.
MR Linac configurations

- MR Linacs can have either fixed perpendicular or parallel beam field or both

---

Table 1: Different Types of MR-linac Configurations

<table>
<thead>
<tr>
<th>MR-linac System Radiation</th>
<th>Magnetic Field Configuration</th>
<th>Magnetic Field Orientation</th>
<th>Tesla Strength (T)</th>
<th>Bore Size (cm)</th>
<th>Rotating Couch/Gantry</th>
</tr>
</thead>
<tbody>
<tr>
<td>ViewRay</td>
<td>Cobalt-60</td>
<td>split superconducting</td>
<td>Perpendicular</td>
<td>0.35</td>
<td>70</td>
</tr>
<tr>
<td>ViewRay</td>
<td>MRIdian Linac</td>
<td>6 MV</td>
<td>split superconducting</td>
<td>Perpendicular 0.35 T</td>
<td>0.35</td>
</tr>
<tr>
<td>MagnetRx</td>
<td>Aurora RT</td>
<td>6 MV</td>
<td>superconducting rotating</td>
<td>Parallel</td>
<td>0.5</td>
</tr>
<tr>
<td>Australian MRI Linac</td>
<td>6 MV</td>
<td>superconducting open bore</td>
<td>Parallel/ Perpendicular</td>
<td>1.0</td>
<td>82</td>
</tr>
<tr>
<td>Elekta Unity</td>
<td>7 MV</td>
<td>superconducting close bore</td>
<td>Perpendicular</td>
<td>1.5</td>
<td>70</td>
</tr>
<tr>
<td>MRgRT Suite</td>
<td>6 MV, Ir-92</td>
<td>MR on rails</td>
<td>NA</td>
<td>1.5</td>
<td>70</td>
</tr>
</tbody>
</table>

MR = magnetic resonance; MRgRT = magnetic resonance guided radiotherapy; MV = megaelectronvolt; NA = not applicable; RT = radiotherapy; T = tesla.
There are several MR-linac systems available:

- Elekta Unity that incorporates a Philips 1.5 Tesla MRI and a 7.5 megavolt (MV) (acceleration rate) linear accelerator,\textsuperscript{73}
- MRIdian by ViewRay that integrates a 0.35 Tesla magnet with a 6 MV Linac,\textsuperscript{74}
- The rail-mounted MRgRT Suite.\textsuperscript{40}
- Aurora RT radiotherapy system from MagnetTx, combines a 6 MV linear accelerator and a 0.5 Tesla MRI magnet, and has a non-clinical working prototype.\textsuperscript{75}
• the **international MR-linac Consortium** established in 2012
• It published its study **MOMENTUM (Multiple Outcome Evaluation of Radiotherapy Using the MR-linac)** in 2019\(^ \text{54} \)
• has selected tumour sites for which MRgRT will initially be used, though later it might be expanded to all sites\(^ \text{31} \)
  
  – Brain
  – Breast
  – Cervix
  – Esophagus
  – Lung
  – Oropharynx
  – Pancreas
  – Prostate
  – rectum
Technical design and concept of a 0.35 T MR-Linac

Sebastian Klüter

Department of Radiation Oncology, University Hospital Heidelberg, Heidelberg Institute for Radiation Oncology (HIRO), National Center for Radiation Research in Oncology (NCRO), Heidelberg, Germany

Abstract

The integration of magnetic resonance (MR) imaging and linear accelerators into hybrid treatment systems has made MR-guided radiation therapy a clinical reality. This work summarizes the technical design of a 0.35 T MR-Linac and corresponding clinical concepts. The system facilitates 3D-conformal as well as IMRT treatments with 6MV photons. Daily MR imaging provides superior soft-tissue contrast for patient setup and also enables on-table adaption of treatment plans, which is fully integrated into the treatment workflow of the system. Automated beam gating during delivery is facilitated by cine MR imaging and structure tracking. Combining different novel features compared to conventional image-guided radiotherapy, this technology offers the potential for margin reduction as well as dose escalation.

© 2019 The Author. Published by Elsevier B.V. on behalf of European Society for Radiotherapy and Oncology. This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/).
Fig. 2

(a) Schematic drawing of the system depicting the main hardware components: superconducting double-donut magnet, circular radiation gantry and patient couch; (b) schematic drawing of the radiation gantry with linac components and MLC. Images courtesy of ViewRay Inc.
Original Article

ESTRO-ACROP recommendations on the clinical implementation of hybrid MR-linac systems in radiation oncology

Stefanie Corradini, Filippo Alongi, Nikolaus Andratschke, David Azria, Omar Bo, Anna Bruynzeel, Juliane Hörner-Rieber, Ina Jürgenliemk-Schulz, Frank Lagerwaard, Bas Raaymakers, Tine Schytte, Alison Tree, Vincenzo Valentini, Lotte Wilke, Dario Sica, Jürgen Illhardt

* Department of Radiation Oncology, University Hospital, LMU Munich, Germany; † Department of Advanced Radiation Oncology, IRCCS Sacro Cuore, Verona, Italy, University of Brescia, Italy; ‡ Department of Radiation Oncology, University Hospital of Zurich, University of Zurich, Switzerland; § Department of Radiation Oncology, Montpellier-Asnières, INSERM U1040, Montpellier Cancer Institute, University of Montpellier, INSERM U1040, Montpellier, France; ¶ Department of Oncology, University Hospital, Amsterdam, Netherland; †† Department of Oncology, University of Heidelberg, Heidelberg, Germany; †‡ Department of Radiation Oncology, University Medical Center Utrecht, The Netherlands; †§ Department of Radiation Oncology, University of Southern Denmark, Odense, Denmark; †¶ Department of Radiation Oncology, University of Tübingen, Germany.

Clinical MRgRT workflow

Pre-treatment plan on fx 12

Daily adapted plan on fx 12

Pre-treatment plan fx3

Adapted plan fx3

Fig. 2. Exemplar of MRgRT workflow.

Fig. 1. Example daily plan adaptation. (A) Full re-optimization for a lung cancer patient on treatment fraction 12 to fulfill constraints of organs at risk. (B) Full re-optimization for a prostate patient on treatment fraction 3 to fulfill constraints of organs at risk.
The Patient Experience of the MR-Linac

Amber Robinson • Mikki Campbell • Darby Erler

DOI: https://doi.org/10.1016/j.jmir.2020.07.046 • Check for updates
ONGOING TRIALS

• UMBRELLA-II

The MR-Linac Technical Feasibility Protocol (UMBRELLA-II)

The safety and scientific validity of this study is the responsibility of the study sponsor and investigators. Listing a study does not mean it has been evaluated by the U.S. Federal Government. Know the risks and potential benefits of clinical studies and talk to your health care provider before participating. Read our disclaimer for details.

Sponsor:
The Netherlands Cancer Institute

Collaborator:
Elekta Limited

Information provided by (Responsible Party):
The Netherlands Cancer Institute
Purpose/Objective(s): To present our institutions initial clinical experience with a high field MR-Linac with regards to patients treated, data collected, functional imaging performed and general performance of the machine.

Materials/Methods: From Aug 15, 2019 to Feb 7, 2020, thirty-three patients were treated on our 1.5 T MR-Linac with all patients enrolled in the MOMENTUM study (ClinicalTrials.gov, identifier: NCT04075305). Two types of workflows were used: one accounting for daily patient shifts only (adapt o position or ATP) and the other involving online plan adaptation through re-contouring and re-optimization based on daily MRI images (adapt to shape or ATS). Of the thirty-three patients, thirty were CNS brain patients (15 GBM and 15 other) treated using ATP and three were prostate cancer patients treated using ATS and SBRT to a dose of 40 Gy in 5 fractions. Imaging involved T1 (brain ATP) or T2 (prostate ATS) weighted scans captured online for registration/planning. Functional imaging sequences for brain ATP (DWI, MT, BOLD, CEST) were taken before, during and post irradiation in addition to T2-FLAIR. DWI was done for the prostate cases before, during and post irradiation. Timing was recorded for the various stages of the workflows. Machine performance was characterized in terms of unscheduled downtime events.

Results: A total of 540 fractions were delivered on the MR-Linac over its initial 25 weeks of use. The average session time (n = 200 fractions) for the brain ATP workflow (excluding post imaging) was 26.9 minutes (3.7 min setup, 5.5 min pre-tx imaging, 3.1 min image registration, 4.5 min plan optimization, 2.0 min physics QA, and 6.1 min beam on). The minimum session time was 24 minutes for the brain ATP. The average session time for the prostate ATS workflow (n = 10 fractions) was 47.7 minutes (6.6 min setup, 3.2 min pre-tx imaging, 3.5 min image registration, 15.1 min contouring, 5.6 min plan optimization, 1.5 min physics QA, 2.9 min verification imaging and 9.3 min beam on). Additional post beam research scans took, on average, 12.5 minutes for the prostate cases. The following multi-parametric imaging maps were generated for the brain patients: T1 and T2, ADC, T2-FLAIR, CEST asymmetry and Amide MTR. The brain T2-FLAIR signal, in some cases, reduced over the treatment course. Changes in ADC maps were observed for both brain and prostate over the treatment. In some instances, brain re-planning was done offline based on daily online T2-FLAIR imaging. In terms of downtime, patients were transferred to a standard Linac for 7.1% of fractions due to either a magneton change, modulator tank replacement, or a cooling issue.

Conclusion: An MR-Linac program has been implemented at our institution involving a multi-disciplinary group with both machine data and patient data being captured. The current status, clinical and technical considerations, and most recent image-based findings will be presented.

Online Adaptive Radiation Therapy: Implementation of a New Process of Care

James Lamb 1, Minsong Cao 2, Amar Kishan 1, Nzhde Agazaryan 1, David H. Thomas 3, Narek Shaverdian 2, Yingli Yang 1, Suzette Ray 1, Daniel A. Low 4, Ann Raldow 1, Michael L. Steinberg 5, Percy Lee 1

1. Department of Radiation Oncology, University of California, Los Angeles  2. Department of Radiation Oncology, University of California Los Angeles  3. Department of Radiation Oncology, University of Colorado, Denver  4. None  5. Department of Radiation Oncology, UCLA Medical Center

☑️ Corresponding author: James Lamb, jlamb@mednet.ucla.edu
Disclosures can be found in Additional Information at the end of the article
Clinical implementation of artificial intelligence-driven cone-beam computed tomography-guided online adaptive radiotherapy in the pelvic region

Patrik Sibolt⁷, Lisa M. Andersson, Lucie Caimels, David Sjöström, Ulf Bjelkengren, Poul Geertsen, Claus F. Behrens

Keywords:
- Online Adaptive Radiotherapy (oART)
- CBCT Image-guided radiotherapy
- Artificial Intelligence
- Automated treatment planning
- Bladder cancer

Background and purpose: Studies have demonstrated the potential of online adaptive radiotherapy (oART). However, routine use has been limited due to resource demanding solutions. This study reports on experiences with oART in the pelvic region using a novel cone-beam computed tomography (CBCT)-based, artificial intelligence (AI)-driven solution.

Material and methods: Automated pre-treatment planning for thirty-nine pelvic cases (bladder, rectum, anal, and prostate), and one hundred oART simulations were conducted in a pre-clinical release of Ebos (Varian Medical Systems, Palo Alto, CA): Plan quality, AI-segmentation accuracy, oART feasibility, and an integrated calculations-based quality assurance solution were evaluated. Experiences from the first five clinical oART patients (three bladder, one rectum and one sarcoma) are reported.

Results: Auto-generated pre-treatment plans demonstrated similar planning target volume (PTV) coverage and organs at risk doses, compared to institution reference. More than 75% of AI-segmentations during simulated oART required none or minor editing and the adapted plan was superior in 88% of cases. Limitations in AI-segmentation correlated to cases where AI model training was lacking. The five first treated patients complied well with the median adaptive procedure duration of 17.6 min (from CBCT acceptance to treatment delivery start). The treated bladder patients demonstrated a 42% median primary PTV reduction, indicating a 24%-30% reduction in V150Gy to the bowel cavity, compared to non-oART.
ONLINE ADAPTIVE RADIOTHERAPY
The challenges involved in delivering on-couch adaptive therapy are addressed, in the Ethos system, through a replanning workflow that has been reduced to well-defined and predictable clinical decision points in order to lower the cognitive load of the clinician.
FOUR Decision points

• Accepting the image
• Assessing and modifying the ‘influencer’ structures or OARs
• Assessing and modifying the target organs – creating the session model
• Selecting the plan – scheduled or adapted
Fig. 1: Ethos therapy on-couch adaptive workflow
• Deep learning convolutional neural network [CNN] and hyperparameters in these models are used

• Uses the acquired 3D iCBCT as input to the neural network and gives a similar output that the clinician can assess and accept

Fig. 2: An example of Varian’s deep convolution neural network architecture.
Fig. 3: Machine learning model production process
• Once image is approved, **deformable registration** is used by the system to make an image sCBCT that conforms with the CBCT

• Then the IOE (Intelligent optimization engine) generated IMRT/VMAT plans with high degree of dose conformity and OAR doses, and an intelligent trade off clinically

• The IOE works by having Q-functions [quality functions] laid down before hand for the planning purpose
  - Target upper dose [TUD] goal
  - Target lower dose [TUD] goal
  - Organ upper dose [OUD] goal
It works by making physics volumes, reiterations, more control functions.
**Decision-making guided by AI**

The goal of Ethos therapy was to design a simple adaptive therapy workflow for both the initial planning and daily re-planning sessions.

During initial planning, Ethos therapy automatically produces several plan candidates with various beam geometries and techniques using prioritized target and organ at risk goals from the physician’s intent. The clinician chooses the most suitable plan and authorizes it for delivery. This step provides confidence that the goals and patient geometry are compatible, and that plan automation can be performed each day. Each treatment day, once the daily anatomy is reviewed and accepted, Ethos therapy will prepare a new adapted plan using the beam geometry of the initial plan, the initial set of target and organ and risk goals, and give the clinician the choice of either the original or adapted plan for delivery.

The process is guided by the technology, as follows:

- A decision tree guides the entire adaptive therapy process
- Treatment management and treatment planning applications are tightly coupled and context-aware
- Clinician approvals move the process from one step to the next
- Every step of the workflow is optimized for speed and engineered for safety

**Automated dose accumulation**

Each day, the Ethos therapy system automatically reconstructs delivered dose in relation to today’s anatomy. This capability:

- Demonstrates that the patient is receiving the intended dose
- Improves understanding of the treatment progress
- Helps identify when re-simulation may be required
- Simplifies off-line adaption
Online adaptive radiotherapy compared to plan selection for rectal cancer: quantifying the benefit

R. de Jong, K. F. Crama, J. Visser, N. van Weeringen, J. Viersma, E. D. Gelissen and A. Bel

Abstract

Background: To compare online adaptive radiation therapy (ART) to a clinically implemented plan selection strategy (PS) with respect to dose to the organs at risk (OAR) for rectal cancer.

Methods: The first 20 patients treated with PS between May–September 2016 were included. This resulted in 10 short (SCRT) and 10 long (LCRT) course radiotherapy treatment schedules with a total of 300 Conebeam CT scans (CBCT). New dual arc VMAT plans were generated using auto-planning for both the online ART and PS strategy. For each fraction bowel, bladder and mesorectum were delineated on daily Conebeam CTs. The dose distribution planned was used to calculate daily D95. Coverage of the CTV was calculated, as defined by the dose received by 99% of the CTV volume (D99%). The volume of normal tissue irradiated with 95% of the prescribed fraction dose was calculated by calculating the volume receiving 95% of the prescribed fraction or more dose minus the volume of the CTV. For each fraction the difference between the plan selection and online adaptive strategy of each OAR parameter was calculated, as well as the average difference per patient.

Results: Target coverage remained the same for online ART. The median volume of the normal tissue irradiated with 95% of the prescribed dose dropped from 440 cm³ (IQR: 493–217 cm³) to 154 cm³ (IQR: 15–191 cm³) for SCRT and from 310 cm³ (IQR: 140–294 cm³) to 79 cm³ (IQR: 7–41 cm³) for LCRT. The OARs reduced dose to the OARs for all tested dose levels for SCRT and LCRT (p < 0.001). For V15 Gy of the bowel bag the median difference over all fractions of all patients was −120 cm³ in LCRT, while the average difference per patient ranged from −86 cm³ to −40 cm³, for SCRT the median difference was −62 cm³, while the range of the average difference per patient was −105 cm³ to −51 cm³. For V15 Gy of the bladder the median difference over all fractions of all patients was 24% in LCRT, while the average difference per patient ranged from −34 to 12%. For SCRT the median difference of 99.6% was −8%, while the range of the average difference per patient was −29 to 0%.

Conclusions: Online ART for rectal cancer reduces dose to the OARs significantly compared to a clinically implemented plan selection strategy, without compromising target coverage.

Trial registration: Medical Research Involving Human Subjects Act (WMCT) does not apply to this study and was retrospectively approved by the Medical Ethics review Committee of the Academic Medical Center (W16-3357 # 19420, Amsterdam University Medical Centers, Location Academic Medical Center, Amsterdam, The Netherlands).