

PROGRAM AND ABSTRACTS

Virtual 8th MR in RT Symposium

April 19th -21st 2021
hosted by German Cancer Research Center
Heidelberg, Germany

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Virtual Satellite Symposium:

Dosimetry and QA in MR-guided Radiotherapy-from primary standards to clinical solutions
April 18th 2021

www.dkfz.de/mrinrthd2021

HOST:
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Content

WELCOME

Dear Participants,

It is our great pleasure to welcome you on behalf of the organizing and scientific committees to the **Virtual 8th MR in RT Symposium**. As you may know the meeting was initially scheduled for May 2020 in Heidelberg, but due to the pandemic had to be cancelled. Considering the ongoing critical situation, we decided early to organize a fully virtual meeting **from Monday, April 19th to Wednesday, April 21st, 2021**. We are very happy, that the commitment of all people involved has been exceptional and we are happy to tell you that we were able to put together a very exciting program with many experts, that we invited for talks, a large number of interesting scientific abstracts, which were submitted and last not least also a strong commitment of our industry sponsors, which helped us a lot to organize this meeting. Our experienced organizational team has been working hard over the last months to organize all the details of the meeting and to provide an excellent platform for the virtual sessions.

The fast technological development and the rapid clinical implementation of MRI for radiotherapy are currently the most exciting as well as most challenging developments in radiation oncology. Also, radiation oncology is probably the most advanced area in medicine, where modern data sciences have a stronger and stronger impact and where AI in medicine is not just a buzz word, but becoming more and more a reality. With this science symposium we would not only like to bring together specialists from all involved disciplines, but also to foster a discussion about the scientific direction of the field. The latest developments in physics and technology of MR-guided radiotherapy as well as clinical directions and results and some of the underlying approaches from data science will be presented.

Prior to the symposium (April 18th, 2021) we organized a Virtual Satellite Symposium about "Dosimetry and QA in MR Guided Radiotherapy: from primary standards to clinical solutions" for a limited number of attendees to have a more in-depth look into some aspects of clinical procedures for QA and dosimetry at an MR-Linac.

Please note also our special issue on MR in radiotherapy in the PHiRo journal (https://www.phiro.science/mri) where many of the speakers followed our invitation to publish their work of 2020 and which is an interesting collection of articles. We would like to thank Prof. Daniela Thorwarth, who, as an editor, suggested and strongly supported this idea.

At this point, we would like to thank all the people, who contributed to organizing this event: the scientific committee members, the local organization team at DKFZ, the numerous scientists, who submitted their work as abstracts and again the industry sponsors, for their generous financial support to this meeting. We hope that there will also be some chances for you to use the 1-1video rooms, our meet-and-greet-sessions or the networking tables to chat and discuss with colleagues and by doing so, to complement the scientific talks with some personal exchange.

We are wishing you a fruitful meeting and send you a warm welcome from Heidelberg!

Prof. Dr. Oliver Jäkel

Prof. Dr. Dr. Jürgen Debus

PROGRAM VIRTUAL SATELLITE SYMPOSIUM

DOSIMETRY AND QA IN MR GUIDED RADIOTHERAPY: FROM PRIMARY STANDARDS TO CLINICAL SOLUTIONS

APRIL 18TH 2021

Time	Topic
8:30-8:50	**Welcome Lounge**
8:50-9:00	**Welcome words by the organizers**
9:00-10:35	**Session A01: Dosimetry in magnetic fields – connection to primary standards** **Chair:** Christian Karger/Ralf-Peter Kapsch
15+1 min *9:00-9:16*	**A01.01: ID 147:** Water calorimetry at the Elekta MR-Linac to determine $k_{Q,B}$ *Leon de Prez (VSL, Delft, Netherlands)*
15+1 min *9:16-9:32*	**A01.02: ID 130:** Water calorimetry at the ViewRay MR-Linac to determine $k_{Q,B}$ *Achim Krauss (PTB, Braunschweig, Germany)*
15+1 min *9:32-9:48*	**A01.03: ID 134:** Monte Carlo for simulation of $k_{Q,B}$ of ion chambers: how to setup the system? *Ilias Billas (NPL, London, Great Britain)*
15+1 min *9:48-10:04*	**A01.04: ID 132:** $k_{Q,B}$ correction factors for ion chambers and the role of dead volumes *Stefan Pojtinger (PTB, Braunschweig, Germany)*
15+1 min *10:04-10:20*	**A01.05: ID 148:** Protocols for dosimetry in magnetic fields *Simon Woodings (UMC, Utrecht, Netherlands)*
10:20-10:35	**Discussion**
10:35-11:10	**Coffee break**
11:10-12:30	**Session A02: Installation and Clinical commissioning of MR-Linac devices** **Chair:** Sebastian Klüter/Simeon Nill
15+1 min *11:10-11:26*	**A02.01: ID 140:** From Installation to first patient treatments with the ViewRay system *Anil Sethi (Loyola University, Chicago, USA)*
15+1 min *11:26-11:42*	**A02.02: ID 138:** From Installation to first patient treatments with the Elekta system *Marcel Nachbar (University Hospital Tübingen, Germany)*
15+1 min *11:42-11:58*	**A02.03: ID 144:** The MagnetTx AuroraRT system: How to arrive at the first patient treatment? *Gino Fallone (CCI, Edmonton, Canada)*
15+1 min *11:58-12:14*	**A02.04: ID 149:** The Australian MRI-Linac system: How to arrive at the first patient treatment? *Paul Keall (ACRF Image X Institute, Sydney, Australia)*
12:14-12:30	**Discussion**
12:30-13:30	**Lunch Break**

APRIL 18TH 2021

13:30-14:50	**Session A03: New procedures for regular machine QA** **Chair:** Daniela Thorwarth/Davide Cusumano
15+1 min *13:30-13:46*	**A03.01: ID 150:** Special requirements for measurement equipment in MRgRT *Jochem Wolthaus (UMC, Utrecht, Netherlands)*
15+1 min *13:46-14:02*	**A03.02: ID 135:** Isocenter accuracy and image distortion measurements at MR-Linacs *Stefan Dorsch (DKFZ, Heidelberg, Germany)*
15+1 min *14:02-14:18*	**A03.03: ID 136:** MRI quality control for MRgRT-systems Andreas *Wetscherek (ICR / RMH, London, Great Britain)*
15+1 min *14:18-14:34*	**A03.04: ID 153:** QA for MR-guided gating *Kim Taeho (Washington University St. Louis, USA)*
14:34-14:50	**Discussion**
14:50-15:20	**Coffee break**
15:20-16:55	**Session A04: Verifying the adaptive process & online QA** **Chair: Stefan Dorsch/Jochem Wolthaus**
15+1 min *15:20-15:36*	**A04.01: ID 131:** End-to-end-Tests for adaptive MRgRT *Alina Elter (DKFZ, Heidelberg, Germany)*
15+1 min *15:36-15:52*	**A04.02: ID 129:** Failure mode and effect analysis in MRgRT *Oliver Schrenk (PTW Freiburg, Germany)*
15+1 min *15:52-16:08*	**A04.03: ID 143:** Online-QA in the adaptive process with the ViewRay system *Stephanie Tanadini-Lang (University Hospital Zürich, Switzerland)*
15+1 min *16:08-16:24*	**A04.04: ID 128:** Online-QA in the adaptive process with the Elekta system *Simeon Nill (ICR / RMH, London, Great Britain)*
15+1 min *16:24-16:40*	**A04.05: ID 137:** Dose reconstruction using linac log files and online MRI: a promising tool for daily patient QA? *Martin Menten (Imperial College London, Great Britain)*
16.40-16:55	**Discussion**
16:55-17:00	**Closing** Christian Karger, Sebastian Klüter, Stefan Dorsch

All times indicated are given as **Central European Summer Time** (CEST).

Scientific committee: Christian Karger, Sebastian Klüter, Stefan Dorsch

A01.01 ID 147

Water calorimetry at the Elekta MR-Linac to determine k_(Q,B)

Leon de Prez, Ionizing Radiation Standards, VSL - Dutch Metrology Institute

With the introduction of new treatment modalities in radiotherapy, there is a continuous demand for (on-site) characterization of detectors in terms of absorbed-dose-to-water (D_w) against primary standards under new conditions. An example of this was the recent introduction of MRI-guided radiotherapy (MRgRT). It had been shown earlier that detector responses could be affected significantly by the magnetic field. To quantify this effect, VSL developed a transportable water calorimeter as a primary standard in magnetic fields. The calorimeter was used to measure ion chamber specific correction factors, k_Q and k_B in an Elekta Unity MRL at University Medical Centre Utrecht (UMCU). Currently, MRL-compatible absorbed-dose-to-water primary standards have been developed by several other groups.

This presentation will provide insight in the application of today's primary standards for direct realization of the quantity D_w in MRgRT-devices. It will then focus on water calorimetry and specifically on the design, commissioning and application of the VSL water calorimeter and its measurement of $k_{Q,B}$ of a set of commonly used ion chambers at the MRL-facilities of UMCU. This will include a description of the measurements performed with the calorimeter in a 1.5-T magnetic field and, after ramp-down, without magnetic field. To evaluate the primary standard on a fundamental basis, realisation of D_w at 1.5 T was evaluated parameter by parameter.

The uncertainty evaluation showed that it is possible to reach a similar accuracy for realization of D_w in MRgRT as in conventional external beam radiotherapy. It is therefore concluded that water calorimetry can be applied as a valid method for realisation of the quantity D_w in magnetic fields. This provides direct access to the international traceability framework via national metrology institutes (NMIs) or designated institutes (Dis), both operating as primary standards dosimetry labs (PSDLs).

A01.02 ID 130

Water calorimetry at the ViewRay MR-Linac to determine kB,Q,Qo

Achim Krauss, Department of Dosimetry for Radiation Therapy and Diagnostic Radiology, Physikalisch-Technische Bundesanstalt

Katharina Spindeldreier[1], Sebastian Klüter[1]
[1]Department of Radiation Oncology, Heidelberg University Hospital

Introduction

With the increasing clinical application of MR-linacs, there is the demand for accurate reference dosimetry with ionization chambers in the presence of magnetic fields. So, the influence of magnetic fields on the response of ionization chambers must be considered. Most directly, this can be done by using an absorbed dose to water standard for MR-linac irradiation conditions. At PTB, a water calorimeter has been developed for this purpose and which was used to determine k_{B,Q,Q_0} factors of ionization chambers in the Viewray 6 MV 0.35 T MR-linac at Heidelberg University Hospital. The k_{B,Q,Q_0} factors correct the chambers response for beam quality and for the presence of the magnetic field.

Materials and Methods

The water calorimeter is operated at a water temperature of 4 °C and is designed for horizontal irradiations and to fit into the 70 cm bore of an MR-linac. The water calorimeter measures $D_{w,Q}$ at a water depth of 10 cm first. Secondly, after replacing the calorimetric detector, ionization chambers can be calibrated inside the water phantom of the calorimeter. This way, k_{B,Q,Q_0} factors for cylindrical ionization chambers with sensitive volumes ranging from 0.015 cm3 to 0.65 cm3 were determined. The chambers were positioned both perpendicular and parallel to the direction of the magnetic field of the MR-linac.

Results

The k_{B,Q,Q_0} factors were determined within standard uncertainties of less than 0.6 %. So, accurate experimental data for reference dosimetry in an MR-linac can be provided by help of water calorimetry.

A01.03 ID 134

Monte Carlo for simulation of $k_{Q,B}$ of ion chambers: how to setup the system?

Ilias Billas, National Physical Laboratory

In the context of MRI guided radiotherapy (MRIgRT), the constant magnetic field of the MRI scanner can have a significant effect on radiation dosimetry. The trajectories of the charged particles traversing the air-cavity of an ion chamber, considered as a reference class detector, are altered due to the Lorentz force and measurements of absorbed dose are more challenging.

Existing protocols for the determination of absorbed dose to water may be extended to allow measurements in the presence of a magnetic field. This requires the inclusion of a magnetic field strength-dependent correction factor, $k_{Q,B}$, defined as the ratio of chamber calibration coefficients, with and without a magnetic field. This correction reduces to unity when the field strength vanishes. Values for $k_{Q,B}$ may be measured in MRI-linacs and may also be calculated by Monte Carlo (MC) simulation, however it is essential that MC simulations of electron transport in the presence of a magnetic field are set up correctly.

The MC code system used must be able to transport radiation in the presence of magnetic fields and in heterogenous media. A Fano cavity test, specialised for magnetic fields, can help to determine MC transport parameters. It has become clear that the magnetic field enhances the sensitivity of ion chamber response to some details of design that in conventional conditions were less important (such as the presence of small air gaps, the dead volume, manufacturing tolerances and intra-type variability). Experimental validation of MC simulations by experimental measurements must be made wherever possible.

Monte Carlo simulations have become an essential part of reference dosimetry and their precise setup is all the more critical for MRIgRT.

A01.04 ID 132

$K_{Q,B}$ correction factors for ion chambers and the role of dead volumes

Stefan Pojtinger, Physikalisch-Technische Bundesanstalt

Ralf-Peter Kapsch[1], Daniela Torwarth[2]
[1]Physikalisch-Technische Bundesanstalt
[2]Biomedical Physics, University Hospital Tübingen

The response auf ionization chambers is altered in the presence of magnetic fields. As a consequence, the signal of a ionization chamber must be corrected by a magnetic field correction factor $k_{Q,B}$, if the ionization chamber is used for absolute dosimetry in the presence of a magnetic field. This correction is mandatory for the determination of the absorbed dose to water at MR-linacs, where the magnetic field cannot be ramped down easily. The experimental determination of $k_{Q,B}$ is challenging, since experimental setups for this purpose are rare and, in addition, measurements of $k_{Q,B}$ at MR-linacs are mostly based on the use of radiation detectors which are usually not available at hospitals (e.g. calorimeters or alanine). An alternative option for the determination of $k_{Q,B}$ is by Monte-Carlo simulations, but it was shown in several publications, that the results of Monte Carlo simulations of ionization chambers in magnetic fields do not align with experimental results. Several authors have speculated, that this discrepancy could be explained by dead volumes that can be found close to the guard ring of ionization chambers.

In this talk, several methods are presented for the determination of the magnetic field correction factors $k_{Q,B}$. These include an experimental procedure in which measurements performed at a combination of a big electromagnet and a conventional linac are combined with measurements performed at a MR-linac. Another approach is presented, which is based on a cross-calibration with the chemical radiation detector alanine. In addition, a simulation method is presented, which can be used to include the dead volume of ionization chambers into Monte-Carlo simulations.

A01.05 ID 148

Protocols for dosimetry in magnetic fields

Simon Woodings, UMC Utrecht

All national and international protocols for reference dosimetry for linear accelerator x-ray beams ignore the effect of a magnetic field on (i) the dose distribution and (ii) the sensitivity of the detector.

With the advent of commercially available MRI – linear accelerators (MR-linacs) in widespread clinical use around the world, the reference dosimetry protocols are no longer adequate to provide accurate dosimetry and calculations.

Thankfully several articles have been published which describe additions to the existing protocols to include the effect of a magnetic field. Several of these new protocols will be described here, including the relationships and consistency between them. The use of primary standard calorimeters, alanine and ion chambers will be discussed.

For ion chambers the existing data demonstrates that the relative orientation of magnetic field, radiation beam and detector is critical. Considerable, consistent data exists for a subset of detectors and orientations. It is likely that future protocols will recommend specific combinations. It is unlikely that all possible combinations of field strength, detector and detector orientation could ever be included within a protocol.

A strong magnetic field and its Lorentz force on charged particles introduces additional uncertainty in dose measurements where there are air gaps or air layers. Setups and techniques must consider these factors. For relative dosimetry there are additional questions regarding effective measurement point and angular sensitivity of a detector.

For the regular clinic, these questions will shortly have definitive answers, as several organisations are currently developing recommendations or codes of practice that will address dosimetry in a magnetic field.

A02.01 ID 140

From Installation to First Patient Treatments with the ViewRay System

Anil Sethi, Department of Radiation Oncology, Stritch School of Medicine, Loyola University Medical Center

The coupling of online MR imaging with a linac is a novel and exciting concept for improved patient care. MR images provide superior soft-tissue contrast thereby enabling real-time gating, tumor tracking and plan adaptation. MR linacs have shown great potential for minimizing normal tissue toxicity and escalating target dose in regions prone to deformation due to respiration, cardiac motion, organ filling/emptying, peristalsis, etc. The hybrid MR/RT platform however poses unique clinical challenges for the medical physicist. Safe implementation of MR guided RT (MRgRT) requires an understanding of MR/RT physics. Some of the physics challenges include dose measurements in the non-standard geometry, minimizing interference effects between MR and RT systems, and validating MR/RT iso-center coincidence. The array of additional QA checks, detectors and phantoms call for further guidance and training. The presentation will highlight acceptance testing and commissioning tasks required for the safe and effective implementation of MRgRT on the ViewRay's MRIdian system (6MV linac and 0.35 T MRI). We will review important steps & QA protocols necessary for acquiring high quality MR images, beam data acquisition, and treatment planning system commissioning. Importance of comprehensive system QA (end-to-end test) will be discussed. QA thresholds and consistency checks for each step in the process chain will be presented.

Learning Objectives

Present fundamentals of MR imaging in the RT environment while highlighting unique advantages of MR/RT system.

Outline important steps in the beam data acquisition & validation.

Review available MR safe detectors and phantoms for commissioning/QA.

Discuss importance of comprehensive QA for planning and delivery systems.

A02.02 ID 138

From Installation to first patient treatments with the Elekta Unity system

Marcel Nachbar, Section for Biomedical Physics, Department of Radiation Oncology, University Hospital and Medical Faculty. Eberhard Karls University Tübingen

David Mönnich[1], Daniela Thorwarth[2]
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Introduction

Integration of magnetic resonance imaging (MRI) into external beam radiotherapy for the implementation of online adaptive workflows is no longer just in a research state but has increasing numbers of installations worldwide. The installation, commissioning and validation of a hybrid MR-linac system differs from a conventional accelerator in various aspects and, in addition, depends on the strength of the static magnetic field. In this session a talk about the experience on one of the first installations of the 1.5 T MR-linac systems will be given.

Materials and Methods

The installation of the 1.5 T MR-linac system in Tuebingen started in 2017 and the first patient was treated in a MR-guided online workflow in September 2018. Up to this treatment four major milestones have been reached, which will be reviewed upon. (1) The technical and constructional installation of the MR-linac system into an existing site. (2) Commissioning and acceptance of the system followed by additional physics training and validation onsite. (3) Patient selection and review of dose distributions, influenced by the magnetic field. (4) First patient treatment, post treatment validations and workflow limitations.

Results and Conclusion

In this talk, challenges related to the installation of a 1.5 T MR-linac system in contrast to a conventional accelerator will be discussed. Focus will be on the commissioning and validation of both system components, MRI and linear accelerator. In addition, vendor supplied testing and potential pitfalls will be reviewed.

A02.03 ID 144

The Alberta Rotating bi-Planar System (MagnetTx Aurora-RT) Going Clinical

B. Gino Fallone, Medical Physics, Cross Cancer Institute, University of Alberta

Brad Murray[1], Keith Wachowicz[2]
[1]MagnetTx Oncology Solutions
[2]Medical Physics, Cross Cancer Institute, University of Alberta

Introduction

The Alberta bi-planar Linac-MR system is going clinical winter-spring 2021. The system and results of ACR MR imaging QA, gantry-rotation fidelity and radiation output commissioning are presented. A series of clinical trials have been approved and funded which would commence spring of 2021 for imaging of patients followed by a series of treatments following protocols.

Materials and Methods

The system consists of 0.5 bi-planar MR with Bo configured in parallel to a 6 MV linac beam with a radiation beam-stop. The system rotates in unison around the patient (360 degrees) to place the beam at the correct angle for beam delivery. The clear patient opening of 110 cm x 60 cm x length of couch rotates strategically, to avoid any collision with the patient and to allow positioning of central or peripheral tumors to be treated isocentrically. The couch has +/- 25 cm vertical and +/- 25 cm lateral displacements, while the dual-focus 120 leaf MLC projects a leaf width of < 5 mm at the system's SAD of 120 cm. Currently, the MR frame rate is at 4 frames per second with bSSFP and a comprehensive set of available pulse sequences. The MRI portion of the system, which uses a high-temperature superconductor magnet, can be turned on/off safely within minutes and does not require any cryogens or exhaust vent

through the outside of the building. In addition, because the installation can also be done through the door or maze of the vault of a conventional medical-linac, it can be installed anywhere in the building.

Results and Conclusions

ACR phantom studies show excellent compliance with respect to CNR, SNR, spatial and contrast resolution and image distortion. Gantry rotation and MLC rotations are well below one mm, with excellent agreement for depth doses and profiles between measurements with the magnet on and model-based major commercial dose calculations performed without magnetic fields. The system is expected to proceed with clinical trials in early spring 2021.

A02.04 ID 149

The Australian MRI-Linac system: How to arrive at the first patient treatment?

Paul Keall, Image X Institute, University of Sydney

There are four MRI-Linac system designs in the world today. Two of these, the MRIdian and Unity, are in widespread clinical use with advanced technological capabilities. The perpendicular class of MRI-Linac, where the radiation beam is perpendicular to B0, are represented by the MRIdian and Unity with low and high magnetic fields respectively. The inline class of MRI-Linac, where the radiation beam is parallel to B0, are represented by the Aurora and Australian MRI-Linacs with low and high magnetic fields respectively. No patients have yet been treated with an inline MRI-Linac.

There are advantages and disadvantages of the perpendicular and inline approaches, low and high fields, and many other differentiating features of each of the systems. The research and development of the Australian MRI-Linac has been with the inline high field approach. For this system we have proposed the clinical trial Mri-linAc Treatments for RAdiotherapy Patients. A Pilot Study on the use of the Australian MRI-Linac to Treat Cancer Radiotherapy Patients (MANTRA).

The objective of the MANTRA trial is to test the feasibility of the Australian MRI-Linac to treat cancer patients. By understanding the clinical pathways, advantages, and challenges of the MRI-Linac, the information acquired will be used to focus, inform and improve future technology development enabling higher quality treatments for future patients and drive the research program directions and priorities. Aligned with the first Unity patient treatments [1], the initial patients accrued will have simple palliative treatments.

At the time of the abstract submission all of the necessary ethics approvals had been given for the clinical trial.

[1] Raaymakers, B. W., et al. "First patients treated with a 1.5 T MRI-Linac: clinical proof of concept of a high-precision, high-field MRI guided radiotherapy treatment." Physics Med Biol 2017.

A03.01 ID 150

Special requirements for measurement equipment in MRgRT

Jochem Wolthaus, UMC Utrecht

Similar to conventional radiotherapy, the acceptance, commissioning and periodic QA of the MRgRT treatment machines is required before clinical use. Additionally, also End-to-End testing and patient specific QA have to be performed to complete the quality chain of clinical operation. With the introduction of MRgRT systems, existing “conventional” QA tests and measurements have been adapted to be compliant for use in these systems. Some changes were needed to fulfill the geometrical conditions of an MR-Linac, e.g. limited space in the bore or absence of guides for alignment. Other changes of the tests were required to include or correct for the effects of the high magnetic field. A clear example is the standard Farmer ion chambers, used in reference dosimetry. Farmer chambers have a different response to dose for different field strength and different orientations with respect to beam and B-field.

This lecture will discuss the requirements and conditions to use the most common detectors in beam measurements (commissioning and machine QA) and patient specific plan QA. Is it MR-safe? Does it have to be imaged? Which detector correction factors should be known and what are the geometrical conditions, including alignment of the measurement equipment? And what is the best detector orientation? Finally, what are the shorts cuts to perform a measurement efficiently?

Some of the answers to these questions are in line with the solutions for the conventional clinical. However, omitting or neglecting the effect of the magnetic field easily corrupts your measurement with significant clinical impact as a consequence.

A03.02 ID 135

Isocenter accuracy and image distortion measurements at MR-Linacs

Stefan Dorsch, Department of Medical Physics in Radiation Oncology, Deutsches Krebsforschungszentrum

Purpose

As magnetic resonance guided radiotherapy (MRgRT) has become increasingly important in clinical applications in recent years, the development of new quality assurance (QA) methods has also been given high importance. In addition to QA for dose delivery and dosimetry, also machine-related geometric methods such as detection and measurement of geometric distortions of the MR and measurement of the alignment of the irradiation and imaging isocenters are key elements.

Materials

To determine and measure geometric distortions in MRI, phantoms with known dimensions are normally used to compare the MR image with an undistorted ground truth. Several solutions have been published for this purpose and also a number of commercial solutions are available. With the help of these phantoms, the correction algorithms of the device should be checked for correctness and constancy on a regular basis.

Additionally, several methods like ion chamber-array measurements [1], polymer gel (PG)-based methods [2] and the use of EPID and film measurements [3] have been presented to determine the alignment between imaging and irradiation isocenter. It has been shown, that the additional use of high-density material [3] in the proximity of the dosimeter may become necessary for star shot-based irradiation isocenter measurements to reduce the range of secondary electrons and thus their deflection by the magnetic field. PG-based methods allow for 3-dimensional (3D) online evaluation, however, PG may not always be a practical solution to be easily integrated into the clinical workflow.

Results/Conclusion

Several different methods and products to measure the isocenter alignment accuracy have been described in the literature and some commercial solutions are already available. This holds also for phantoms measuring image distortions in MRI.

[1] K Latifi et al 2019 Tech Cancer Res & Treat. 18 [2] S Dorsch et al 2019 Phys Med Biol 64 205011 [3] H M van Zjip 2016 Phys Med Biol 61 N50–N59

A03.03 ID 136

MRI quality control for MRgRT-systems

Andreas Wetscherek, Radiotherapy & Imaging, The Institute of Cancer Research

Objectives

MR-guided radiotherapy systems house an MR scanner and a linac in close proximity. As images acquired on an MRgRT system are used for RT planning, they need to be spatially accurate and artefact-free. In this presentation, potential sources of image artefacts in MRgRT and tests for quality control are explained, with particular focus on interactions between the MRI and the linac system.

Materials and Methods

Following[1], components of the MRI system that affect spatial accuracy of the images are: homogeneity and temporal stability of the B_0 field, performance and spatial linearity of the field created by gradient coils and the performance of the RF transmit and receive coils. Dedicated phantoms, such as the Large MRI phantom of the American College of Radiology (ACR) can be used to test simultaneously several aspects of MR imaging, such as geometric accuracy, spatial resolution, slice thickness & position accuracy, ghosting and detectability of low-contrast objects. Further, suitable phantoms and guidelines for quality control may be provided by the system vendor. As the patient's body outline is of particular relevance for accurate dose planning, large bore-filling phantoms are used to measure B_0 homogeneity

and gradient nonlinearity. The impact of the gantry position on MR imaging isocenter shifts needs to be tested and is of particular importance for imaging during treatment delivery[2].

Results and Conclusion

A full characterisation of the MRI in MRgRT systems takes significant time, which is why in a clinical setting only a small set of tests can be performed daily. Wear and tear of MRI components could become apparent in daily tests before noticeable image degradation. MRI QC cannot replace attentiveness to implants and metal objects carried by patients. Future MRgRT using quantitative MRI and automatic segmentation could require more comprehensive QC.

References

1Tijssen RHN et al. Radiother Oncol 2019;132:114
2Lewis BC et al. J Appl Clin Med Phys 2020;21:20.

A03.04 ID 153

QA for MR-guided gating

Taheo Kim, Washington University School of Medicine, Saint Louis, USA

Introduction

MR-guided gated radiotherapy is one of the most promising treatment technologies, delivering high-energy radiation beams directly to the moving target with MR-guidance. Gating uncertainty can depend on image quality, target tracking performance, and radiation beam control, requiring routine QA tests. In this presentation, QA procedures of MR-guided gated treatment on a 0.35T magnetic resonance-linear accelerator (MR-LINAC) will be discussed.

Materials & Methods

Under the institutional guideline, we performed MR-guided gating QA tests using a dedicated motion phantom. Prior to the MR-LINAC system upgrade in 2020, an MRI-compatible programmable motion drive (a prototype version of the Model 008M MRI Linac Dynamic Phantom, CIRS, Norfolk, VA) was clinically used. Post upgrade, the CIRS motion phantom was replaced with an MRI^{4D} QUASAR motion phantom (ModusQA, Ontario, Canada) for gating system tests. The QA procedure has been changed based on features of the motion phantoms but the basic concept of MR-guided gating QA remains unchanged. In a monthly basis, two dosimetric measurements have been performed with/without designated phantom motion.

Results & Conclusion

The MR-guided gating QA tests have been performed on a monthly basis using the dedicated motion phantom in a 0.35T MR-LINAC. The dosimetric impact of the gating uncertainty has been monitored and recorded for gating system tests.

A04.01 ID 131

End-to-end-Tests for adaptive MRgRT

Alina Elter, Department of Medical Physics in Radiation Oncology, Deutsches Krebsforschungszentrum (DKFZ) Heidelberg

Adaptive treatment procedures in MRgRT allow compensating for changes in the patient's anatomy between and within treatment sessions (inter- and intra-fractional motion). To quantify the residual overall uncertainty in these highly complex treatments, dedicated end-to-end tests are of high importance. They are especially required to validate the overall geometric and dosimetric accuracy of adaptive treatment scenarios. While providing major benefits compared to conventional image-guidance systems using x-rays, such as a superior soft-tissue contrast and no additional exposure to the patient, the integration of MRI into the irradiation procedure poses additional challenges on the development of such tests. For this, phantoms are required that, in the optimal case, (i) are able to simulate the respective variation of the patient's anatomy in a highly reproducible manner, (ii) provide anthropomorphic imaging contrast in both CT and MRI, and (iii) allow for accurate dose measurements in 1D to 3D. Although end-to-end tests covering the entire course of treatment may not be feasible in clinical practice on daily or weekly basis due to the high effort that is typically required, they are an important tool for the commissioning of new

treatment devices and workflows as well as for quality assurance procedures repeated on longer time scales.

A number of phantoms have been developed to perform end-to-end tests under clinical conditions for both inter- and intra-fractional adaptive MRgRT and some phantoms have been described in the literature or are already commercially available. In this presentation, the requirements and realization of end-to-end tests in adaptive MRgRT are discussed and an overview of the existing phantoms and workflows is given.

A04.02 ID 129

Risk management for the clinical introduction of adaptive Magnetic Resonance-guided radiotherapy

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Objectives

The clinical introduction of on-table adaptive radiotherapy with Magnetic Resonance (MR)-guided linear accelerators (Linacs) yields new challenges and potential risks. Since the adapted plan is created within a highly interdisciplinary workflow with the patient in treatment position, time pressure or erroneous communication may lead to various possibly hazardous situations. To identify risks and implement a safe workflow, a proactive risk analysis has been conducted.

Materials and Methods

A process failure mode, effects and criticality analysis (P-FMECA) was performed within a group of radiation therapy technologists, physicians and physicists together with an external moderator. The workflow for on-table adaptive MR-guided treatments was defined and for each step potentially hazardous situations were identified. The risks were evaluated within the team in order to homogenize risk assessment. The team elaborated and discussed possible mitigation strategies and carried out their implementation.

Results

In total, 89 risks were identified for the entire MR-guided online adaptive workflow. After mitigation, all risks could be minimized to an acceptable level. Overall, the need for a standardized workflow, clear-defined protocols together with the need for checklists to ensure protocol adherence were identified among the most important mitigation measures. Moreover, additional quality assurance processes and automated plan checks were developed.

Conclusions

Despite additional workload and beyond the fulfilment of legal requirements, execution of the P-FMECA within an interdisciplinary team helped all involved occupational groups to develop and foster an open culture of safety and to ensure a consensus for an efficient and safe online adaptive radiotherapy workflow.

A04.03 ID 143

Online-QA in the adaptive process with the ViewRay system

Stephanie Tanadini-Lang, University Hospital Zurich

Introduction

Magnetic resonance guided adaptive radiotherapy improves the current standard of care radiotherapy workflow by adjusting the radiation dose to the anatomy of the day. This leads to better organ at risk sparing and improved target coverage. However adaptive radiotherapy is a complex process that is performed under time pressure and therefore needs comprehensive quality assurance. This quality assurance goes beyond the classical secondary verification of the dose and has to consider all steps of the adaptive workflow.

Materials and Methods

As a basis of such a quality assurance program a failure modes and effects analysis is often performed. This pinpoints the critical steps during the adaptive workflow, which have to be quality assured.

Results and Conclusions

The four main steps during the adaptive workflow are imaging, segmentation, plan re-optimisation and treatment delivery. Image acquisition, registration and segmentation are the starting point, they are error prone and manual checking of contours and registrations is regularly performed. Additionally, comparisons of volumes between initial and new target structures and of equivalent path length for all beams can detect uncertainties in these steps. After the new plan is created plan quality as well as plan parameters have to be checked and a secondary check of the dose distribution should be performed. This secondary check is in non-adaptive radiotherapy often performed using measurements but other solutions such as secondary Monte Carlo dose calculations are needed for adaptive treatments. Treatment delivery is very similar to non-adaptive treatments and therefore ideas to guarantee the correctly applied dose can be used from non-adaptive treatments, such as in-vivo dosimetry or logfile analysis.

A04.04 ID 128

Online-QA in the adaptive process with the Elekta Unity MR Linac

Simeon Nill, The Institute of Cancer Research and The Royal Marsden NHS Foundation Trust

In room MR image guidance (MRgRT) enables the online adaptation of treatment plans based on the current patient anatomy while the patient is on the treatment couch. The Elekta Unity system combines a 1.5T MR scanner with a 7MV FFF linear accelerator. The general adaptive process on the Unity system comprises the acquisition of a session MR image, plan adaption based on the acquired image, and the possibility to monitor the internal anatomy during treatment delivery using 2D cine images. The complete workflow takes on average between 20 and 60 minutes depending on the indication and the online plan adaptation method.

Online adaptive MRgRT therefore compresses the timespan of a typical Radiotherapy pathway including imaging, delineation, plan generation, and verification from weeks to minutes. This acceleration and the incapability to perform traditional pre-treatment plan verification for the adaptive treatment plans introduces new challenges to the multi-disciplinary staff group of radiographers, medical physicists, and clinicians.

Within this presentation, the methods developed to address those challenges for a typical online adaptive MR guided treatment on the Elekta Unity system will be discussed. This includes the use of a secondary dose calculation instead of pre-treatment measurements and the development of a series of automated plan quality indicators to ensure a safe delivery of the adapted treatment plan.

Conflict of interest: ICR and RMH are a member of the Elekta MR Linac consortium.

A04.05 ID 137

Dose reconstruction using linac log files and online MRI: a promising tool for daily patient QA?

Martin Menten, Imperial College London

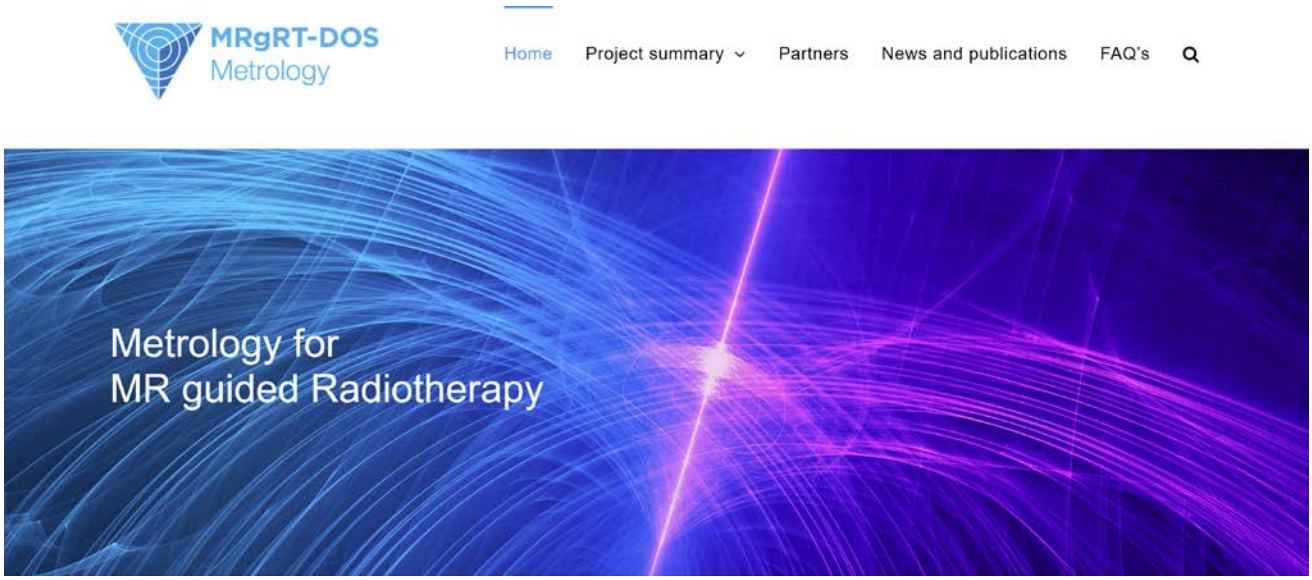
Quality assurance in radiotherapy aims at ensuring the safe and accurate delivery of a previously created treatment plan. This treatment plan is commonly designed based on a static anatomical representation, such as a planning CT or MR image. In reality, the plan's intended dose distribution is never delivered and the actually administered dose is unknown as the patient's anatomy changes over the course of treatment. Resolving the delivered dose is crucial to link radiation doses to clinical outcomes and ultimately improve the standard of care.

In order to calculate the actually delivered dose, one needs to combine continuous information about the treatment machine's status with a dynamic model of the patient's anatomy. Linac log files record the treatment machine's status at a high frequency. They include the treatment beam state (on or off), delivered monitor units, gantry angle and the multileaf collimator's leaf and jaw positions. If the treatment is adapted in real-time via treatment beam gating, multileaf collimator tracking or intrafractional treatment plan re-optimization, this will also be reflected in the treatment log files. Radiotherapy treatment

machines with integrated MR imaging are a powerful tool to continuously survey the patient during treatment. MR imaging with its versatility, non-invasiveness and high soft-tissue contrast can be used in many different ways to derive a dynamic patient model.

This presentation will highlight the need to consider intrafractional anatomical changes during the quality assurance workflow, especially as real-time adaptive radiotherapy techniques are entering clinical practice. It will introduce an example dose reconstruction workflow that is able to calculate the delivered dose of the day during prostate radiotherapy based on MR-linac machine log files, 3D and 2D cine MR imaging. Finally, it will outline potential improvements to this workflow that could increase its accuracy and adapt it to other cancer sites.

Find out about metrology for dosimetry in magnetic fields:



http://mrgrtmetrology.com/

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PROGRAM VIRTUAL 8TH MR IN RT SYMPOSIUM 2021

MONDAY 19TH 2021

Mon. April 19, 2021	Main Stage	Poster sessions	Virtual Exhibitions	Industry
8:30 -9:00	**Welcome Lounge**			
9:00-9:25	**Welcome:** M. Ladd *Vice president DGMP*		**Further Recordings & Virtual e-Poster Exhibition**	**Virtual Industrial Exhibition**
	Opening: O. Jäkel, J. Debus			
9:30-9:55	**Keynote:** L. Henke – How we got to the SMART trial (20+ 5)			
	Chairs: O. Jäkel, J. Debus			
10:00-11:00	**S1: Clinical 1**	Poster Session 1: **Quality Assurance & Workflows**		
	Chairs: S. Combs, H.-P. Schlemmer	**Chairs:** S. Dorsch, B. Raaymakers		
	S01.01: ID: 151: J. Debus: Challenges of Clinical Trials in MRinRT (12+3)	P01.01: ID 47: L. S. Stark: Development of a phantom for adaptive end-to-end testing in magnetic resonance guided radiotherapy		
	S01.02: ID 142: S. Corradini: Early clinical trial experience of online of adaptive MR-guided at LMU Munich (12+3)	P01.02: ID 66: K. I. Penev: Physiological targeting features of a 4D deformable tumor phantom for MR/CT IGRT QA		
	S01.03: ID 98: N. Tyagi: Ablative SBRT treatment of pancreas patients on Elekta Unity MR-Linac (8+2)	P01.03: ID 4: J. Wyatt: Using CBCT for Dosimetric Quality Assurance of MR-Only Radiotherapy		
	S01.04: ID 45: E.-M. Kretschmer: Same-day MRI-linac guided single fraction radiosurgery for painful non-spine bone metastases (8+2)	P01.04: ID 29: X. Miao: Patient-specific QA of geometric accuracy in MRI-based RT planning		
	Discussion	P01.05: ID 87: E. Hellwich: Quantification and reduction of susceptibility artefacts for a quality assurance phantom in MRgRT		
		Discussion		
11:00-11:30	**Coffee Break**			
11:30-12:25	**S2: MR Imaging in Radiotherapy 1**	Poster Session 2: **Dosimetry**	**Further Recordings & Virtual e-Poster Exhibition**	**Virtual Industrial Exhibition**
	Chairs: S. Nill, M. Ladd	**Chairs:** L. Burigo, C. Karger		
	S02.01: ID: 120 H.-P. Schlemmer: New developments in functional MRI (12+3)	P02.01: ID 103: M. Marot: Validation of charged particle transport algorithm in magnetic field in TOPAS Monte Carlo code		
	S02.02: ID 69: I. Sidibe: 3D MR spectroscopic imaging for differentiating progression from pseudoprogression in glioblastoma (8+2)	P02.02: ID 85: M. Schneider: Experimental determination of the EPOM for ionization chambers in a 1.5 T MR-Linac		

Mon. April 19, 2021	Main Stage	Poster sessions	Virtual Exhibitions	Industry
	S02.03: ID 16: F. Raschke: Dose dependent cerebellar atrophy in glioma patients after radio(chemo)therapy (8+2)	P02.03: ID 27: T. Mertens: Beam model validation of the MRIdian® Linac with the THALES 3D MR SCANNER.		
	S02.04: ID 96: W. Bano: Joint radial trajectory correction for fast T2* mapping on an MR-Linac (8+2)	P02.04: ID 34: F. Jäger: A Monte Carlo study of proton dosimetry of Farmer-type ionization chambers in magnetic fields		
	Discussion	P02.05: ID 20: I. Bessieres: Non-isocentric positioning of the ArcCHECK system for Patient Specific QA on 0.35T MR-linac		
		Discussion		
12:30-13:25	**Lunch Break and Industrial Session 1**	**Lunch Break**		
	Moderation: O. Jäkel		**Further Recordings & Virtual e-Poster Exhibition**	**Virtual Industrial Exhibition**
	12:35 - 12:55: Sponsor: Elekta: K. Brown: Elekta Unity: Designed for now and the future			
	13:00 - 13:20: Sponsor: Philips: R. Hoogeveen & L. Warner: Leading MR-RT innovations for clinical practice			
13:30-14:25	**Young Investigator Session 2020**			
	Chair: G. Gillmann, N. Wahl			
	YI01.01: ID 19: S. Gantz: Experimental investigation of ghosting artefacts in in-beam MRI during proton pencil beam scanning (6+2)			
	YI01.02: ID 67: M. Rabe: Experimental validation of generating 4 Hz 4D-MRI from orthogonal cine-MRI on a 0.35 T MR scanner (6+2)			
	YI01.03: ID 82: S. Pojtinger: Influence of beam quality on magnetic field correction factors for ionization chambers in MRgRT (6+2)			
	YI01.04: ID 51: S. Schneider: Reduction of respiratory pancreas motion using an MRI and proton therapy compatible abdominal corset (6+2)			
	YI01.05: ID 30: T. Bruijnen: Free-breathing motion compensated 3D T2-weighted turbo spin-echo MRI for body imaging (6+2)			

Mon. April 19, 2021	Main Stage	Poster sessions	Virtual Exhibitions	Industry
14:30-15:30	**S3: MR guided Particle Therapy 1**	Poster Session 3: **Clinical**	**Further Recordings & Virtual e-Poster Exhibition**	**Virtual Industrial Exhibition**
	Chairs: G. Landry, O. Jäkel	**Chairs:** J. Hörner-Rieber, S. Corradini		
	S03.01: ID: 116: K. Parodi: MRI-guided particle therapy: challenges and prospects (12+3)	P03.01: ID 8: F. Weykamp: MR-guided stereotactic body radiotherapy of liver tumors: Initial clinical experience		
	S03.02: ID: 126 E. Troost: MR-integrated proton therapy - yet another hype? (12+3)	P03.02: ID 9: S. Koerber: Stereotactic MRI-guided radiation therapy for Localized prostatE cancer – the SMILE protocol		
	S03.03: ID 46: L. Burigo: Proton IMPT planning in a 1 T perpendicular split-bore MRI system (8+2)	P03.03: ID 12: P. Hoegen: MR-guided adaptive stereotactic radiotherapy for hepatic metastases - the MAESTRO trial		
	S03.04: ID 3: G. Meschini: Time-resolved respiratory motion modeling for gated carbon ion radiotherapy of pancreatic cancer (8+2)	P03.04: ID 33: M. Felter: SABR for infra-diaphragmatic soft tissue metastases: SOFT, a phase 2 study		
	Discussion	P03.05: ID 97: E. Palmér: Synthetic CT for 2D and 3D patient positioning in head and neck radiotherapy		
		Discussion		
15:30-16:00	**Coffee Break**			
16:00-16:55	**Panel 1: How to generate Clinical Evidence?**		**Further Recordings & Virtual e-Poster Exhibition**	**Virtual Industrial Exhibition**
	Moderation: P. Parikh, J. Debus			
	Statement Speakers: C. Chung, V. Valentini, M. Philippens, M. Guckenberger, A. Tree			
17:00-17:55	**S4: MR guided Radiotherapy and Treatment Planning 1**	Poster Session 4: **MR Imaging in Radiotherapy**		
	Chairs: C. Thieke, J. Lagendijk	**Chairs:** J. M. Balter, T.Platt		
	S04.01: ID: 118: B. Raaymakers: Getting from on-line to real-time MRI guided adaptive radiotherapy (12+3)	P04.01: ID 84: A. Pakaeva: Measurement of B0 field variations with gantry position on an MR-linac system.		
	S04.02: ID 90: M. Lo Russo: 1.5 T MR-linac planning study to compare two different strategies of rectal boost irradiation (8+2)	P04.02: ID 57: E. Kaza: ACR phantom comparison of coil setups for head and neck radiation therapy MRI simulation.		
	S04.03: ID 55: P. Borman: MLC-tracking on the Elekta Unity MR-linac: first experimental validation for central lung SBRT (8+2)	P04.03: ID 5: J. Wyatt: Evaluating the image quality of PET-MR images acquired in the radiotherapy position		
	S04.04: ID 59: M. Terpstra: Real-time 3D motion estimation with deep learning for real-time adaptive MRI-guided radiotherapy (8+2)	P04.04: ID 41: D. Bird: Evidence of OAR dose reduction for anal and rectal cancer MR-only planning treatments		
	Discussion	P04.05: ID 88: S. Dorsch: Performance of deformable image registration for the integration of diagnostic MR images to treatment planning		
		Discussion		

Mon. April 19, 2021	Main Stage	Meet and Greet	Virtual Exhibitions	Industry
18:00-18:50	**S5: Radiomics/Data Science**	Meet the hosts of the symposium (**Prof. Jäkel & Prof. Debus**) online from 6 – 6.50pm for further discussions in a live online meeting room on our platform.		
	Chairs: N. Dinapoli, K. Giske			
	S05.01: ID: 121: K. Maier-Hein: Deep learning in Medical Imaging (12+3)			
	S05.02: ID 43: R. Dal Bello: Investigation of delta radiomics during fractionated SBRT in patients treated for liver metastases (8+2)			
	S05.03: ID 38: C. Jamtheim Gustafsson: Deep learning based classification for standardization of prostate cancer RT structure annotations (8+2)			
	S05.04: ID 63: M. F. Spadea: Deep Convolutional Neural Network (DCNN) multiplane approach to pseudoCT generation from MR images (8+2)			
	Discussion			
19.00	**End**			

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TUESDAY 20TH 2021

Tue. April 20, 2021	Main Stage	Poster sessions	Virtual Exhibitions	Industry
8:30 -9:00	**Welcome Lounge**			
9:00-9:55	**S6: Functional Imaging**	Poster Session 5: **MR guided Radiotherapy and Treatment Planning**	**Further Recordings & Virtual e-Poster Exhibition**	**Virtual Industrial Exhibition**
	Chairs: T. Nyholm, M. Ladd	**Chairs:** L. Burigo, C. Kurz		
	S06.01: ID: 124: D. Thorwarth: Functional Imaging on MR-Linacs: Potential and limitations (12+3)	P05.01: ID 113: A. Sethi: Evaluation of Dosimetric Benefits of MR Guided Adaptive RT		
	S06.02: ID 107: R. Winter: R2* MRI based tumor control probability modelling for dose painting by contours in rectal cancer (8+2)	P05.02: ID 70: N. Tyagi: Interfraction motion assessment of upper GI organs during MR-guided ablative SBRT treatment		
	S06.03: ID 100: S. Böke: Serial DWI measurements in HNC treated on a 1.5T MR-Linac and benchmark against a 3T MR-scanner (8+2)	P05.03: ID 23: A. Dunlop: MRgRT workflow development and recommendations for H&N treatment using the Elekta Unity MR-linac		
	S06.04: ID 60: C. Beijst: MRI/PET for radiotherapy simulation: high-resolution pathophysiological guidance for small tumors (8+2)	P05.04: ID 102: P. Borman: Respiratory motion mitigation using visual biofeedback on the Unity MR-linac		
	Discussion	P05.05: ID 52: P. Kimstrand: Prototyping real-time adaptive treatments for IMRT/SBRT on the Elekta Unity MR-Linac		
		Discussion		
10:00-11:00	**S7: QA/QA and Workflows**	Poster Session 6: **Functional Imaging**		
	Chairs: M. Philippens, C. Karger	**Chairs:** C. Gillmann, D. Thorwarth		
	S07.01: D. Jaffray (12+3): Quality as an Innovation Enabler in RT	P06.01: ID 28: E. Kooreman: First T1ρ mapping results on a 1.5 T MR-linac		
	S07.02: ID: 128: S. Nill: Quality Assurance for online adaptive MRgRT (12+3)	P06.02: ID 21: D. Barten: Development of a 3D cine-MRI acquisition technique to quantify bowel motion in cancer patients		
	S07.03: ID 68: B. Pouymayou: Analysis of Spatial Integrity on a 0.35T MR-Linac: characterizing the influence of metallic implants (8+2)	P06.03: ID 36: F. Mayer: Accelerated non-Cartesian cine MRI reconstruction on CUDA capable architectures		
	S07.04: ID 42: M. Schneider: MATLAB-scripted QA workflows for MR in RT, via Access-i-based remote control on MAGNETOM MR scanners (8+2)	P06.04: ID 53: Y. Zhang: Development of a hierarchical model of abdominal configuration from golden angle radial MRI		
	Discussion	P06.05: ID 40: G. Ekchian: MRI-Measured Quantitative Oxygen Sensors		
		Discussion		
11:00-11:30	**Coffee Break**			

Tue. April 20, 2021	Main Stage	Poster sessions	Virtual Exhibitions	Industry
11:30-12:25	**Young Investigator Session 2021**		**Further Recordings & Virtual e-Poster Exhibition**	**Virtual Industrial Exhibition**
	Chair: N. Wahl, C. Gillmann			
	YI02.01: ID 54: L. Bosma: Quantitative investigation of dose accumulation error from intra-fraction motion for prostate cancer (6+2)			
	YI02.02: ID 32: L. Dünger: Reduced white matter diffusion in glioblastoma patients after radiotherapy with photons and protons (6+2)			
	YI02.03: ID 31: H. Eijkelenkamp: Planning Target Volume margin assessment for online adaptive MR-guided boost in rectal cancer (6+2)			
	YI02.04: ID 65: A. Elter: Development of anthropomorphic phantom materials for end-to-end testing in MR-guided ion therapy (6+2)			
	YI02.05: ID 11: S. Gantz: Experimental investigation of a stopping proton beam in liquid water using MR imaging (6+2)			
	YI02.06: ID 35: -M. Groot Koerkamp: Bulk-density and deep learning synthetic CT for single-fraction neoadjuvant PBI on an MR-linac (6+2)			
12:30-12:55	**Highlight Talk:** ID 146: N. Dinapoli: Machine Learning: What is achievable and what is the benefit for RO? (20+5)			
	Chairs: K. Giske, J. Hörner-Rieber			
13:00-13:55	**Lunch Break and Industrial Session 2**	**Lunch Break**		
	Moderation: S. Klüter		**Further Recordings & Virtual e-Poster Exhibition**	**Virtual Industrial Exhibition**
	13:05 - 13:25: Sponsor: RaySearch Laboratories: E. Traneus: MR based planning in RayStation			
	13:30 - 13:50: Sponsor: Siemens Healthineers: N. Mistry: Synthetic CT re-imagined – an AI-based approach for MR-only workflows in brain and pelvis			

Tue. April 20, 2021	Main Stage	Poster sessions	Virtual Exhibitions	Industry
14:00-14:55	**S8: Dosimetry**	Poster Session 7: **MR guided Particle Therapy**	**Further Recordings & Virtual e-Poster Exhibition**	**Virtual Industrial Exhibition**
	Chairs: S. Klüter, L. de Prez	**Chairs:** N. Wahl, S. Nill		
	S08.01: ID: 145: J. de Pooter: Radiation dosimetry in magnetic fields: from reference fields towards small fields (12+3)	P07.01: ID 76: B. Gebauer: Determination of magnetic field correction factors for dosimetry in MR-integrated proton therapy		
	S08.02: ID 93: T. Tekin: Magnetic field correction factors of diode detectors and the role of enhanced density components (8+2)	P07.02: ID 92: G. G. Rincon: An extension of the analytical treatment planning system matRad for MR-guided proton therapy		
	S08.03: ID 108: I. Blum: Investigations of the role of chamber's construction towards the magnetic field correction factors (8+2)	P07.03: ID 104: C. Sepúlveda: Beam modeling of a proton pencil beam scanning beam line integrated with a low-field open MR scanner		
	S08.04: ID 99: N. Tyagi: Evaluation of irradiation geomtery and airgaps in the IROC QA mini-phantom for a 1.5T MRlinac system (8+2)	P07.04: ID 91: D. Pross: Fast Monte Carlo dose calculations in constant magnetic fields for MR-guided proton therapy		
	Discussion	Discussion		
15:00-15:55	**Panel 2: Directions for Functional Imaging**	**Meet & Greet**		
	Moderation: U. van der Heide, D. Thorwarth	"Image-guided versus MR-only guided RT – workflows, challenges and pitfalls", organized by S. Stefanowicz and T. Jagt for young medical physicists and everyone who is interested!		
	Statement Speakers: D. Zips, P. Parikh, M. Intven, T. Nyholm, M. Ladd			
16:00-16:30	**Coffee Break**			
16:30-17:25	**S9: MR guided Radiotherapy and Treatment Planning 2**	Poster Session 8: **MCS, Data Modelling, Radiomics**	**Further Recordings & Virtual e-Poster Exhibition**	**Virtual Industrial Exhibition**
	Chairs: U. Oelfke, M. Alber	**Chairs:** G. Fallone, R. Floca		
	S09.01: ID: 127: J. Balter: Human modeling using MRI for RT (12+3)	P08.01: ID 105: S. Rahbek: Decomposition-based framework for prediction of radiotherapy response from longitudinal DW-MRI data		
	S09.02: ID 78: M. Boekhoff: Dosimetric evaluation of in-silico simulated MR-guided esophageal cancer radiotherapy (8+2)	P08.02: ID 48: T. Tekin: Influence of the magnetic field on the effective point of measurement of ionization chambers		
	S09.03: ID 83: B. Eiben: Respiratory motion models for the MR-Linac: how much data is required? (8+2)	P08.03: ID 25: D. Cusumano: Delta Radiomics analysis in pancreatic cancer patients treated using MR-guided Radiotherapy		
	S09.04: ID 109: F. Reinders: MR–guided elective neck irradiation targeting individual lymph nodes: a new concept (8+2)	P08.05: ID 81: G. Zhao: Segmentation-oriented Generative Adversarial Network for Synthetic-CT in MR-only Treatment Planning		
	Discussion	Discussion		

Tue. April 20, 2021	Main Stage	Poster sessions	Virtual Exhibitions	Industry
17:30-18:30	**S10: Clinical 2**		**Further Recordings & Virtual e-Poster Exhibition**	**Virtual Industrial Exhibition**
	Chairs: D. Zips, J. Hörner-Rieber			
	S10.01: C. D. Fuller: Clinical experience with the MR Linac at MDA (12+3)			
	S10.02: ID: 117: B. Slotman: Five years of MRI guided adaptive radiotherapy (12+3)			
	S10.03: ID 64: J. van Timmeren: Adaptive radiotherapy for head-and-neck cancer – volume changes and migration of salivary glands (8+2)			
	S10.04: ID 1: S. Regnery: MAGELLAN: MR-guided adaptive stereotactic body radiotherapy for lung tumors in ultracentral location (8+2)			
	Discussion			
18.30	**End**			
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WEDNESDAY 21ST 2021

Wed. April 21, 2021	Main Stage	Virtual Exhibitions	Industry
8:30-9:00	**Welcome Lounge**		
9:00-9:55	**Debate Pro and Contra:** **The MR Linac will make X-Ray guided RT obsolete**	**Further Recordings & Virtual e-Poster Exhibition**	**Virtual Industrial Exhibition**
	Debate Speakers: J. Lagendijk vs. F. Lohr		
	Moderation: P. Keall, O. Jäkel		
10:00-10:55	**S11: MR Imaging in Radiotherapy 2**		
	Chairs: M. Intven, J. Seco		
	S11.01: ID: 115: U. van der Heide: MRI for personalized radiotherapy (12+3)		
	S11.02: ID 10: A. van Lier: Geometric MRI errors in prostate cancer patients with hip implants on a 1.5T MR-linac: hit or miss? (8+2)		
	S11.03: ID 110: T. Bruijnen: Parallel imaging stream for multi-purpose real-time adaptive MRI-guided prostate radiotherapy (8+2)		
	S11.04: ID 49: F. Tensaouti: Quality control of 3D MR spectroscopy imaging data in glioblastoma: can we do without the expert? (8+2)		
	S11.05: ID 14: L. Meijers: Online correction for geometric fidelity in MR-Linac treatments (8+2)		
	Discussion		
11:00-12:00	**Coffee Break & Industrial Session 3**	**Coffee Break**	
	Moderation: C. Karger.	**Further Recordings & Virtual e-Poster Exhibition**	**Virtual Industrial Exhibition**
	11:05 - 11:25: Sponsor: TheraPanacea: A. Schulte: Get smarter - AI in Radiation Oncology		
	11:30 - 11:50: Sponsor: Qfix: MR image & Treat – Image & Treat on the Same Device		
12:00-12:25	**S12: MR guided Particle Therapy 2**		
	Chairs: O. Jäkel, E. Troost		
	S12.01: ID 152: J. Debus: The ARTEMIS Project Heidelberg (10+2)		
	S12.02: ID 24: E. Semioshkina: Magnetic shielding factor for artefact-free in-beam MR imaging during proton pencil beam irradiation (8+2)		
	Discussion		
12:30-13:25	**Panel 3: Which Technological Developments are needed?**		
	Moderation: G. Liney, O. Jäkel		
	Statement Speakers: J. Lagendijk, P. Keall, D. Jaffray, U. Oelfke, J. Debus		
13:30-13:45	**Closing:** O. Jäkel, J. Debus		
	Award Ceremony		
	Proposals and Voting next meetings and adjourn		
14:00	**End**		

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Further Recordings (max. 8 minutes)

The pre-recorded talks are available the whole time on our virtual platform 24/7.

Topic: MR Imaging in RT

RO2.01: ID 17: M. Lerner: MRI-only based treatment with a commercial deep-learning generation method for synthetic CT of brain

RO2.02: ID 72: S. Doussin: Movement Assessment of OAR and breast using free-breathing, self-gated 4D MRI

RO2.03 ID 101: F. Putz: 4D evaluation of Head and Neck tumors – new ways of tumor assessment and contouring

RO2.04: ID 39: D. Bird: MR and sCT reference images for CBCT verification within an anal and rectal cancer MR only workflow

Topic: MR guided RT & Treatment Planning

RO4.01: ID 114: G. Grimbergen: Tumor Motion Analysis of Pancreatic Cancer Patients During Ungated MRgRT with Abdominal Corset

RO4.02: ID 71: M. Chamberlain: Head and neck radiotherapy on the MR-Linac: a multicentre planning challenge on MRIdian-platform

RO4.03: ID 106: R. Goodburn: Ultrashort Echo-Time Trajectory Correction with a Gradient Impulse Response Function on an MR Linac

Topic: QA/ QA and Workflows

RO7.01: ID 22: L. Nierer: Use of treatment plan complexity analysis as a QA tool in MR-guided online adaptive radiotherapy

RO7.02: ID 58: S. Dorsch: Measurement of isocenter accuracy and image distortion in MRgRT

RO7.03: ID 89: E. Palmér: Treatment planning and quality control of an MRI only workflow for H&N patients using CNN based sCT

RO7.04: ID 26: E. Kaza: Multi-slice setup and automated data analysis for ViewRay MRIdian Linac receive coil QA

RO7.05: ID 2: R. Speight: IPEM Guidance on the use of MRI for external beam radiotherapy treatment planning

Topic: Dosimetry

RO8.01: ID 86: J. Begg: Magnetic field correction factors via a cross-calibration using a conventional linac

RO8.02: ID 111: I. Blum: Investigation of diode-type detectors under small field conditions in magnetic field

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E-Posters

Topic: MR Imaging in Radiotherapy

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EP04.02: ID 73: M. Habatsch: Novel RT Planning Workflow for Breast MRI in Supine Setup

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EP05.01: ID 15: D. den Boer: Comparison of Library of Plans and MR-Linac strategies for whole bladder RT based on MR-Linac data

EP05.03: ID 62: J. Chick: Treatment of patients with artificial hips on the Elekta Unity MR-Linac

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TOPIC CLINICAL

Keynote ID 133

How we got to the SMART trial (and how we can smartly get to other trials)

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Magnetic resonance image-guided radiotherapy (MRgRT) was first implemented clinically in 2014. Its principle, unique clinical offerings at this time are MR-guided setup, cine MRI gating, and online adaptive radiotherapy (ART), all used with the goal of improving the dosimetric therapeutic index of radiotherapy. A favored emerging use of MRgRT, abdominal SBRT, incorporates all of these indications in the form of stereotactic, MR-guided online ART (SMART). SMART was clinically developed in a stepwise manner. This began with vetting of the onboard imaging quality, to ensure adequacy of the technology to visualize abdominal disease. Second, an in silico dosimetric evaluation of potential dosimetric gains was performed, to evaluate the possible impact of SMART on abdominal SBRTs therapeutic index. When dosimetric data indicated the possibility for therapeutic advantage, a Phase I clinical trial of feasibility and safety was conducted, proving clinical achievability of the approach. After implementation of SMART, early additional retrospective data indicated a particular clinical advantage for borderline or unresectable pancreatic adenocarcinoma, a disease site long-limited by challenges of daily precision and accuracy and resultant inadequate dose. From this setting, the Phase II SMART pancreas trial has arisen, in a stepwise and logical fashion, with the goals of furthering the level of evidence for SMART and evaluating the clinical efficacy of SMART's established dosimetric gains. Although the study continues to accrue, and we await its clinical lessons, we can already apply the trial design lessons it has taught us to other disease sites. Formalized and stepwise evaluation of MRgRT indication, beginning with an identified clinical challenge, then evaluating potential MRgRT dosimetric advantages, and finally embarking on collaborative, prospective (and ideally, eventual randomized) clinical trials, is a framework that can and should be applied intentionally, elsewhere. Indeed, the future success and advance of MRgRT hinges on this logical and collaborative pursuit of high-level clinical evidence.

S01.01 ID 151

Challenges of Clinical trials in MR in RT

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Hybrid devices for radiotherapy combining magnetic resonance imaging (MRI) and linear accelerators (MR-Linacs) allow for the visualization and tracking of target volumes during the entire treatment without exposing the patient to additional dose. This enables gated treatments and dosimetrically beneficial (adapted) treatment plans with promising clinical outcomes. Clinical studies are needed to reveal which patients will benefit most from this technique. As MR guided radiotherapy (MRgRT) is associated with prolonged treatment times compared to conventional techniques and thus requires high patient compliance, feasibility and patient tolerance are critical factors in gaining clinical evidence. Other important aspects that need to be addressed are device-specific exclusion criteria, patient acceptance and cost-effectiveness.

Recently, a low-field hybrid MR-Linac has been introduced in Heidelberg and jn 2018 the first patient was treated our institution. An important feature of the setup is a video feedback system for assistance in gated breath-hold delivery using cine-MRI. In this talk we will share our clinical experience with this new technique and discuss the further needs to utilize its full potential in order to improve tumor control and reduce side effects in cancer therapy.

S01.02 ID 142

Early clinical trial experience of online of adaptive MR-guided at LMU Munich

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A hybrid magnetic resonance image (MRI)-guided radiotherapy system (Viewray Inc., Mountain View, CA) was first introduced at LMU Munich in 01/2020. Current published clinical experiences with this new technology are increasing. However, clinical studies are needed to define the role of this revolutionary concept of oMRgRT systems. The ability to acquire MR images for adaptive treatment planning and online imaging during treatment delivery combined with the daily adaptive treatment planning strategies allow improving targeting accuracy while avoiding critical structures. We report our initial institutional experience and early clinical trial experience of online adaptive MR-guided radiotherapy (oMRgRT) at LMU Munich.

S01.03 ID 98

Ablative SBRT treatment of pancreas patients on Elekta Unity MR-Linac

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Introduction

MR-guided adaptive RT offers significant advantages in the clinical management of pancreatic cancer (PC). We report on our early experience of treating pancreas patients with ablative SBRT doses of 50 Gy in 5 fractions using a compression belt (CB) workflow on the Elekta Unity 1.5T MR-linac system.

Methods and Materials

Ten locally advanced PC patients were treated with daily online plan adaptation including daily recontouring and plan optimization using Adapt-to-Shape (ATS) workflow. Three orthogonal plane cine MRI were acquired to assess belt pressure during MR simulation as well as during each treatment (tx) fraction to assess stability of CB in minimizing tumor motion. Three sets of 3D T2w MR (TR/TE = 1300/87ms) scans called pre-tx (MRI_{pre}), verification (MRI_{ver}) and post-tx (MRI_{post}) MRI were acquired for online planning. To assess the dosimetric impact of intrafraction organ motion, a post-tx QA was performed before the next fraction by propagating pre-tx plan and structures to both MRI_{ver} and MRI_{post} and by contours editing and dose recalculation. GTV coverage (% volume receiving Rx) and selected organs-at-risk dose constraints (<25 Gy to 5cc volume) were evaluated on MRI_{ver} and MRI_{post}. Organ motion was assessed for the initial fractions and conservative strategies (such as larger PRV margins) were employed in later fractions if needed.

Results

Average ATS planning and delivery time was 72(55 – 90) mins. Average tumor motion in the belt for all fractions was 0.2±0.07, 0.24±0.1 and 0.41±0.21 cm in AP, LR and SI direction. Average GTV coverage was 78 % (75 – 83) of Rx dose for all fractions. Average 5cc stomach_duodenum dose was 24.3 Gy (18.4 – 26.8) on MRI_{ver} and 24.6 Gy (18.3 – 30.5) on MRI_{post}. Average 5cc small bowel dose was 24.5 Gy (18.2 – 32.8) on MRI_{ver} and 24.6 Gy (16.0 – 33.6) on MRI_{post}.

Conclusion

Because of lack of motion management techniques on Unity MR-Linac, the CB workflow and post-tx QA allow safe delivery of ablative radiation doses for abdominal radiotherapy.

S01.04 ID 45

Same-day MRI-LINAC Guided Single Fraction Radiosurgery for Painful Non-spine Bone Metastases

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Purpose

The efficacy of high-dose single-fraction stereotactic body radiotherapy (SBRT) for painful bone metastases was recently shown (1). The aim of this prospective registry study was to assess the feasibility of a same-day-workflow with MR-only planning and application in one single radiosurgical session without previous simulation, aiming to provide fast as possible pain relief.

Materials and methods

This prospective, single-institution registry study enrolled patients with radiologically confirmed painful bone metastases with a pain scores ≥ 3 / 10 (on 0 to 10 numeric rating scale= NRS). Patients received single-fraction SBRT with12 Gy at an MR-Linac (ViewRay) with same-day planning and delivery of radiosurgery. We analyzed the procedure regarding process times and analyzed pain response and treatment tolerance.

Results

13 patients were enrolled from June 2019 until June 2020 and 15 lesion have been irradiated. Mean age 64 years (range30- 87 y). Mean GTV size was 26.0 ccm, median was 15.6 ccm (range 1.1 to 84.4 ccm). Mean on-table for SBRT time for contouring, SBRT planning and delivery was 70 minutes, median was 65. No treatment interruption was observed. Median pre-treatment pain score was 6 points which was reduced by 5 points NRS (P=0.0028) at the 4-weeks follow-up. None of the patients developed a pain flare (figure). No grade 3 or 4 toxicities were observed.

Conclusion

Same-day MR-guided SBRT planning and treatment was technically feasible and achieved promising pain response. Future prospective trials investigating this intervention are warranted, especially in palliative patients with a need for rapid pain response and improved quality of life.

S10.02 ID 117

Five years of MRI guided adaptive radiotherapy

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[1]AmsterdamUMC

Developments in the field of radiotherapy have enabled the delivery of higher tumor doses with better sparing of normal tissue, resulting in improved local control rates with less side effects. With the advent of MRI guidance and adaptation, the next step in radiotherapy is possible due to a better visibility of the soft tissues, continuous imaging during the treatment delivery and the daily adaptation of the treatment plan based on the anatomy of the day. At Amsterdam University Medical Centers, location VUMC, the first patient was treated using MRI guided and adaptive radiotherapy in May 2016. Since 2018 two MRIdian linac systems are operational. In the first five years more than 1000 patients have been treated with daily adaptive MRI guided stereotactic radiotherapy. The indications included prostate (40%), lung (14%), pancreas (11%), liver (8%), kidney (7%), adrenal gland (7%) and other tumors (13%). Since the treatment time per fraction for stereotactic delivery with on-table adaptation adaptive is considerably longer (30-50minutes) compared to conventional treatment, only hypofractionated schemes (typically 5 factions) are used. In addition, a strategy for partial recontouring of the organs at risk around the tumor was developed to streamline the workflow. In prostate cancer, a prospective phase two study was performed. Gastrointestinal toxicity (CTCAE) was seen in only 5%of patients (Grade 2 only) and genitourinary toxicity in 24% (Grade 2 only). This is much lower than for moderately hypofractionated schemes without MR guidance and daily plan adaptation. Long-term clinical outcome is awaited but

interim results are promising. In pancreatic cancer, studies have already shown the feasibility of delivering hypofractionated schemes of 40 Gy in 5 fractions without significant toxicity. Clinical studies are now underway to investigate higher doses using MRI guidance and daily plan adaptation. For patients with early-stage lung cancer, conventional SBRT already leads.

S10.03 ID 64

Adaptive radiotherapy for head-and-neck cancer – volume changes and migration of salivary glands

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Objectives

The aim of this study was to evaluate volume changes and migration of parotid glands and submandibular glands in head-and-neck cancer (HNC) patients receiving magnetic resonance imaging (MRI)-guided adaptive radiotherapy.

Patients and Methods

HNC patients receiving MRI-guided radiotherapy on the ViewRay MRIdian Linac were included. All patients received 35 fractions of 2 Gy daily, resulting in a total of 70 Gy to the macroscopic tumor, 60 Gy to the involved nodal levels and 50 Gy for elective nodal irradiation. Every week an offline plan-adaptation was performed based on the actual MR-treatment Image. The glands' volume and inter-gland distances were evaluated. Distances were calculated using the geometrical centers of the glands. Wilcoxon signed-rank test was used to evaluate the values with respect to baseline, and p-values below 0.05 were considered significant.

Results

Nine patients were included into the analysis. The mean [range] change in parotid volume was -8.7% [-29.7 – 7.2] after one week of treatment (p=0.0001), and -33.1% [-47.5 - -15.8] after five weeks (p<0.0001). For the submandibular glands, this was -8.9% [-23.6 – 2.8] after one week (p=0.0021) and -29.4% [-49.4 – 0.0] after five weeks (p=0.0007). Linear regression showed an average decrease of 0.21 mL per day and 0.07 mL per day for parotids and submandibular glands, respectively. Inter-parotid distance changed on average by -5.3% [-8.1% - -1.0%] after five weeks (p=0.0078). The inter-submandibular gland distance did not change significantly.

Conclusion

We observed significant volume reduction of parotid glands and submandibular glands during the course of radiotherapy, and significant migration of the parotids. This stresses the importance of plan adaptation during treatment. To this extend, weekly adaptation using MR-linac technology is a feasible approach to avoid excessive irradiation of these important salivary glands and the impact on xerostomia will be investigated in a future study.

MAGELLAN: MR-guided adaptive stereotactic body radiotherapy for lung tumors in ultracentral location

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Introduction

Stereotactic Body Radiotherapy (SBRT) is a standard treatment in inoperable patients with primary and secondary lung tumors. Yet, SBRT of ultracentral lung tumors (ULT) with contact to vulnerable mediastinal structures conveys a risk of severe toxicity [1]. Magnetic resonance (MR)-guided SBRT of ULT could mitigate this risk based on online MR-imaging with gating of the radiation beam as well as daily plan adaptation [2]. MAGELLAN is an upcoming prospective multicenter phase I trial investigating MR-guided SBRT of ULT with dose escalation. The aim is to find the maximum tolerated dose (MTD) as an ideal balance between safety and efficacy.

Patients and Methods

A maximum of 38 patients with primary and secondary ULT (< 5 cm) will be enrolled. ULT are defined as overlap of the planning target volume (PTV) with the proximal bronchial tree or esophagus. SBRT will be delivered at a 0.35 Tesla MR-linac (MRIdian® ViewRay Inc.) employing gating as well as daily plan adaptation. The starting dose is 10 x 5.5 Gy, with step-wise dose escalation to 10 x 6.5 Gy or de-escalation to 10 x 5 Gy. A modified time-to-event continual reassessment method (TITECRM) will be used with alternating allocation of patient cohorts to an escalating dose level or backup level based on all available toxicity data so far. This enables continuous accrual despite potentially delayed toxicity after up to 12 months. Planned trial initiation is winter 2020.

Conclusion

MAGELLAN is a prospective dose escalation study investigating the safety of MR-guided SBRT for ULT. Its design allows continuous accrual with dynamic dose escalation.

References

[1] Chen et al., Safety and Effectiveness of Stereotactic Ablative Radiotherapy for Ultra-Central Lung Lesions: A Systematic Review. 2019.

[2] Henke et al., Phase I trial of stereotactic MR-guided online adaptive radiation therapy (SMART) for the treatment of oligometastatic or unresectable primary malignancies of the abdomen. 2018.

TOPIC DOSIMETRY

S08.01 ID 145

Radiation dosimetry in magnetic fields: From reference fields towards small fields

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MR guided Radiotherapy based on MRI-linacs requires new approaches for radiation dosimetry. The presence of the constant magnetic field (B_0) impacts the response of ionization chambers and detectors as well as the dose distribution. Consequently, existing methods and procedures for reference dosimetry (e.g. TRS-398) and small field dosimetry (e.g. TRS-483) are inadequate. This presentation will discuss the relevant issues for both reference and small field dosimetry in the presence of magnetic fields for orthogonal MRI-linac facilities.

For reference dosimetry the focus will be on the response change of reference ionization chambers due the presence of magnetic fields and factors affecting this response change (such as dead volume effects). Additionally, measurement and Monte Carlo simulation-based methods to determine correction factors for this response change will be presented. Approaches how these correction factors can be adequately implemented in a formalism for reference dosimetry in line with codes of practice as TRS-398will be discussed [1].

Small field dosimetry is usually performed with other types of detectors (e.g., small ion chambers and diodes) than those for reference dosimetry. Moreover, other characteristics of the radiation field (such as lateral charged particle equilibrium and field size) become more important. The impact of the B_0 field on the response of these chambers as well as on the characteristics of small radiation fields will be addressed.

[1] JA de Pooter, I Billas, LA de Prez, et al., Reference dosimetry in MRI-linacs: evaluation of available protocols and data to establish a code of practice, Phys Med Biol. 2020

S08.02 ID 93

Magnetic field correction factors of diode detectors and the role of enhanced density components

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Introduction

Diode detectors are used at MR-Linac in the situations where high-resolution measurements are necessary, such as small fields or profiles measurements. However, limited investigations have been done so far on the change of dose response of diode detectors in magnetic fields. This work studies systematically the behavior of various clinical diode detectors in magnetic fields experimentally and using Monte Carlo methods. The underlying mechanisms for the observations have been elucidated using detailed Monte Carlo analysis.

Materials and methods

Three diode detectors were investigated (PTW microDiamond 60019, PTW microSilicon 60023 and IBA Razor Diode). The ratios M/M_B were measured up to 1.4 T using a 4 cm x 4 cm 6 MV photon beam from a conventional linac at the Physikalisch-Technische Bundesanstalt (PTB, Braunschweig) equipped with electromagnets; and simulated up to 1.5 T for the same setup. Together with the simulated detector-independent dose-conversion factors $D_{w,B}/D_w$, the corresponding magnetic field correction factors, $k_{B,Q}$, were computed. The detectors were aligned with their symmetry axes parallel to the beam's axis. Furthermore, the detector models in the Monte Carlo simulations were modified stepwise to allow the understanding of the role of different detector components. This analysis was further supported by simplified models, where the density of an upstream and a downstream density layer from a thin sensitive volume was changed systematically.

Results and Conclusion

The results showed that the dose responses of the investigated diode detectors decrease in magnetic fields by up to 10% at 1.5 T. The agreement between the calculated and measured dose responses is better than 1%. Detailed Monte Carlo study reveals that the role of the sensitive volume itself is negligible, whereas other enhanced density components within the detector, especially the diode chip, contributed strongest to the observed changes in dose response in magnetic field.

S08.03 ID 108

Investigations of the role of chamber's construction towards the magnetic field correction factors

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Introduction

Compact ionization chambers are commonly used in small fields and profiles measurements. In this work, the dose response of three compact ionization chambers in magnetic field have been investigated experimentally and using Monte Carlo simulations. The influence of the nonsensitive region within the air cavity and the chamber's design towards the magnetic field correction factors $k_{B,Q}$ was examined.

Materials and methods

$k_{B,Q}$ of Semiflex 3D 31021 and PinPoint 3D 31022 (both from PTW Freiburg); as well as SNC 125c (Sun Nuclear Corporation) have been determined. The detector-dependent part of $k_{B,Q}$, that is, the ratios of measured signals without and with magnetic field M/M_B, were measured using a 6 MV 4 cm x 4 cm field. The magnetic field was varied up to 1.4 T using an electromagnet. All chambers were positioned with their axes either parallel or perpendicular to the beams' axis in 5 cm water depth. Additionally, the ratios M/M_B up to 1.5 T were obtained using Monte Carlo simulations with the EGSnrc code. The effective sensitive volumes of the chambers were assessed using a high-resolution proton microbeam and calculated with finite element analysis. The detector-independent part of $k_{B,Q}$, that is, the dose-conversion factor in water $D_{w,B}/D_w$, were assessed using Monte Carlo simulations by replacing the detector models with a small water voxel. To further elucidate the role of chamber's design, the dependence of the number of secondary electrons and their average path length within the air cavity on the magnetic field and detector's orientations has been analyzed.

Results and Conclusion

For all investigated chambers, $k_{B,Q}$ deviate by not more than 4% from unity up to 1.5 T. The correction factors derived from Monte Carlo simulations considering the effective sensitive volumes of the chambers show agreement better than 1% to the measurements. Systematic analysis reveals the role of the chamber's stem and the shape of air cavity on the dose response.

S08.04 ID 99

Evaluation of irradiation geometry and airgaps in the IROC QA mini-phantom for a 1.5T MRlinac system

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Introduction

A majority of institutions participate in the OSLD Remote Dosimetry Program by IROC Houston QA center. Our goal was to investigate the impact of side scatter (SS) and back scatter (BS) and the presence of airgaps on OSLD measurements in the standard IROC homogeneous acrylic mini-phantom (MP) geometry on the Unity MRL.

Methods

The following irradiation geometries were investigated using OSLDs and A26 MR ion-chamber (IC): (a) IC/OSLD in IROCMP (partial SS, no BS) (b) IC/OSLD in a MP placed on a solid water (SW) stack at a depth of 1.5 cm (partial SS, full BS) (c) IC/OSLD placed at a depth of 1.5 cm between inside a 3 cm slab of SW or buildup material (full SS, no BS) (d) IC/OSLD centered inside a 3cm slab of SW or buildup material at a depth of 1.5 cm placed on top of a SW stack (full SS, full BS). Average of two irradiated OSLDs with and without water was used at each setup. The above geometries were also simulated in Monaco Monte Carlo system with 0.5% statistical uncertainty. An airgap of 1mm and 2mm, mimicking presence of potential airgap around the OSLDs in the IROC geometry was also simulated. The calibration condition of the machine was 1cGy/MU at SAD=143.5cm, d=5cm and 10x10cm^2.

Results

The expected dose using 100 MUs at OSLD depth was 110 cGy. The dose values calculated using Monaco for the 4 setups were 107.9, 108.1, 109.4 and 110.0 cGy. In the presence of 1mm and 2mm airgap, the calculated doses were 124.7 and 140.7 cGy due to electron return effect. The IC measurements in the 4 configurations were 109.0±0.03, 109.5±0.06, 110.2±0.02 and 109.8±0.03 cGy. Without water, OSLDs measurements were ~10% higher than the expected 110cGy. With added water, the values were 112.0, 111.98, 107.61, 111.85 cGy.

Conclusions

IROC MP geometry with partial SS and BS did not have any impact at the measurement depth. A minimal amount of air around or within the OSLDs in the acrylic MP can cause output discrepancies of 10% or higher when placed in a high B-field.

R08.01 ID 86

Magnetic field correction factors via a cross-calibration using a conventional linac

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Introduction

Magnetic field correction factors, k_B, are required for dosimetry in magnetic fields. Current methods for determining k_B include: transfer from calorimeters, chemical dosimetry, measurements during magnet ramp up/down or monte carlo simulations. This work aims to validate a method for calculating k_B via cross-calibration measurements on a conventional linac and a MR-Linac (MRL).

Materials and Methods

k_B is a ratio of the absorbed dose to water calibration factor in the magnetic field (B) to 0 T at the same beam quality (N_{DwQ}^B/N_{DwQ}^{0T}). k_B considers i. dose to water ratio at B to 0T (D_w^B/D_w^{0T}) and ii. dosimeter charge ratio at 0T to B (M^{0T}/M^B). The proposed method involves measuring the charge ratios between a microdiamond and 2 Farmer chambers, a PTW30013 and IBA FC65-G, at 0 and 1T positions on the

Australian MRL and 0T on a conventional linac, with the effective point of measurement at 10 cm depth in solid water. These measurements enabled: 1. Calculation between a conventional linac and MRL at 0T to assess the impact of beam quality changes ($[M_F/M_{uD}]^{0T\text{-}conv}x[M_{uD}/M_F]^{0T\text{-}MRL}$); 2. Calculation between 0 and 1T on the MRL to determine k_B ($[M_F/M_{uD}]^{0T\text{-}MRL}x[M_{uD}/M_F]^{1T}$);3. Calculation between 0T on a conventional linac and 1T on the MRL to determine k_B via the proposed method ($[M_F/M_{uD}]^{0T\text{-}Conv}x[M_{uD}/M_F]^{1T}$).

Results and Conclusion

Results between the conventional linac and 0T position for both chambers were within 0.1 % of unity indicating no change due to beam quality. kB calculated via 0 and 1T on the MRL and 0T on a conventional linac and 1 T on the MRL was 0.995±0.007 and0.992±0.008 for the PTW30013 and FC65-G respectively. The results were consistent with monte carlo for the PTW30013[1] and Alanine measurements for the FC65-G[2]. This work validated the proposed method. Future work will investigate applicability to perpendicular MRLs.

References

[1] Spindeldreier et al, PMB 62(16):6708, 2017

[2] Billas et al, NPL Report IR 46, 2018

R08.02 ID 111

Investigation of diode-type detectors under small field conditions in magnetic field

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Introduction

The aim of the present work is to investigate the field size and magnetic field dependence of the small field output correction factors of a silicon diode and a synthetic diamond detector experimentally and with Monte Carlo simulations down to the smallest nominal field size of 5 mm x 5 mm and up to a magnetic field strength of 1.5 T.

Materials and Methods

The signal ratios M/MB of two diode-type detectors, PTW microDiamond 60019 and PTW microSilicon 60023 under the influence of magnetic field (B) have been measured at a clinical linear accelerator using a 6 MV photon beam of quadratic fields with nominal side lengths between 5 mm and 40 mm. An electromagnet positioned in the beam generated magnetic field strengths up to 1.4 T. Both detectors were positioned with their axis parallel to the beams' axis in 5 cm water depth. The 2D dose profiles were measured using calibrated EBT3 radiochromic films. Simulations were performed using the EGSnrc code by implementing photon virtual sources derived from the film profiles to obtain the ratios M/M_B under the same condition as during the measurements. Together with the associated Monte Carlo simulated dose-conversion factors D_B/D, the magnetic field-dependent dose response at different field sizes were computed.

Results and Conclusion

The magnetic field correction factors at 4 cm nominal field size $k_{B,Qmsr}$ of both investigated diode-type detectors increase with increasing magnetic field. At smaller field sizes, the measured small field output corrections factors in magnetic field $k_{B,Qclin,Qmsr}$ show field size dependence that differ by up to 8% from the field-free case at the smallest field size studied. This observation agrees with the simulations within 1.4% for both detectors.

Time-resolved dosimetry in MR-linac without image distortion

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Introduction

Patient treatment where the tumor is continuously imaged during irradiation has become possible with the introduction of the MR-linac, combining MV x-rays and online magnetic resonance (MR) image guidance. To exploit the full potential of this technique, and to evaluate, e.g. the accuracy of advanced gating treatment plans, we are developing a measurement system that can provide time-resolved dosimetry in a MR-linac without image distortion. In particular, the system is designed to measure the dose per linac pulse.

Materials and Methods

To avoid image artifacts from metals and graphite found in conventional clinical detectors, we propose to use plastic scintillation detectors (PSD) attached to PMMA optical fiber cables. Both the scintillator and PMMA have magnetic susceptibility close to water, and it is our hypothesis that this enables the detector to be compatible with MR-imaging. The proposed system is based on BCF-60 scintillators and the optical fiber cables are 15 m long (1 mm diameter) such that the readout electronics (ME40, developed at DTU) can be placed remotely outside the treatment bunker. Traceable dosimetry is provided via alanine dosimeters. The detector is positioned in a dynamic MRI compatible phantom (CIRS) during irradiation in a ViewRay MRIdian linac. The dosimetry is carried out in treatment-delivery mode, which includes imaging while delivering a radiation beam. Fast time acquisition (200 μs) allows the dose during each individual accelerator pulse to be recorded, and alanine detectors are used as a reference, collecting the total accumulated dose.

Results

It is demonstrated that the PSD system situated in the CIRS phantom causes no image distortion neither statically nor dynamically. These images are compared to fiber-coupled Al_2O_3:C crystals and conventional detectors which show varying degrees of distortion. Initial measurements have demonstrated that beam-on time directly correlates with scanner framerate in gated treatments.

We believe that MRI is changing the field of RT and will continue to advance and drive the precision of treatment. MRI in RT benefits from the continual advances in MRI technology and the ever-increasing computing power for AI-based solutions for image reconstruction, registration, segmentation, analysis, and QA. We look forward to meeting you digitally to reinforce and build on our valuable collaboration.

What awaits you

- Company presentation **"Synthetic CT re-imagined – an AI-based approach for MR-only workflows in brain and pelvis"** with speaker Nilesh Mistry, Ph.D. on **Tuesday April 20, 2021, 1:30 p.m.**
- MReadings 7th Edition featuring the clinical experience of Dr. James Balter, University of Michigan, USA, with the Encompass Coil from Qfix[1]
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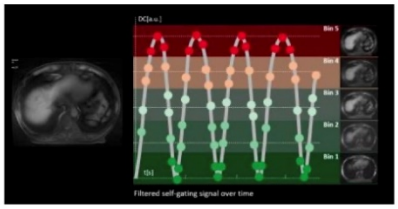

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TOPIC FUNCTIONAL IMAGING

S06.01 ID 124

Functional Imaging on MR-Linacs: Potential and limitations

Daniela Thorwarth, Section for Biomedical Physics, University Hospital for Radiation Oncology Tübingen

Introduction

Biological and functional properties of tumors have been identified as key factors determining treatment outcome after radiotherapy (RT). Consequently, it is hypothesized that prognostic functional information on tumors, assessed by quantitative imaging biomarkers (IB) may allow biologically adapted online magnetic resonance (MR) guided RT interventions in order to overcome treatment resistance.

Material and Methods

Recent studies have shown promising results in terms of prognostic potential of IBs such as apparent diffusion coefficient (ADC) values assessed by diffusion weighted (DW) MR to predict RT outcome. According to the IB roadmap [1], new IBs need to be established for future interventional studies by crossing 'translational gaps' through validation and quantification.

In this presentation, the current status of IB assessment in hybrid MR-Linacs will be reviewed and discussed.

Results and Conclusion

Recent phantom studies have revealed that quantitative measurement of ADC from DW-MR is possible on 1.5 T MR-Linacs. However, certain limitations exist due to the technical specifications of current hybrid MR-Linac systems which need to be taken into account.

Recent results on repeatability and reproducibility of DW-MR measurements in MR-Linacs will be summarized. Furthermore, first data on repeatability derived from test/re-test investigations in clinical studies will be discussed.

After thorough technical and clinical validation of quantitative IBs, interventional trials assessing the efficacy of IB-driven MR-guided RT interventions will be possible in the future.

Literature

[1] O'Connor JPB, et al. Nat Rev Clin Oncol 2017;14(3):169-86.

S06.02 ID 107

R2* MRI based tumor control probability modelling for dose painting by contours in rectal cancer

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Background

Chemoradiotherapy (CRT) response in rectal cancer varies due to adverse factors such as tumor hypoxia. The MRI derived parameter R2* has potential in assessing tumor hypoxia and has been associated with RT outcome in several tumor types. Our aim was to investigate the feasibility and value of individual radiation dose adaptation via dose painting by contours (DPBC) based on R2* in rectal cancer.

Material and Methods

Dynamic susceptibility contrast (DSC) and diffusion-weighted MRI (DWI) of 35 patients with rectal cancer were analyzed (OxyTarget study NCT01816607). Data was acquired before CRT and surgery. R2* area-under-the-curve (AUC) and apparent diffusion coefficient (ADC) were calculated. R2*-AUC maps were segmented into different subregions presumed to be more radioresistant or radiosensitive according to a threshold value found significant for patient stratification into good (TRG0-1) and poor (TRG2-3) responders ($p<0.01$, Mann-Whitney U). A Poisson-based linear quadratic tumor control probability (TCP)

model was used to assess the potential advantage of a DPBC-based dose boost to the R2*-defined radioresistant subregion over a uniform dose boost (UDB) to the entire tumor volume (equal total dose). In TCP modelling, tumor cell density was estimated based on the ADC. Finally, clinical proof of concept was evaluated in a patient case, comparing dose volume histograms (DVHs) between DPBC and standard dose.

Results

R2*-AUC based DPBC maps were successfully generated. 16 patients showed resistant subvolumes >1cm^3. Resistant subvolumes were significantly larger in patients with TRG3 than in patients with TRG1-2. TCP modelling predicted a higher TCP for DPBC than for UDB. For the patient case, the target dose was achieved for the DPBC plan, while DVHs of organs at risk were comparable to the standard plan.

Conclusion

DPBC based on R2*-AUC may be a promising strategy to improve CRT response in rectal cancer patients. Further analysis and validation would be needed for clinical implementation of such functional imaging-based treatment adaptation strategy.

S06.03 ID 100

Serial DWI measurements in HNC treated on a 1.5T MR-Linac and benchmark against a 3T MR-scanner

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Background

MR-Linacs (MRL) offer the possibility of longitudinal acquisition of functional imaging using DWI including assessment of ADC values. DWI has shown to be a prognostic biomarker in head and neck cancer (HNC). Consequently, this might offer the potential for biological adaptation of RT. As a first step for future real-time interventions using a MRL we report on the first three patients with serial weekly DWI at a 1.5T MRL during radiotherapy (RT) in comparison to two scans at a diagnostic 3T MR.

Methods

Patients with HNC were treated at the 1.5T MRL. DWI (b=200, 500, 800 s/mm2) performed once per week was compared to DWI (b=50, 800 s/mm^2) at the 3T scanner before start and after 2 weeks of RT. GTV of the primary tumor (GTV-P) and lymph nodes (GTV-LN) were delineated in 3D-Slicer. Mean ADC values were analyzed for GTV-P and GTV-LN at the different time points. A Wilcoxon signed rank test (Matlab) was performed for the ensemble of VOIs.

Results

Mean pre-treatment ADCs for GTV-P were 0.96, 0.86 and 1.18·10^{-3}mm^2/s at the MRL and 1.04, 0.99 and 1.37·10^{-3}mm^2/s at the 3T scanner for the three patients. Mean ADCs for GTV-P after 2 weeks were 1.06, 1.26 and 1.40·10-3mm^2/s and 1.15, 1.38 and 1.54·10-3mm^2/s for MRL and 3T MRI, respectively. Wilcoxon signed rank test did not show a significant discordance between ADC measurements at the MRL and the 3 T diagnostic scanner (p=0.21). Mean ADC in GTV-P and GTV-LN increased for all patients during RT except for one GTV-LN in patient 2, where the lymph node was initially necrotic with a large ADC value.

Conclusion

In this pilot study, serial DWI at the MRL showed very good agreement with the measurements at a 3 T reference scanner. This initial data represent an important prerequisite for real-time response adaptive RT on the basis of functional MRI.

Funded by the German Research Foundation (ZI 736/2-1).
COI: Radiation Oncology Tübingen receives financial/technical support from Elekta AB under a research agreement

MRI/PET for radiotherapy simulation: high-resolution pathophysiological guidance for small tumors

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Introduction

The Unity 1.5T MR-linac will be able to provide stereotactic precision for every (moving) location in the body. This potential stresses the need for accurate multi-functional imaging for target definition. PET has a high sensitivity and specificity for many tumors, offering complementary information to MRI. We aim to develop an integrated 1.5T MRI/PET system providing excellent anatomical localization of the PET signal due to the intrinsic registration between both modalities. The MRI/PET MR-linac combination allows for treatment of small tumors and multiple poly/oligometastases in thorax and abdomen. Compared to other methods based on direct use of PET imaging for treatment guidance (RefleXion), the Unity/MRI/PET combination allows stereotactic targeting and provides additional morphological information due to superior soft-tissue contrast.

Materials and Methods

We designed an integrated MRI/PET specifically for the application in radiotherapy. This system is based on the Philips 1.5T Ingenia platform. The PET detector array, with axial length of 15 cm, is integrated in the gap of a split gradient coil using an innovative RF shielding design maximizing the bore size to 70 cm. The initial PET performance was evaluated using 2 PET detectors.

Results

The PET system has been tested in a regular 1.5T Ingenia radiotherapy simulator. The 2 PET modules demonstrated a stable PET data flow under MR operational conditions with an energy resolution of 11% and a coincidence timing resolution of 282ps. The tests showed that using the proposed shielding design, wide bore MRI/PET is feasible.

Conclusion

A dedicated MRI/PET prototype has been designed for multi-modality radiotherapy simulation. The combination of the MR-linac with the MRI/PET allows the use of PET information in the stereotactic targeting of the Unity system. The system has been especially designed for the search for small tumors and multiple poly/oligometastases in thorax and abdomen.

TOPIC MR IMAGING IN RADIOTHERAPY

S02.01 ID 120

New developments in functional MRI

Heinz-Peter Schlemmer, Radiology, German Cancer Research Center (DKFZ)

Functional magnetic resonance imaging (MRI) techniques are increasingly applied in oncology. Increasing evidence prove the potential for clinical decision concerning various aspects inclusing diagnosis and treatment decision making as well as treatment planning, guidance and monitoring. MR imaging biomarkers with high spatial and temporal resolution enable to detect cancer, characterize the biologic aggresiveness, determine the localization and spatial heterogeneity as well as monitor individual response to treatment. This information is an important supplement to biochemical or histological markers. The exploitation of Radiomics and deep learning approaches enbale furthermore to extract valuable information otherwise inaccessible for visual analyses. The lecture will give an overview about clinically established and future MR biomarkers for oncology with particular focus on radiotherapy.

S02.02 ID 69

3D MR spectroscopic imaging for differentiating progression from pseudoprogression in glioblastoma

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Introduction

Differentiating early tumor progression (ETP) from pseudoprogression (PSP) in patients with glioblastoma (GBM) is crucial to improve prognosis. Objective of this study was to investigate the ability of 3D magnetic resonance spectroscopic imaging (MRSI) in distinguishing ETP from PSP in patients with GBM.

Methods

Among the 180 patients included in the prospective phase III Randomized SPECTROGLIO trial (NCT01507506) (1), 46 patients were suspected with progression within 6 months after the end of radiotherapy. Ratio of choline/creatine (Cho/Cr), choline/N-acetyl aspartate (Cho/NAA) and lactate/N-acetyl aspartate (Lac/NAA) were extracted after co-registration of 3D-MRSI with the FLAIR and T1-weighted images before and after gadolinium administration. Voxels were analysed according to the region to which they belonged: contrast-enhanced (CE) lesion, necrosis and infiltrative edema. Mann-Whitney test was used for comparison between groups. The diagnostic performance for differentiating ETP from PSP was evaluated by using univariable and multivariable logistic regression.

Results

Twenty-eight patients were classified as PSP and 18 as ETP, based on the trial recommendations and RANO criterias on new MRI one month after progression suspicion. There was no significant difference between two groups in terms of gender, arm of treatment, type of surgery and MGMT status. Significantly

higher ratios of Lac/NAA, Cho/NAA and Cho/Cr were observed in ETP patients compared to those with PSP (median respectively 1.2 vs 0.5, p=0.0004; 3 vs 2.3, p=0.0274 and 3 vs 2.2, p=0.0014) within the CE regions. Within the FLAIR edema, Lac/NAA was higher in ETP patients compared to those with PSP (median 1 vs 0.4, p=0.0086). After multivariable regression analysis and backward elimination, Cho/Cr ratio was the most significant predictor of ETP (p=0.012).

Conclusion

These data demonstrated the interest of 3D MRSI in differentiating ETP from PSP. 1. Laprie A et al, BMC Cancer 2019

S02.03 ID 16

Dose dependent cerebellar atrophy in glioma patients after radio(chemo)therapy

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Introduction

Radiotherapy is a standard treatment option for high-grade gliomas. Brain atrophy has previously been associated with radiotherapy. The goal of this study was to investigate dose dependent cerebellar atrophy using prospective, longitudinal MR data from adult glioma patients who received radiotherapy.

Patients and Methods

Cerebellar volumes were measured using T1-weighted MR images from 91 glioma patients before radiotherapy (N = 91) and from longitudinal follow-ups acquired in three monthly intervals (N = 349). Relative cerebellar volumes were calculated as ratios to the corresponding baseline values. Univariate mixed effects models were used to determine factors that were significantly associated with relative cerebellar volumes. These factors were subsequently included as fixed effects in a final multivariate linear mixed effects model.

Results

In multivariate analysis, cerebellar volume decreased significantly as a function of time ($p < 0.001$), time × dose ($p < 0.001$) and patient age (p=0.007). Considering a 55 year patient receiving a mean cerebellar dose of 0 Gy (10 Gy), the linear mixed effects model predicts a relative cerebellar volume loss of 0.4 % (2.0 %) after 1 year and 0.7 % (3.6 %) after 2 years. Compared to patients treated with photons, the cerebellar dose was significantly lower in patients treated with proton therapy ($p < 0.001$, $r = 0.62$).

Conclusion

Cerebellar volume decreased significantly and irreversibly after radiotherapy as function of time and mean cerebellar dose. Further work is now needed to correlate these results with cognitive function and motor performance.

S02.04 ID 96

Joint radial trajectory correction for fast T2* mapping on an MR-Linac

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Measuring T2* while delivering MR-guided radiotherapy can characterize tumor hypoxia, which is associated with treatment resistance. T2* mapping with radial trajectories allows for efficient coverage of k-space but is susceptible to errors arising from gradient delays and short-term eddy currents. We propose a method that jointly estimates gradient delays and T2* for MR-guided radiotherapy on an MR-Linac.

The proposed approach combines Trajectory Auto-Corrected Image Reconstruction (TrACR) (1) with model-based reconstruction (2) of T2* maps. Numerical simulations were performed where varying gradient delays in x and y axes ([1,-1] and [1, 2]) and different levels of complex Gaussian noise (0, 0.1, 0.5, and 2.5) were added to the raw data. T2* maps were estimated using the proposed (joint) approach and a sequential approach, where T2* estimation was performed after gradient delay correction. Root mean squared error (RMSE) was calculated from reconstructed and ground truth T2* maps.

In-vivo data was collected in five prostate patients undergoing radiotherapy on a 1.5 T MR- Linac (Elekta AB. Stockholm, Sweden) using a radial stack of stars spoiled multi-gradient echo sequence. T2* maps were compared visually with and without gradient delay correction.

T2* maps reconstructed from the joint estimation had less error (RMSE for [1,-1] = 35.9, 36.5, 37.9, 43.8 ms; RMSE for [1,2] =76, 77, 77.5, 117 ms) compared to the sequential reconstruction (RMSE for [1,-1] = 38.3, 39.8, 43.9, 53.1 ms ; RMSE for [1,2] = 79, 82, 87, 127 ms) for all the noise levels. T2* maps reconstructed with the proposed approach in vivo showed less streaking artifacts as compared to the sequential reconstruction.

This is a proof-of-concept study to implement radial T2* mapping on an MR-Linac while accounting for gradient delays. Future work will include fast computation methods to facilitate clinical implementation.

1. Ianni et al. (2016) MRM.

2. Bano et al. (2018) ISMRM.

S11.01 ID 115

Integration of quantitative imaging biomarkers in MR-guided radiotherapy

Uulke van der Heide, Radiation Oncology, the Netherlands Cancer Institute

MRI-guided radiotherapy systems have the potential to bring two important concepts in modern radiotherapy together: adaptive radiotherapy and biological targeting. For this purpose, quantitative MRI biomarkers need to be identified that reflect radio-insensitive parts of the tumor that potentially could be the target for dose escalation [1].

With MRI-guided radiotherapy systems high-frequency imaging of QIBs becomes feasible without increasing the patient burden, logistical challenges, and costs. A wealth of valuable data will be collected during treatment, creating new opportunities to advance QIB research at large.

The feasibility of quantitative MRI has been demonstrated on both the MRIdian and Unity systems. The success of a potential MRI biomarkers relies on the accuracy, repeatability, and reproducibility of the measurements across institutes and over time. To increase the general applicability of findings, consistency between data from MRI guided radiotherapy platforms and diagnostic MRI scanners needs to be established.

To harnass the potential of the MR-linac for MRI biomarker discovery, a working group has been formed within the Elekta MR-linac consortium. Recommendations have been developed for consistent measurement of diffusion-weighted MRI. Consensus statements for other quantitative techniques are in

preparation. Moreover, a standard template to integrate MRI biomarker discovery in clinical trials, has been designed. In this presentation an overview will be given of the activities of the working group.

[1] Van Houdt et al. 2020 Front. Oncol. | doi: 10.3389/fonc.2020.615643;

S11.02 ID 10

Geometric MRI errors in prostate cancer patients with hip implants on a 1.5T MR-linac: hit or miss?

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Objectives

Creating a work-flow for safe and accurate prostate treatment of patients with a hip implant on a 1.5T MR-linac (MRL), by:

• Quantification of geometric MRI accuracy

• Scoring MR image quality

Patients and Methods

Six patients with a hip implant eligible for prostate EBRT on a 1.5T MRL (Unity, Elekta) were analyzed. Pre-treatment 3T MR (Ingenia, Philips, incl. B0 map) and simulation MRL 1.5T scans (T2 3D TSE, BW: 496 Hz/mm, B0 map) were made. MRs were rigidly registered around the prostate. A structure (‘ring’) was created by adding margins to the PTV (2/2/1 cm in AP/LR/FH). All structures used for on-line re-contouring and plan adaptation are contained within ‘ring’.

Image quality was scored by presence of artifacts in the ‘ring’. Geometrical errors for the 1.5T MRL scan is given by: B0 error (Σ_{B0}), gradient error (Σ_G) and total error (Σ_T). Σ_{B0} is based on patient specific B0 maps (abs, scaled to mm using bandwidth of 1.5T T2 3D scan), Σ_G is machine-specific and derived from a vendor-supplied measurement (vector). Σ_{B0} only acts in the frequency encoding direction, therefore Σ_T is: $\Sigma_T = \mathrm{sqrt}(\Sigma_{G,\text{phase enc. a}}^2 + (\Sigma_{G,\text{ freq enc}} + \Sigma_{B0})^2 + \Sigma_{G,\text{phase enc. b}}^2)$

Results

Image quality was good in 4/6 and 6/6 pts on 3T and 1.5T, resp. However, extent of the implants was not accurately visualized. Maximum Σ_T in the ring per patient was 0.4, 0.5, 0.6, 0.7, 1.0 mm. In 5/6 patients, Σ_T was dominated by Σ_G (additional Σ_{B0} effect < 0.1 mm vs. 0.49 mm for patient with Σ_T = 1.0 mm). B0 error at 3T was predictive of the error at 1.5T (B0 1.5T(Hz) ≈ ½ B0 3T(Hz)); the outlier patient (Σ_{B0}, Σ_T = 0.80, 1.02 mm) could be identified at 3T.

Conclusion

Σ_T was barely affected by the implant in most patients, this is however highly case dependent (i.e. Σ_{B0} in line with[1]). Therefore, we propose to assess Σ_{B0} by pre-treatment B0 mapping at 3T. All patients were treated on the MRL; online planning strategies robust to imperfect implant visualization were used.

1. doi:10.1016/j.phro.2020.07.010

S11.03 ID 110

Parallel imaging stream for multi-purpose real-time adaptive MRI-guided prostate radiotherapy

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Purpose

Real-time 3D imaging enables fast motion estimation for online adaptive MR-linac prostate radiotherapy. The Elekta Unity (Elekta AB, Stockholm, Sweden) currently uses a 3D CINE scan with 2 mm3 spatial resolution and 11 seconds temporal resolution. In this work we adapt the 3D CINE scan to increase the temporal resolution, decrease the reconstruction latency and to include multiple image streams for improved motion detection. The CINE scan is modified in two ways: 1) data is sampled using a Cartesian

Acquisition with SPiral profile ordering (CASPR), which enables view-sharing and multi-resolution image reconstruction [1]; 2) k- space data is relayed and processed using an in-house built reconstruction framework (ReconSocket) [2] to produce multiple image streams with low reconstruction latency. In this work we describe the design of the CASPR-CINE and demonstrate preliminary results.

Methods

CASPR-CINE was implemented on a 1.5T MR-linac and connected to the ReconSocket to generate the three image streams:

• Image stream 1 generates high frequency 1D navigators (FH projection) to detect extreme bulk motion with 10 Hz.

• Image stream 2 generates low-resolution (6 mm3) images to detect large internal soft-tissue movements (e.g. gas bubbles) with high temporal resolution (0.5 Hz).

• Image stream 3 generates high resolution images for dose accumulation and online replanning with a moderate temporal resolution (0.1 Hz).

Results

The k-space data was streamed in real-time using the ReconSocket and reconstructed in-vivo images for all three data streams simultaneously with high quality. The image reconstruction times were 1 ms, 1 s and 5 s for image stream 1-3, respectively.

Conclusions

The proposed 3D CASPR-CINE produces multiple image streams with low reconstruction latency. Future work will focus on the integration of the multiple-image stream to facilitate start-and-stop real-time adaptive prostate radiotherapy.

[1] Bruijnen et al. (2019) [2] Borman et al. (2019)

S11.04 ID 49

Quality control of 3D MR spectroscopy imaging data in glioblastoma: can we do without the expert?

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Introduction

1H MR spectroscopic imaging (MRSI) is a non-invasive technique to extract tumor metabolic information. Manual inspection is still considered the gold standard for identifying poor quality spectra. However, this method is time consuming and subjective. Automatic methods for quality check (QC) are required for the integration of MRSI in radiotherapy workflow. The aim of this work is to present an automatic QC of glioblastoma MRSI data, acquired prospectively [1], using random forest (RF) method.

Materials and Methods

Twenty-five patients with a total of 7760 MRSI spectra, acquired in Pre-RT exam, were used in this study. Post- processing of the data was carried out with the syngo.MR spectroscopy (VB40A, Siemens) and (jMRUI) software [2]. Twenty-eight features that summarize the information encoded in each spectrum were extracted to assess quality spectra. Three spectroscopists assessed manual QC of MRSI data and classified each spectrum as good or poor-quality. The first 20 patients (6192 voxels) were assigned to the training set and the remaining 5 patients (1568 voxels) were used to test the model. The statistical analyses were performed using RF analysis. Variable importance was also evaluated by error increase. All analyses were conducted with R (3.6.1).

Results

The RF method is able to classify the spectra with an AUC of 0.95, with a sensitivity of 77.4% and a specificity of 92.1%. The most important features for the classification was the residuum lipids versus fit obtained with syngo.MR spectroscopy.

Conclusion

RF-based method for automatic QC is able to distinguish between good and poor-quality spectrum with high performance comparable to that obtained by manual inspection. Moreover, the method can be used by radiation oncologist, not being expert in spectroscopy. Our study shows a novel set of MRS signal feature that show very high correlation with spectral quality.

References

[1] Laprie A et al. BMC Cancer 2019
[2] Stefan D et al. Meas Sci Technol 2009

S11.05 ID 14

Online correction for geometric fidelity in MR-Linac treatments

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Introduction

MR guided radiotherapy is currently finding widespread adoption in clinical practice where onboard MR images are used for online adaptive treatments. The geometric fidelity, however, is a potential source of error. It is important to report the total geometric distortion from the combined effect of 1) gradient inaccuracies and 2) B_0 field inhomogeneities caused by system imperfections and patient-induced susceptibility variations [1].

Materials and Methods

The clinical imaging protocols of 35 patients treated on a 1.5T Elekta Unity system (Elekta AB, Sweden) were used to retrospectively determine the geometric accuracy; Prostate(5), Prostate having a partial hip implant(3), Rectum(5), Abdomen(5), Esophagus(3), Lung(7), Pelvic lymph nodes(5) and Breast(2). The protocols consisted of a B0 field map and either a 3D T1 or T2 weighted image intended for treatment planning purposes. An in-house developed visualization tool [2] was used to assess the patient specific geometric fidelity in the PTV determined as the maximum B_0 induced-, the maximum gradient induced- as well as the maximum total distortion.

Results and Conclusion

The geometric distortion caused by gradient inaccuracies were found dominant resulting in a range of 0.25-1.04 mm for all patients, where the distortion correlated positively with isocenter distance. The B_0 induced distortion resulted in 0.02–0.52 mm and was highest in lung and breast cancer patients. The total distortion within the PTVs was found to be in the range of 0.28–1.25 mm. One lung and two breast cancer patients resulted in a total geometrical distortion > 1 mm, predominantly caused by the gradient inaccuracies due to an isocenter distance > 15 cm. Integration of the tool in an online workflow at the MR-Linac for geometric fidelity assessment needs to be explored and eventually the displacement could be used to determine tumor position specific CTV-PTV margins.

[1] Goodburn et al. ESTRO 37. 2018, [2] Tijssen et al. MR in RT 2019

R02.01 ID 17

MRI-only based treatment with a commercial deep-learning generation method for synthetic CT of brain

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Objectives

To show feasibility of synthetic computed tomography (sCT) images generated using a commercially available software, enabling MRI-only treatment planning for the brain in a clinical setting.

Patients and Methods

20 and 16 patients with brain malignancies, including post-surgical cases, were included for validation and treatment, respectively. Dixon MR images of the skull were exported to the MRI Planner software (Spectronic Medical AB), which utilizes convolutional neural network algorithms for sCT generation.

In the validation study, sCT images were rigidly registered and resampled to CT geometry for each patient. Treatment plans were optimized on CT and retrospectively recalculated on sCT images for evaluation of dosimetric and geometric endpoints. Clinical robustness in patient setup verification was assessed by rigidly registering cone beam CT (CBCT) to sCT and CT images, respectively.

The treatment study was performed on sCT images, using CT solely for QA purposes.

Results

All sCT images were successfully generated in the validation study. Mean absolute error of the sCT images within the body contour for all patients was 62.2 ± 4.1 HU. Average absorbed dose differences were below 0.2%. Mean pass rate of global gamma (1%/1mm) for all patients was 100.0 ± 0.0 % within PTV and 99.1 ± 0.6 % for the full dose distribution. No clinically relevant deviations were found in the CBCT-sCT vs CBCT-CT image registrations. Areas of bone resection due to surgery were accurately depicted in the sCT images. Finally, treatment success rate was 15/16. One patient was excluded due to sCT artifacts from a haemostatic substance injected during surgery.

Conclusion

15 patients have successfully received MRI-only RT for brain tumours using the validated commercially available sCT software. Validation showed comparable results between sCT and CT images for both dosimetric and geometric endpoints

R02.02 ID 72

Movement Assessment of OAR and breast using free-breathing, self-gated 4D MRI

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Introduction

The aim of this study was to assess motion of breast and organs at risk (OAR) in supine position without using external surrogates for respiration by means of the 4Drespiratory-self-gating (4D MRI) capability of the scanner.

Methods

A temporal 3D stack-of-stars, 4D MRI during free-breathing (FB)and a 3D gradient echo acquisition during a Deep Inspiration Breath hold (DIBH) were used to scan volunteers (n=5, age: 56±9years, weight: 68±17 kg, height: 167±7 cm) at 1.5T (MAGNETOM Sola, Siemens, Erlangen, Germany). Volunteers were immobilized with indexed Tabletop and Breast board (Qfix, Avondale, USA) and arms up. No abdominal compression was used. Coil holders were deployed to an 18-channel body array coil. A 32-channel spine coil received signal from posterior. The 4D MRI (7phases, 3500 radial views) was

applied in both axial, covering jugulum to liver, and coronal from nipple of breast to posterior lung lobe (each with TE=2.46 ms, TR= 3.6 ms, FA=10°).

Results

Outcome of the supine MR breast position is a visible movement of heart and lungs. Arms over head seemed to be the major reason for restricted breast motion during respiratory cycle. The described setup and acquisition parameters yielded excellent image quality and allow to distinguish different breathing phases when propagating volumes to all phases during post-processing (RT Image Suite). Very promising was the depiction of lymph nodes in all phases of the 4D MRI images, which add valuable information to clinicians. OAR moved mainly in the head-feet direction. The distance between heart and chest wall measured in axial views comprising the nipple (across all volunteers) was 2,3±0,6cm, 2,8±0,7cm and 3,7±1,4cm for FB exhale, FB inhale and DIBH, respectively. Negligible chest movement was observed between FB exhale and F

R02.03 ID 101

4D evaluation of Head and Neck tumors – new ways of tumor assessment and contouring

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Objective

To establish a protocol for motion assessment of head & neck (H&N) tumors and organs at risk (OAR) to improve RT treatment planning using two different 4D MRI techniques, an automatically sorted (4D-RSG) and a temporal sequence (4D-GRASP).

Methods

The developed protocol consists of radial 3D GRE sequences, a self-gating respiration-resolved (4D-RSG, 7 bins, 3500 radial views, 1.5x1.5x3mm^3) and a compressed sensing reconstructed acquisition (4D-GRASP, 1.4s/phase, 206 phases, 1.1x1.1x2mm^3) at 1.5T (MAGNETOM Sola, Siemens, Erlangen, Germany).

RT positioning is achieved with a RT tabletop (Qfix, Avondale, USA), a wooden mask holder, two 18-channel Ultraflex coils around the head and a Body 18-channel coil on the chest. Movement of H&N primary, nodal metastases, and OARs (geometric center, 23 structures in total) was assessed in two patients using non-rigid-registration based contour propagation. Motion patterns observed in both 4D MRI techniques were studied qualitatively and correlated to a high temporal resolution True FISP (2D-TRUFI) sequence (1.0x0.8x6mm^3, 240 phases).

Results

In 4D-RSG, mean max. random motion was 0.9mm (range, 0.0-1.7, primary 1.3) whereas in 4D-GRASP, mean max. random motion was 0.8mm (0.0-1.4, primary 1.3) and mean systematic motion was 0.6mm (0.0-1.8, primary 0.9).

Maximum motion of targets and OARs in both 4D-MRI was weakly correlated (Pearson's r 0.208, p=0.341) with qualitative assessment and comparison with 2D-TRUFI indicating 4D-RSG was able to capture regular motion related to pulsatile expansion of vessels not visible in 4D- GRASP. Motion was most pronounced in anterior-posterior and least in left-right direction in both 4D sequences. Reviewing physicians determined the 4D protocol added important information for margin design and contouring.

Conclusion

We describe a novel 4D MRI protocol to comprehensively assess target and OAR motion for H&N treatment planning. Recruiting is ongoing and data from additional cases will be demonstrated.

MR and sCT reference images for CBCT verification within an anal and rectal cancer MR only workflow

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Introduction

MR-only planning is now clinically achievable in the pelvis with CE marked synthetic-CT generation products. For anal and rectal cancers the standard clinical pathway includes cone beam CT (CBCT) patient position verification using reference CT simulation. MR-only treatment pathways therefore require either the MR-simulation or synthetic-CT (sCT) as an alternative reference image. This study aims to be the first to assess the impact of using RT position T2-SPACE MR or sCT as a reference image for CBCT patient position verification using XVI (Elekta) software for a cohort of anal and rectal cancer patients.

Materials and Methods

32 patients (18 rectum and 14 anus; 16 male and 16 female; undergoing radical VMAT EBRT) received pre-treatment CT and T2-SPACE MR simulation. Routine CBCTs at various fractions were also acquired and a validated research model generated sCTs. MRs and sCTs were rigidly registered to CT and resampled into the CT frame of reference. DICOM tags were copied from CT to MR and sCT to allow import into XVI (Elekta). The routine clinical registration protocol, using the XVI greyscale registration algorithm, was undertaken for all routine CBCTs (216 CBCTs; 110 anus, 116 rectum) using CT, MR and sCT as the reference image. Linear mixed effects modelling identified systematic differences between modalities.

Results and Conclusions

Systematic translation and rotation differences to CT in the X, Y and Z planes for MR were between; -0.3to +0.3 mm and -0.1 to 0.4° for anal cancers; and -0.4 to 0.0 mm and 0.0 to 0.1° for rectal cancers, and for sCT were between;-0.4 to +0.8 mm, -0.1 to 0.2° for anal cancers; and -0.6 to +0.2 mm, -0.1 to +0.1° for rectal cancers.T2-SPACE MR or sCT can successfully be used as reference images for XVI-based CBCT position verification for anal and rectal cancer patients with systematic differences to CT <1 mm and <0.5°. However, support is required from vendors to clinically enable MR as a reference image.

TOPIC MR GUIDED RADIOTHERAPY & TREATMENT PLANNING

S04.01 ID 118

Getting from on-line to real-time MRI guided adaptive radiotherapy

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Hybrid MRI radiotherapy systems enable the generation of volumetric, soft-tissue contrast images, directly from the treatment table. These are used for daily plan adaptation and/or re-planning in order to accommodate inter-fraction anatomical changes. Daily, on-line plan adaptation is a clinical reality and leads to more conformal dose distributions. The integrated MRI functionality also enables the acquisition of anatomical data from the treatment table, during dose delivery. As such the intra-fraction motion can be tracked in 1D, 2D or 3D as function of time. This presentation will address the status and challenges to exploit the intra-fractional MRI data for fast, ultimately, real-time, plan adaptations in order to mitigate the impact of anatomical motion on the dose distribution. This aim is the continuation of daily plan adaptation, that is, daily adaptation accounts for inter-fraction anatomical changes by MRI guidance, then intra-fraction adaptation can re-iterate this for intra-fraction motion.

The various steps that need to be accelerated to get to a new, or adapted, plan will be addressed; imaging, contouring, dose accumulation, clinical decision making, treatment planning and quality assurrance (QA). Basically, the same steps as for a conventional radiotherapy treatment preparation, but then all executed with the patient on the treatment table. Besides accelerating the performance of the steps, automation of the workflow and decisions is crucial on the route towards real-time adaptive. These developments will be illustrated with examples from the current clinic, e.g. 0.1 HZ volumetric MRI and dose accummulation, and from research, 7-16 Hz volumetric updates are feasible. Automated contouring is assisting the delineation process and automated treatment plan generation can be performed within 4 minutes. QA on planning, contouring and non-rigid registration is getting more important in automated workflows and needs to be transformed in a time-resolved dosimetry

S04.02 ID 90

1.5 T MR-linac planning study to compare two different strategies of rectal boost irradiation

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Introduction

Radiation dose escalation in patients with locally advanced rectal cancer (LARC) is a viable strategy to increase tumor response. However, a precise dose escalation to the rectal tumor leads to several challenges, as choosing the best timing. The purpose of this planning study was to compare treatment plans of two different rectal boost strategies: up-front versus adaptive boost at the 1.5 T MR-Linac.

Materials and Methods

We selected patients with LARC underwent long-course neoadjuvant radiochemotherapy (50.4 Gy in 28 fractions). Prior and after the treatment session T2-weighted MRI were acquired, based on which gross tumor volumes (GTVs) and organs at risk were contoured. This dataset was used to simulate four different boost strategies (all with 15 Gy/5 fractions in addition to 50.4 Gy): up-front boost (5 daily fractions in the first week of treatment) and an adaptive boost (one boost fraction per week). Both strategies were planned using standard and reduced PTV margins. MRI contours were used to assess intra-fraction motion.

Results and Conclusion

Five patients were included and a total of 44 MRI was evaluated. The median PTV volumes of the adaptive boost were significantly smaller than for the up-front boost (81.4cm3 vs 44.4cm3 for PTV with standard margins; 31.2cm3 vs 15cm3 for PTV with reduced margins; p=0.031). With an adaptive boost and reduced margins the rectum was significantly better spared rather than with an up-front boost: V60Gy and V65Gy were 41.2% and 24.8% compared with 59% and 29.9%, respectively (p=0.031). Median GTV intra-fractional motion was 2 mm (range 0-8mm). The data suggest that the adaptive boost strategy exploiting tumor-shrinkage and reduced margin might result in better sparing of rectum. The 1.5 T MR-Linac may represent a solution for a safe dose escalation in patients with rectal cancer through individualized margins, motion management and real- time adaptive treatment.

S04.03 ID 55

MLC-tracking on the Elekta Unity MR-linac: first experimental validation for central lung SBRT

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Introduction

Intra-fractional tumour motion induced by respiration is a major source of uncertainty in lung SBRT. In MLC-tracking radiotherapy this uncertainty is minimized by continuously reshaping the treatment beam according to the observed target position, thus achieving a 100% linac duty cycle with the smallest possible PTV margin. In this study, we experimentally quantify the MLC-tracking performance of the Elekta Unity MR-linac for lung SBRT for the first time.

Materials and Methods

MLC-tracking on Unity was enabled by in-house developed software and Elekta-provided research software. The Quasar MRI4D phantom was used to generate periodic (Lujan) motion (cos^4, T=4s, A=10mm), w/ or w/o a cranial drift of 1mm/min. Motion was estimated from 2D cineMR (T1-GRE, 4Hz, 2.5x2.5x10mm^3) using cross-correlation based template matching. System latency was compensated using a linear (ridge) regression prediction filter (look-ahead: 213–463ms). A prototype film dosimetry insert (Modus Medical Devices Inc.), consisting of a 3cm diameter spherical target intersected by a film cassette, was positioned in the centre of the body oval. 15-beam IMRT plans were created for a central lung SBRT fractionation (8x7.5 Gy). The PTV margin was calculated for both mid-position (midP) based motion management (3-5 mm) and MLC-tracking (3 mm).

Results

A local Gamma analysis (2%/2mm/75cGy thresh.) was performed to compare dose differences between motion types. For the midP plan, the periodic+drift vs. periodic motion resulted in a pass rate of 29%. For the tracking plan, periodic vs static and periodic+drift vs. static resulted in pass rates of 100%. The prediction filter reduced the geometric tracking error (RMSE) from 2.5mm to 0.2mm.

Conclusions

Dynamic MLC-tracking on the Unity MR-linac allows for accurate and efficient delivery of central lung SBRT, compensating for both periodic and drift motion allowing for a PTV margin reduction of 2mm compared to the midP plan.

S04.04 ID 59

Real-time 3D motion estimation with deep learning for real-time adaptive MRI-guided radiotherapy

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Introduction

Online adaptive MRI-guided radiotherapy (MRgRT) may facilitate irradiation of highly conformal dose distribution and sparing organs-at-risk[1] when performing intra-fraction motion compensation. To achieve intra-fraction motion compensation, it is crucial that images and organ motion are available with high temporal resolution and low latency. MR acquisition must be highly accelerated, as this is the most time-consuming part, hindering accurate motion estimation due to introduced image artifacts. We have previously shown that deep learning-based motion estimation can be performed for highly undersampled 2D MRI[2]. In this work, we extend the 2D approach to perform real-time 3D deep learning motion estimation.

Materials and Methods

Free-breathing fat-suppressed golden angle stack-of-stars T1-w GRE MRI were acquired for 6 min in 28 patients with lung cancer on a 1.5T MRI at 2.2x2.2x3.5 mm^3 with a FOV=350x350x270 mm^3. K-space was retrospectively sorted into 20 respiratory phases (R~7) and reconstructed using the non-uniform Fourier transform. These respiratory-resolved images were used to train a multi-resolution 3D convolution neural network (3 resolution levels up to 4x downsampling) to learn ground- truth optical flow, enabling time-resolved motion estimation. The trained model was validated on a digital phantom, a physical phantom, respiratory-sorted patient data and time-resolved volunteer data acquired on an Elekta Unity MR-linac.

Results

On digital phantoms the error is <3mm with 30-fold retrospective undersampling. At 18-fold acceleration the mean error is <3mm using respiratory-resolved data. For time-resolved data, motion fields can be obtained with 100ms acquisition and 30ms motion estimation, i.e. 7Hz.

Conclusion

Our approach estimates motion from undersampled images in 3D with high precision, high temporal resolution and low latency. This approach could facilitate real-time adaptive MRgRT, enabling other applications such as dose accumulation.

1. Keall et al. Sem. Rad. Onc. 2019, 2. Terpstra et al. PMB 2020

S09.01 ID 127

Human Modeling Using MR for Radiation Therapy

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Introduction

MRI, while not an inherently fast means of imaging, is enormously flexible, opening significant opportunities to advance models of human anatomy, physiology and motion, and to use these models and related analyses to improve not only the efficiency of MR sampling, but also to increase robustness of treatment planning and delivery, dramatically increase the speed of imaging for simulation and further to open new opportunities for treatment monitoring.

Methods

This presentation will explore some of the potential areas of human modeling using MRI relevant to Radiation Therapy (RT). Models that consider the orthogonality of dynamic changes have the potential to hierarchically characterize physiologic changes over time. In addition to generic sparsity that has been in use for efficient MR sampling for years, the availability of prior knowledge and related models has the

potential to not only dramatically reduce additional information needed for simulation and treatment, but to open new paradigms for advanced prediction of changes as treatment is delivered. Understanding the specific accuracy needs of various MR-based samplings (e.g. for anatomical outlining, attenuation mapping, positioning and monitoring) helps determine rational tradeoffs to advance the development and use of human models. Examples from our group as well as others will be presented that highlight the opportunites that exist and are emerging in this field.

Conclusion

Several exciting opportunities exist to advance human modeling, as well as to use models to help optimize the amount of MR sampling necessary to guide various RT decisions. Developments in these areas can dramatically improve the efficiency and flexibility of MR as a tool in various stages of precision RT.

Supported in part by NIHEB016079

S09.02 ID 78

Dosimetric evaluation of in-silico simulated MR-guided esophageal cancer radiotherapy

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Introduction

In current esophageal cancer (EC) radiotherapy (RT) treatment, large CTV-to-PTV margins are used to correct for geometrical uncertainties of the CTV, yielding large irradiation volumes.

The recent introduction of MRLinacs allows for daily target definition and online plan adaptation which could lead to reduced target volumes with lower OAR dose while preserving target coverage.

This study aimed to evaluate the accumulated dose between in-silico simulated MR-guided adaptive and conventional treatment strategies for EC RT and to explore the potential for MRL guided isotoxic GTV-boosting.

Materials and Methods

29 EC patients underwent six sequential MR scans at weekly intervals. Each MR session consisted of a T2-weighted MR scan and two 60s cine-MRI series. The total accumulated dose for each treatment regimen was simulated in a 2-step process. First, for each fraction the projected planned dose was recalculated based on 3D motion trajectories derived from cineMR to incorporate effects of intrafraction motion. Then, these ‘blurred’ fractional doses were projected to the reference scan using deformable image registration techniques to assess the accumulated dose over all fractions. Three treatment regimens were simulated:

A) A CBCT bonematch based treatment with a 10mm margin
B) An online adaptive MRL based treatment with axial margins of 2mm in conjunction with a 5mm cranio-caudal margin
C) Similar to (B) but with increasing boost levels to daily adapted GTVs

Results

CTV target coverage was similar for all regimens. Significant dose reduction for lungs (MLD 8.5Gy->5.8Gy) and heart (MHD 15.7Gy->11.5Gy) were observed for the MRL regimen. Subanalysis revealed that this profit could be employed to increase the GTV dose to ±160% of the prescription dose without exceeding the contemporary CBCT dose levels.

Conclusion

MRL guided EC treatments allow for substantial OAR dose reduction which could in turn be employed to increase the dose to the GTV and thereby potentially improve local control.

S09.03 ID 83

Respiratory motion models for the MR-Linac: how much data is required?

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2D cine-MR images can monitor lung tumour motion during MR-guided radiotherapy (MRgRT), however 3D anatomical and motion information are required for accurate dose calculations and guidance for MRgRT planning and delivery. Our surrogate-driven motion modelling framework [1] fits a motion model to MR-derived surrogate signals and multi-slice 2D images. It reconstructs a motion- compensated super-resolution (MCSR) image and can model breath-to-breath variation. This work evaluates the motion estimates produced by models built using data with different acquisition times.

A patient with locally advanced lung cancer T4N3M0 adenocarcinoma was scanned on a 1.5T MR-Linac with a fast gradient echo sequence (2x2mm^2 in-plane resolution, 10mm slice thickness). We acquired 8 repetitions of a 4-minute scan interleaving sagittal and axial motion slices covering the thorax with a fixed sagittal surrogate slice including the tumour. Two signals were extracted from the surrogate images using principal component analysis. Five models were built using the signals and motion slices from 1, 2, ..., 5 repetitions as training data.

The last 3 repetitions were used as test data to assess the models. We used each model and corresponding MCSR image (2x2x2mm^3) to estimate the motion slices of the test data from the signals. We computed the residual error (RE) using 2D registrations between the acquired and estimated motion slices.

For the models built with 1, 2, 3, 4, 5 repetitions the mean/95th percentile absolute REs over the body in mm were respectively: 1.12/3.34, 1.16/3.50, 1.12/3.32, 1.19/3.45, 1.15/3.41 in SI direction; 1.05/3.27, 1.01/3.11, 1.01/3.11, 1.04/3.14, 1.03/3.15 in AP direction; 1.23/3.53, 1.18/3.35, 1.24/3.46, 1.29/3.54, 1.28/3.57 in LR direction.

Low REs were obtained for all models, implying that accurate motion models can be built from just 4 minutes of training data. Future work will assess the models using further patients and evaluation metrics.

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S09.04 ID 109

MR-guided elective neck irradiation targeting individual lymph nodes: a new concept

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Introduction

Conventional elective neck irradiation (ENI) in head and neck cancer consists of radiotherapy to the lymph node (LN) regional levels contoured on computed tomography. The 1.5 T magnetic resonance imaging linear accelerator (MRL, Elekta, Sweden) enables new ENI strategies that could target individual non-suspect LNs (i-LNs). In this treatment planning study, two new MRL- based strategies targeting i-LNs (i-ENI) were compared to conventional ENI.

Patients and Methods

Ten patients with T2-4aN0M0 laryngeal cancer were retrospectively selected. All i-LNs visible on T2 mDixon MR images were delineated. Three strategies were considered per patient. Strategy A: Conventional ENI (35 x 1.55Gy = 54.25 Gy) delivered with a conventional linear accelerator (6 MV VMAT). Strategy B: MRL-based i-ENI (7MV IMRT) (35 x 1.55 Gy = 54.25 Gy) including a background dose to the conventional elective neck volumes (35 x 1.03 Gy = 36.00 Gy). Strategy C: Strategy B, but without background dose. In all plans the dose prescription to the primary tumor was 35 x 2 Gy = 70 Gy. Mean dose reductions (ΔD_{mean}) in the organs at risk (OAR) were compared using the Wilcoxon signed rank test.

Results

Compared to conventional ENI (A), a significant ΔD_{mean} of 6.0 Gy and 8.0 Gy was observed in the submandibular glands, of 9.4 Gy and 13 Gy in the carotid arteries and of 9.9 Gy and 19.4 Gy in the thyroid for strategy B and C, respectively. Large inter-patient variations of ΔD_{mean} were observed in all OARs.

Conclusion

MRL-based i-ENI is a new promising concept that could reduce the mean dose to OARs in the neck significantly for patients with laryngeal cancer. In selected patients, adapting elective treatment to the i-LNs could lead to less salivary gland dysfunction, carotid stenosis (c.q. stroke) and hypothyroidism. Clinical studies are needed to confirm the expected reduction of RT toxicity when applying MRL-base i-ENI without reducing regional control.

R04.01 ID 114

Tumor Motion Analysis of Pancreatic Cancer Patients During Ungated MRgRT with Abdominal Corset

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Introduction

Stereotactic Body Radiotherapy (SBRT) has been shown to be a promising therapy for unresectable pancreatic tumors, which account for 40% of all pancreatic carcinomas. However, intrafraction motion, caused by respiratory motion and organ drift, is the main concern for efficient dose delivery in ungated upper abdominal RT. The aim of this study is to retrospectively analyze these two causes of intrafraction GTV motion in a clinical cohort.

Patients and Methods

We included 13 patients that underwent online adaptive MR-guided SBRT for malignancies in the pancreatic region (5x8Gy) on the MR-Linac. An abdominal corset was fitted, which has been shown to substantially reduce respiratory motion [1]. Coronal and sagittal Cine MRs of the tumor region were made at 2 Hz during the entire beam-on time of each fraction. We used deformable image registration to obtain GTV motion profiles in all three directions, which were subsequently high-pass and low-pass filtered to isolate the motion respectively caused by respiratory motion and baseline drift.

Results

The mean (range) respiratory peak-to-peak amplitudes were 4.2 (1.4 – 11.7) mm CC, 2.3 (1.0 – 7.7) mm AP and 1.4 (0.5 – 3.0) mm LR, with low variability within patients: mean interfractional SDs were 1.0 mm CC, 0.4 mm AP and 0.4 mm LR. The mean (range) maximum baseline drifts were 1.4 (0.3 – 5.8) mm CC, 0.8 (0.1 – 2.2) mm AP and 0.8 (0.2 – 2.0) mm LR. These motion patterns turned out to have a negligible impact on the delivered dose compared to the planned dose.

Conclusion

Overall tumor motion during treatment has proven to be small and interfractionally stable, allowing the possibility for PTV margin reduction and safe dose escalation in future studies.

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R04.02 ID 71

Head and neck radiotherapy on the MR-Linac: a multicentre planning challenge on MRIdian-platform

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Objective

Purpose of this study is to evaluate planning on an MRI-Linac system (MRIdian, Viewray®) for head and neck cancer through comparison of planning approaches of several centers.

Materials and Methods

14 planners using the MRIdian planning system participated in a treatment planning challenge, centrally organized by Viewray®. One case of oropharyngeal carcinoma was contoured and standard constraints for organs at risk (OAR) were given. Homogeneity, conformity, sparing of organs at risk, and other parameters were evaluated according to ICRU-recommendations anonymously and were then compared between centers. Differences amongst centers were assessed with means of Wilcoxon test. Each plan had to fulfil hard constraints based on DVH parameters and total delivery time. A “plan quality metric” (PQM) was evaluated. The PQM was defined as the sum of 16 submetrics, characterising different DVH goals.

Results

For most dose parameters, the median score of all centers was higher than the threshold that results in maximum score. Six centers achieved the maximum number of points for the OAR dose parameters and none had an unacceptable performance on any of the metrics. Each planner was able to achieve all the requirements except for one with longer delivery time. The number of segments correlated to improved quality metrics and inversely correlated to brainstem- D0.1cc, and to PTV1-D0.1cc. Total planning experience inversely correlated to spinal canal dose.

Conclusions

MR-Linac-based planning for head and neck cancer is already feasible with good quality. Generally, increased number of segments and increasing planning experience are able to provide better results regarding planning quality without significantly prolonging overall treatment time.

R04.03 ID 106

Ultrashort Echo-Time Trajectory Correction with a Gradient Impulse Response Function on an MR Linac

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Introduction

Synthetic CT (sCT) is a key component of adaptive MR-guided radiotherapy. Generation of thoracic sCT is challenging and benefits from ultrashort echo-time (UTE) imaging that provides contrast in short-T2* tissues (bone, lung). However, UTE imaging is susceptible to artifacts caused by system imperfections and gradient delays. Here, we characterise the gradient impulse response function (GIRF) [1] of an MR-Linac to improve UTE image quality. Materials and Methods

A 3-point Dixon UTE sequence was run on a 1.5T MR-Linac system (Unity, Elekta AB, Stockholm) with two 4-channel phased array coils for signal reception of an anthropomorphic phantom (3D Abdominal, CIRS, VA). A 3D uniform stack-of-stars trajectory was employed with parameters: $TE_1/TE_2/TE_3$ 0.14/1.8/3.5 ms, TR 8.1 ms, 2x2x2 mm resolution. The GIRF was characterised as described in [2] by applying 21 triangular gradient pulses in two parallel 3-mm thick slices +/-20 mm from the centre of a spherical phantom. UTE-sequence gradient waveforms were imported into MATLAB (MathWorks, MA)

from a sequence development tool. Images were reconstructed using both nominal and GIRF-corrected k-space sampling locations.

Results

A gradient delay of 5 µs gave optimal image quality in GIRF-corrected images. Image quality was higher in GIRF-reconstructed data, which exhibited reduced background signal in air, improved line-spread function (2 mm FWHM compared to 2.7 mm), fewer phase-destructive artifacts, and visually improved uniformity and contrast.

Conclusion

UTE images acquired on an MR Linac showed higher image quality when reconstructed with GIRF correction. In future work, GIRF- corrected UTE images will be used to develop online methods for generation of thoracic sCT, for which bone and lung contrast are important.

References

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TOPIC MR GUIDED PARTICLE THERAPY

S03.01 ID 116

MRI-guided particle therapy: challenges and prospects

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Introduction

Owing to the growing adoption and ongoing developments of different technological solutions and workflows of integrated Magnetic Resonance Imaging (MRI) in photon therapy, several groups have started investigating the combination of MRI guidance with ion beam therapy. On-site integration of MRI in ion beam therapy is deemed of special interest for overcoming long-standing issues of treatment accuracy for moving soft-tissue tumours, particularly when using the most advanced dose delivery techniques of pencil beam scanning. However, it poses more technological challenges and higher demands than for photon therapy.

Material and Methods

This contribution will review the current state-of-the-art in particle therapy image guidance and ongoing efforts toward the realization of ideally real-time MRI, with emphasis on the more widely used protons. In particular, it will address major aspects related to instrumentation, computational modelling and clinical workflows.

Conclusions

Despite being still in its infancy, on-site MRI guidance promises to be a likely new frontier in the technological advancement of ion beam therapy to promote full exploitation of the superior ballistic accuracy of ion beams for tumour sites challenged by low contrast and non-negligible inter- and especially intra-fractional motion.

S03.02 ID 126

MR-integrated proton therapy - yet another hype?

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In recent years, there has been a rapid uptake of real-time MR-integrated X-ray-therapy (XT) systems. These MR-LINACs enable on-line adaptive radiotherapy methods, in which inter- and intrafractional motion can be reduced and fractionation schedules are intensified, with the aim to improve treatment outcome.

Alongside these technological advances in XT, an increasing number of clinics offer proton therapy (PT), motivated by an advanced sparing of healthy tissue. PT aims at widening the therapeutic window and has shown clinical promise for various tumor sites, including base of skull and brain tumors, hepatocellular and pancreatic carcinoma. However, image guidance in PT still lags behind that for XT. Most PT sites rely on orthogonal X-ray imaging for positioning verification, some use implanted markers for tumor demarcation, and only few sites have access to in-room computed tomography (CT) or on-board cone-beam CT. However, these X-ray based imaging techniques provide poor soft-tissue contrast, expose healthy tissues to radiation dose, and have limited intrafractional imaging capabilities.

Since MRI can overcome these limitations, there is an increased interest to investigate the feasibility and potential of MR-guided PT. Three scenarios are studied: near-room, in-room, and in-beam MRI. Near-room and in-room MRI may account for interfractional changes and enable adaptive treatment, but require post-imaging patient repositioning and do not account for intrafractional changes. In-beam MRI would facilitate imaging in treatment position, both prior to and during dose delivery. The latter would allow for high-precision PT using hypofractionated schemes in moving soft-tissue tumors.

To bring in-beam MRI-PT into clinical reality, this contribution highlights the required technical steps and expected clinical values to keep up with the achievements reached in MR-integrated XT.

S03.03 ID 46

Proton IMPT planning in a 1 T perpendicular split-bore MRI system

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Introduction

The clinical implementation of MR-guided proton therapy will require the establishment of novel treatment planning and beam delivery techniques to account for the impact of the MRI on the proton beam. In particular, the fringe field of a MRI scanner is expected to substantially impact the proton beam. A novel method for adapting a TPS for IMPT planning and delivery in the presence of a 1 T perpendicular magnetic field with realistic fringe fields is presented.

Materials and Methods

An independently modelled 3D magnetic field map was used to model the fringe field of a 1T split bore MRI system [1]. A generic proton beam mimicking the beam optics and energy spectrum of a clinical beam was modelled using the Monte Carlo (MC) code TOPAS version 3.5 and integrated with the research TPS matRad for MC-based IMPT planning in magnetic fields [2]. A custom algorithm was implemented to adapt the beam scanning parameters in order to correct the Bragg peak positioning in the target volume in the presence of the MRI scanner. The necessary beam delivery adaptation and the impact of the magnetic field on the IMPT plan delivery was evaluated for several treatment sites such as liver and prostate.

Results and Conclusions

Patient specific as well as spot scanning position and energy specific modifications are certainly required for delivery of conformal IMPT plans in the presence of the MRI system. These adaptions included gantry angle and beamline offset, and were shown to restore the beam path in the patient. Through optimisation plan quality was fully restored for the adapted IMPT plan delivery in the presence of the perpendicular magnetic field.

References

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S03.04 ID 3

Time-resolved respiratory motion modeling for gated carbon ion radiotherapy of pancreatic cancer

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Introduction

Although 4DCT remains the current clinical standard, MRI-guidance plays an increasingly central role in respiratory motion management, with fast orthogonal (coronal/sagittal) 2D cine-MRI representing the state-of-the-art for time-resolved imaging. In this study, time-resolved 3D images were derived through a respiratory motion model based on 2D cine-MRI (1.15 min scan) and a reference 3D CT, to investigate breathing motion during gated carbon ion radiotherapy of pancreatic cancer.

Materials and Methods

Data from 9 patients treated at CNAO (Italy) were considered. The model relies on deformable image registration between 2D cine-MRI frames to quantify breathing motion, and on the propagation of obtained 2D vector fields [Paganelli et al. 2018 doi:10.1111/1754-9485.12713] to estimate the 3D motion. With the same approach, inter-fraction variations between CT and 2D cine-MRI are estimated. The CT is then deformed according to estimated 3D vector fields, producing the time-resolved 3D representation of

breathing motion. The resulting motion is compared to that depicted in the 4DCT, as quantified on tumor center of mass.

Results and Conclusion

Inter-fraction variations resulted in a median (IQR) tumor displacement of 2.07 (2.13) mm, compatible with the considered 3 mm setup uncertainty. Median displacement at end-exhale was ≤1.60 mm, confirming the suitability of gated dose delivery. However, for 6 out of 9 patients >50% of estimated residual motion within the gating window was larger than that in the 4DCT and for 2 patients the median motion was >5 mm, i.e. larger than clinically applied tumor margins. Model estimations described cycle-to-cycle breathing variability: end-exhale to end-inhale median motion was in the range 1.46-11.15 mm, vs. 1.83-6.88 mm in the 4DCT.

2D cine-MRI combined with motion modeling can provide a time-resolved 3D description of breathing motion, allowing geometric and, in a future work, dosimetric evaluations of treatment robustness.

S12.01 ID 152

The ARTEMIS- Project Heidelberg

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Therapy with ion beams (protons and carbon ions) is very well established for the treatment of numerous tumors, for example at the base of the skull. The advantage is that high radiation doses can be deposited very specifically in the tumor with ion beams by exploiting the Bragg-Peak of charged particles in matter. However, this requires precise treatment planning which is able to model the properties of the ion beams and the tissue. However, it has been shown in many situations that during the course of the therapy these models no longer describe the patient's anatomical situation with the desired precision at the day of treatment, forfeiting the inherent advantages of ion beam therapy. Therefore, it is necessary to improve the imaging of the patient before and during the ion beam treatment to fully exploit the potential of this beam modality. In contrast to photon-based radiotherapy, MR guidance with an integrated device is not yet established for ion beam therapy.

The aim of ARTEMIS project in Heidelberg is the development of adaptive radiotherapy for ion beams which uses computed tomographic (CT) and for the first time also magnetic resonance (MR) tomographic data during the entire course of the therapy. Towards this goal, a demonstrator system will be created that will be evaluated in experimental and clinical settings. Specifically, the planned device configuration shall be retrofitted in a conventional radiation room. For this purpose, an adapter will be developed that allows patients to be positioned freely and reproducibly in front of a horizontal treatment beam and making a gantry obsolete. By this design concept therapy with protons and ions would also be cheaper in the future, which contributes significantly to the further spread of this treatment modality.

S12.02 ID 24

Magnetic shielding factor for artefact-free in-beam MR imaging during proton pencil beam irradiation

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Introduction

First measurements with a research prototype system for in-beam MR imaging during proton pencil beam scanning (PBS) have shown that the dynamic magnetic fringe fields of the nearby PBS magnets interfere with the static MRI (B_0 =0.22 T) field, causing image ghosting artefacts [1]. Passive magnetic shielding is a possible means of eliminating the artefacts by decoupling the MR and PBS magnetic fields. The aim of this study was to determine the shielding factor required for artefact-free MR imaging during PBS dose delivery.

Materials and Methods

The change in B_0 magnitude (ΔB_0) due to the PBS fringe field was measured with a magnetic field camera positioned in the MR isocenter both as function of (1) the radiation field size [range 4−40 cm] and

(2) the distance between the MR isocenter and the PBS isocenter [range 0.3−2.3 m]. Furthermore, images of the ACR Small Phantom were acquired during dose delivery for (1) and (2), and the percent signal ghosting ratio (PSGR) was assessed to determine the maximum ΔB_0 for which the ACR action criterion of ≤0.025 was met.

Results

The magnetic field camera measurements showed that the maximum ΔB_0 was 5.66 µT in the worst-case scenario of the minimum distance between MRI and PBS isocenter (0.3 m) and maximum scanning field size (40 cm). For this scenario, the PSGR test passed at a field size of 1.2 cm. Here, the maximum ΔB_0 was 0.27 µT. The PSGR test was only passed for field sizes of 4 and 12 cm at distances of 1.3 m and 2.3 m between PBS and MR isocenter, respectively. In both cases, the maximum ΔB_0 was 0.28 µT. Hence, a minimum shielding factor of 5.66 µT/0.28 µT = 20.22 would be required for artefact-free MR imaging during PBS dose delivery.

Conclusion

The magnetic shielding factor required for artefact-free MR imaging during PBS dose delivery was experimentally determined for the in-beam MR imaging research prototype system.

References

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TOPIC QA / QA & WORKFLOWS

S07.02 ID 128

Online-QA in the adaptive process with the Elekta Unity MR Linac

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In room MR image guidance (MRgRT) enables the online adaptation of treatment plans based on the current patient anatomy while the patient is on the treatment couch. The Elekta Unity system combines a 1.5T MR scanner with a 7MV FFF linear accelerator. The general adaptive process on the Unity system comprises the acquisition of a session MR image, plan adaption based on the acquired image, and the possibility to monitor the internal anatomy during treatment delivery using 2D cine images. The complete workflow takes on average between 20 and 60 minutes depending on the indication and the online plan adaptation method.

Online adaptive MRgRT therefore compresses the timespan of a typical Radiotherapy pathway including imaging, delineation, plan generation, and verification from weeks to minutes. This acceleration and the incapability to perform traditional pre-treatment plan verification for the adaptive treatment plans introduces new challenges to the multi-disciplinary staff group of radiographers, medical physicists, and clinicians.

Within this presentation, the methods developed to address those challenges for a typical online adaptive MR guided treatment on the Elekta Unity system will be discussed. This includes the use of a secondary dose calculation instead of pre-treatment measurements and the development of a series of automated plan quality indicators to ensure a safe delivery of the adapted treatment plan.

Conflic of interest: ICR and RMH are a member of the Elekta MR Linac consortium.

S07.03 ID 68

Analysis of Spatial Integrity on a 0.35T MR-Linac: characterizing the influence of metallic implants

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Introduction

A safe access to MR guided radiotherapy for patients carrying metallic implants requires special precautions. Low field MR reduces the hazards associated with such implants but the geometric accuracy is compromised in the implant vicinity. This abstract aims at characterizing the 3D spatial integrity of the MR images produced by a MRIdian Linac (0.35T, 6MV) in the presence of metallic implants (active and passive).

Materials and Methods

We designed a spatial integrity phantom made of 880 control points evenly distributed over 11 parallel planes and covering a field of view (FOV) of 15x15x20cm^3. This phantom was scanned in a water tank with and without different implants (breast clip, hip joint, two models of pacemakers; all 12.5cm away from the imaging isocenter). We acquired images with the clinical sequences (FOV up to 50x44.9x43.2cm^3, resolution 1.5mm^3) at identical linac position. We implemented a program in Matlab (R2019a) to automatically detect the control points. Spatial integrity is assessed by the Euclidian distance to the theoretical point locations. Fringes from the implant artefacts were defined by 30% loss of the intensity signal (ASTM F2119 recommendations).

Results

The breast clip and the hip implant fringes did not reach the spatial integrity pattern and the maximum distortion within a 10cm radius around the isocenter was below 1mm (mean distortion 0.48mm). The two pacemakers caused fringes contaminating the image up to 17cm away from their location. Next to the fringes a spatial integrity below 2mm could be recovered 12cm away from the active devices.

Conclusions

The passive implants did not affect the spatial integrity analysis beyond 5cm from their location while the pacemakers caused pronounced distortions. An acceptable spatial integrity can be recovered 12cm away from the active devices while a distance of 20cm is needed to avoid fringes

S07.04 ID 42

MATLAB-scripted QA workflows for MR in RT, via Access-i-based remote control on MAGNETOM MR scanners

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Objectives

Quality assurance workflows provided by MR manufacturers (on the system) or by phantom vendors (in the cloud) are typically standardized and not freely configurable by the RT physicist. The aim of this study is to provide a flexible environment to realize arbitrary QA measurement workflows, with the ability to react on results, the processing of data, and its documentation.

Materials and Methods

MAGNETOM Sola and Vida scanners (Siemens Healthcare, Erlangen, Germany) running software syngo MR XA20A were equipped with the dedicated scanner remote control product interface Access-i and connected to a commercial PC running MATLAB (R2018b, The Mathworks Inc., Natick, MA, USA). A MATLAB toolbox realized the communication protocol between the PC and the MAGNETOM. Dedicated commands allowed to open, start, and stop arbitrary pulse sequences, to adopt their measurement parameters, and to retrieve previously acquired MR image data in real-time in MATLAB. Evaluation of measurements, intermediate decision steps, data processing, and result documentation were realized via prototypical MATLAB scripts.

Results and Conclusions

Sample QA checks were realized using the ACR phantom, at 1.5T and 3T, with a variety of RF-coils. The function of individual RF coil elements was verified with a noise-covariance test measurement. Slice thickness for 2D scanning was tested according to the MR performance standard IEC 62464-1. Image intensity uniformity and low-contrast object detectability were analyzed according to the ACR phantom test guideline. Geometric accuracy was assessed with the ACR phantom grid and evaluated according to the NEMA MS-12 standard on mapping of geometric distortions in MR.

Basic MATLAB knowledge and a working understanding of MR performance standards is the only prerequisite for realizing arbitrary and automatized QA workflows for MR in RT, when running on MAGNETOM systems equipped with Access-i.

R07.01 ID 22

Use of treatment plan complexity analysis as a QA tool in MR-guided online adaptive radiotherapy

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Objectives

To evaluate the feasibility of identifying inadequate treatment plans in MRgART prior to irradiation using a newly introduced metric related to deliverability.

Materials and Methods

So far, 113 online adapted treatment plans were compared to their corresponding baseline plans, which were used as a starting point for online re-optimization. A new metric was calculated, called small field opening monitor unit ratio (SFOR). SFOR = MU_{SFO} / MU_{FO} is the ratio of the number of monitor units (MU) assigned to small (area < 0.65 cm^2) field openings (MU_{SFO}) and the number of MU assigned to all

field openings (MU_{FO}), where a field opening is an unshielded field of the MLC, which is not connected to other open fields of the same MLC segment. All plans of patients with at least one outlier plan, identified using the SFOR distribution with outliers defined via an interquartile range of 1.5, were measured with a diode array (ArcCheck-MR; Sun Nuclear Corporation, USA) and gamma passing rates (2%, 2 mm) were compared between outlier and non-outlier plans. Statistical analysis of differences of gamma passing rates was performed via Wilcoxon rank-sum test. A significance level of $\alpha = 5\%$ was used.

Results

10 outliers in 3 patients were detected. Patient 14 showed 6 non-outlier and 8 outlier fractions, while patients 2 and 9 showed 1 non- outlier and 1 outlier fraction each. Mean gamma passing rates of outlier and non-outlier plans of patient 14 were 95.4% ± 0.9% and 97.2% ± 1.1%, respectively, while gamma passing rates of patients 2 and 9 were 64.6% and 91.1%, and 91.3% and 95.6%, respectively. Gamma passing rates of patient 14 differed significantly with $p = 0.028$.

Conclusion

Some plans showed an unusual increase in SFOR. Gamma passing rates of these outlier plans differed significantly from the non-outlier plans. Overall, the change in SFOR may be used as an additional quality assurance tool for the fast evaluation of adapted treatment plans in an MRgART setting.

R07.02 ID 58

Measurement of isocenter accuracy and image distortion in MRgRT

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Purpose

Measurement of (i) imaging and radiation isocenter alignment and (ii) the quantification of image distortion are key elements of QA in MRgRT. Here, we present a new phantom for measuring both in a single measurement.

Materials and Methods

The phantom contains a spherical PAGAT polymer gel (PPG)-filled glass flask embedded in 8 grid sheets building up a 3D grid of 1330 control points. To measure the alignment of the irradiation and imaging isocenter, the phantom was irradiated with 5 equidistantly distributed beams at a clinical MR-Linac (MRIdian, ViewRay) and was scanned immediately after irradiation at the MR-Linac using a single-contrast turbo spin-echo sequence (TSE) with a turbo factor of 15. An isotropic resolution of 1mm3 was selected. To increase the signal to noise ratio (SNR) a number of signal averages of 32 was used. To identify geometric distortions of the clinically used MR sequence (balanced steady-state free precession (bSSFP) and the TSE) of the MR-Linac, the individual control points of the grid were compared to CT-measurements as ground truth. The automatic determination of the control points was performed using the Weka segmentation (Image J, NIH). All MR measurements were performed at a gantry angle of 0°.

Results

The Euclidian distance of the imaging and irradiation isocenter was found to be 0.8±0.9 mm. Measurements of the grids of the QA- phantom revealed distortions below 1.5 mm (mean over all control points 0.6±0.3 mm) up to a distance of 150 mm from the isocenter.

Conclusions

A phantom was developed to simultaneously investigate both the irradiation and isocenter alignment and geometric distortions of an MR- Linac. A PPG in combination with a TSE was used to acquire isotropic 3D images with sufficient high SNR immediately after irradiation and the isocenter distance was found to be comparable to the alignment accuracy at conventional Linacs.

R07.03 ID 89

Treatment planning and quality control of an MRI only workflow for H&N patients using CNN based sCT

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Objectives

Assess the dosimetric uncertainty associated with synthetic CT (sCT) data and quality control (QC) of an MRI only head and neck (H&N) workflow.

Materials and Methods

The dosimetric accuracy of the sCT data was evaluated for 44 H&N cancer patients. Clinical treatment plans generated using CT data were recalculated on sCT data. The sCT was generated using a deep convolutional neural network (CNN) based transfer function estimation (TFE) algorithm (pre-release of MRI Planner v.2.2, Spectronic Medical). Differences in relative absorbed dose and paired statistical tests of equivalence were evaluated for dose volume histogram (DVH) parameters. The absorbed dose distributions were compared using 3D gamma evaluation (2%/1mm). Anonymized MRI data of a previously treated patient (test patient) went through clinical treatment planning; from delineation in MRI data to pre-treatment QC using the electric portal imaging device (EPID), simulating an MRI only workflow.

Results and Conclusion

The maximum mean deviation in absorbed dose for all evaluated DVH parameters was 0.30% (0.12 Gy). The absorbed dose distributions for CT and sCT data were considered equivalent (p-value <0.001) and the mean gamma passing rate was 99.4% (range: 95.7-99.9%). The volumetric difference (sCT-CT) between test and original RT structures was -28.7-18.6 cm^3 , the maximum difference was found for PTVN (prescribed dose to lymph nodes). The test data passed the pre-treatment QC for both treatment plan beams with gamma pass rate (4.0%/1mm) of 100% and 99.8% for the EPID measurement. In the treatment planning system, optimization structures could not be added directly in the MRI data due to the lack of HUs and was therefore added in the sCT data.

The use of sCT data resulted in accurate absorbed dose calculations and were considered statistically equivalent compared to CT data-based radiotherapy. The MRI only workflow simulation with a created test patient was successful.

R07.04 ID 26

Multi-slice setup and automated data analysis for ViewRay MRIdian Linac receive coil QA

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Introduction

For ViewRay MRIdian Linac receive coil QA, the manufacturer suggests placing a 24cm diameter spherical phantom at 3 successive positions in an acrylic tube surrounded by the coils. A single slice spin echo sequence assesses whole coil SNR and uniformity and individual coil element SNR. However, sphere positioning in the tube is precarious and time-consuming. Manual ROI selection is tedious and subjective, especially for maximum signal areas of individual elements. We aimed to perform coil QA considering manufacturer recommendations but with a single setup and an objective automated data analysis method.

Materials and Methods

A commercial fluid-filled cylindrical phantom (14cm diameter, 43cm length) was centered in the acrylic tube, supported by plastic boxes. Eighteen 10mm-thick axial slices of the suggested sequence with 100% slice gap to avoid cross-talk were acquired with and without prescan normalization using combined coil elements, and without filter for individual elements. Custom MATLAB scripts identified noise and signal images, defined ROIs of 0.9*phantom diameter and detected their extrema, yielding SNR and uniformity for each combined element slice. SNR of individual elements was calculated using the signal in a circle of 5 pixels radius around the maximum of a smoothed individual element image. The procedure was repeated as monthly coil QA over a year.

Results and Conclusion

The proposed stable configuration reduced mean setup time from 51.0 to 15.5min and enabled large multi-slice coverage. The developed software allowed for objective, automated ROI selection. All SNR and image uniformity results were obtained in few minutes. SNR varied while uniformity was independent of slice location for combined coil images. Slices with maximum signal for a coil element indicated its spatial location. New pass/fail criteria defined by tracking SNR and uniformity over time helped identify instances of malfunctioning coil elements and increased image noise.

R07.05 ID 2

IPEM Guidance on the use of MRI for external beam radiotherapy treatment planning

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The role of MR to guide radiotherapy (RT) treatment planning is growing. The literature shows significant heterogeneity in the way that MR for RT is implemented and there is some evidence that this is, in part, due to a lack of consensus in the literature and guidance from professional bodies [1]. To combat this, The Institute of Physics and Engineering in Medicine (IPEM) commissioned a working party to produce a guidance document on the use of MR for RT treatment planning. The multi-disciplinary party consists of 10 members and first met in February 2018. The guidance is based on the experience of the institutions represented in the IPEM working party, in consultation with other institutions, as well as information taken from the literature. It has multi-disciplinary endorsement from the professional bodies IPEM, Royal College of Radiologists (RCR) and the Society of Radiographer (SoR).

In this presentation we will give an update on the guidance document, which has been submitted for peer review, and discuss its key points. Guidance is only given for MRI acquired for external beam RT treatment planning in a CT-based workflow, i.e. when MRI is acquired and registered to CT with the purpose of aiding delineation of target or organ at risk volumes. The guidelines are designed to be a practical document which

can benefit all involved disciplines and give advice on introducing an RT workload onto a non-RT-dedicated MR scanner, as well as planning for installation of an MR scanner dedicated for RT (referred to as an MR-sim). Next, practical guidance is given on the following, in the context of RT planning: safety; training and education for all staff working in and around an MR scanner; RT patient set-up on an MR scanner; MRI sequence optimisation for RT purposes; commissioning and quality assurance (QA) to be performed on an MR scanner; and MRI to CT registration, including commissioning and QA.

[1] - Speight et al. PMB, 64 (2019), https://doi.org/10.1088/1175021. 361-6560

TOPIC RADIOMICS / DATA SCIENCE

Highlight Talk ID 146

Machine Learning: What is achievable and what is the benefit for RO?

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Introduction

Machine learning (ML) is an evolving branch of computer science which is based on algorithms addressed to emulate human intelligence by learning from the surrounding environment. Arthur Samuel in his seminal work defined ML as “a field of study that gives computers the ability to learn without being explicitly programmed”. In a classical view within the framework of artificial intelligence techniques, ML is considered a subset of application including also the newer deep learning. ML is considered the working horse in the new era of the so- called big data. Radiation oncology, like many fields in medical sciences, has being dramatically changed in last two decades, because of the progressive introduction and use of information technology and its applications in clinical and operational workflows. In this lecture the role of ML and its contribution to the improvement of modern radiotherapy will be analyzed.

Material and Methods

A list of publications in the topic of ML in RO has been reviewed. The purpose is to provide a list of trend topics and the most important achievements got in last years by using ML techniques. Publications containing clinically relevant outcomes have been privileged.

Results and Conclusions

Several points have been found of relevant interest:

1. ML for computer-aided detection of lesions in diagnostic images and their classification.
2. Treatment planning (IGRT and knowledge-based planning)
3. ML for delivery and motion management
4. QA
5. Outcomes modeling

A series of relevant examples will be provided in the lecture.

S05.01 ID 121

Scalable Deep Learning in Medical Imaging

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Despite its vast potential, the actual practice-changing clinical impact of deep learning has so far been rather modest. Why is that? The talk will cover several major challenges that I consider essential in unlocking the full potential of machine learning in radiology, and I will present current examples of our ongoing research that addresses them.

S05.02 ID 43

Investigation of delta radiomics during fractionated SBRT in patients treated for liver metastases

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Objective

MR guided radiotherapy offers a unique opportunity to track changes of the macroscopic tumor in the MR images over the course of therapy. In this study, we investigate the feasibility of analyzing delta radiomics of liver metastases on images acquired with a 0.35 T scanner during online adaptive fractionated SBRT.

Methods

The MR scans of 35 patients with liver metastases treated at the ViewRay MR-Linac were analyzed with an in-house developed radiomic software. Plans with multiple PTVs were excluded. We exported the GTV contours, the simulation scans, two before the application of the first fraction and one at each of the following. We defined σ1 as the inter-day fluctuation of the radiomic features (simulation to first fraction). σ2 as the intra-day fluctuation (two scans at first fraction). For each of the 1395 radiomic features, a unique pair of σi was calculated over the full cohort. We defined a metric proportional to the number of daily scans in which a feature exceeded by more than $C=1.96\cdot\sqrt{(\sigma1^2+\sigma2^2)}$ its baseline (average between simulation and first fraction). [1]

Results

We used the metric to select the radiomic features with the most significant deviation beyond C. The Pearson correlation between the relative delta of the top fifty features and the relative GTV volume change was r = 0.14 [0 – 0.49] (mean [range]). The GTV volume changes with respect to the simulation were limited to +1% [-11.1% - +9.1%] (mean [5th – 95th percentile]). Accounting for inter-features correlation, 16 of those were shown to provide independent information (r < 0.01). In a trend analysis, we have observed heterogenous feature-response and identified sub-sets of patients showing larger delta radiomics signal.

Conclusion

The low correlation of delta radiomics with the change in GTV volume indicates the potential to extract early response information during the course of therapy using low field MR scans. These results are in-line with previously published data in rectal cancer patients [2]. The heterogenous feature-response among the patients will be further exploited as a potential prognostic biomarker.

S05.03 ID 38

Deep learning based classification for standardization of prostate cancer RT structure annotations

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Purpose

Radiotherapy datasets can suffer from variations in annotation of organ at risk (OAR) and target structures. Annotation standards exist, but their description for prostate targets is limited. For example, it is not defined whether prostate gland, vesicles and/or lymph nodes exist together in the same or separate target structures. This restrict the use of such data for machine learning as data must be correctly annotated. The purpose of this work was to develop a modality independent deep learning-based algorithm to automatically classify structure annotations in DICOM RT structure data.

Methods

The prostate OAR, support- and GTV/CTV/PTV target structures (delineated with and without vesicles and/or lymph nodes) from 1854 patients were extracted from CT images, verified and converted to binary structure masks. An InceptionResNetV2 2D classification network was trained in Keras using four different image input channels and a batch size of 72. Input channel 1-3 consisted of binary (i.e. image modality independent), downsampled, orthogonal 2D structure projections. The fourth channel contained a downsampled summation of every other binary patient mask. The network was trained using 10-fold cross validation. Classification performance was assessed on structure masks from independent CT and MR test datasets with 54 and 40 patients respectively, using the 10 cross validation models in majority voting.

Results

A mean training classification accuracy of 99.4% was achieved. For the CT and MR test datasets the classification sensitivity was 99.5% and 98.5%, respectively. Misclassifications in MRI data was due to existence of multiple, but unique, CTV structures.

Conclusions

Our proposed method for data cleaning and standardizing of prostate OAR and target annotations shows great promise on both independent CT and MR datasets. Existing structure annotations was automatically renamed according to a user-defined standard and the DICOM file header was updated.

S05.04 ID 63

Deep Convolutional Neural Network (DCNN) multiplane approach to pseudoCT generation from MR images

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Objectives

The objective was to develop a novel deep convolution neural network (DCNN) mulitplane method for converting MRI images into pseudoCT for proton therapy treatment planning.

Materials and Methods

The image database included 15 pairs of MRI/CT scans of the head. Three DCNNs were trained to estimate, for each voxel, the Hounsfield unit (HU) value from MRI intensities. Each DCNN gave an estimation in the axial, sagittal, and coronal plane, respectively. The median HU among the 3 values was selected to build the sCT. The sCT/CT agreement was evaluated by a mean absolute error (MAE) and mean error, computed within the head contour and on 6 different tissues. Dice similarity coefficients were calculated to assess the geometric overlap of bone and air cavities segmentations. A 3-beam proton therapy plan was simulated for each patient. Beam-by-beam range shift (RS) analysis was conducted to assess the proton stopping power estimation. RS analysis was performed using clinically accepted thresholds of (1) 3.5% ± 1 mm and (2) 2.5% ± 1.5 mm of the total range.

Results and Conclusion

DCNN multiplane statistically outperformed single-plane prediction of sCT ($P<.025$). MAE and mean error within the head were 54 ± 7 HU and -4 ± 17 HU (mean ± standard deviation), respectively. Soft tissues were very close to perfect agreement (11 ± 3 HU in terms of MAE). Segmentation of air and bone regions led to a Dice similarity coefficient of 0.92 ± 0.03 and 0.93 ± 0.02, respectively. Proton RS was always below clinical acceptance thresholds, with a relative RS error of 0.14% ± 1.11%. The multiplane DCNN approach significantly improved the sCT prediction compared with other DCNN methods presented in the literature. The method was demonstrated to be highly accurate for MRI-only proton planning purposes in the brain sector.

TOPIC YOUNG INVESTIGATOR 2020

YI01.01 ID 19

Experimental investigation of ghosting artefacts in in-beam MRI during proton pencil beam scanning

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Introduction

The integration of real-time MRI is expected to improve the targeting precision of proton therapy. We have developed a first prototype setup of an in-beam MRI scanner at a proton pencil beam scanning (PBS) beam line. The aim of this study was to investigate the effects of the dynamic magnetic fringe fields of the PBS beam steering magnets on the MR image quality during simultaneous irradiation and MR image acquisition.

Materials and Methods

A 0.22 T open MR scanner was positioned in front of the horizontal PBS research beam line. 2D planar dose spot application was achieved by magnetic beam steering in horizontal and vertical direction through a pair of fast scanning magnets.

A proton pencil beam of 220 MeV was subsequently scanned along a horizontal and vertical central line in the MR imaging field. The irradiation time matched the acquisition time of a single-slice gradient echo sequence, while imaging a homogeneous transversal slice of the ACR Small Phantom. The image quality was evaluated qualitatively and compared to reference images acquired without beam scanning.

Results and Conclusions

MR images acquired during vertical beam scanning showed no visual differences to reference images, whereas images acquired during horizontal beam scanning showed coherent ghosting artefacts in phase encoding direction. The artefacts exhibit a systematic behavior in which the number of ghosts is inversely proportional to the number of dose spots scanned. The phase maps of the k-space data prove that the artefacts are caused by phase offsets between adjacent lines, which result from changes in the MR resonance frequency due to the dynamic fringe fields of the beam scanning magnets in the PBS nozzle.

Now the origin of the ghosting artefacts is well understood, appropriate means for magnetic shielding or k-space data post-processing have to be implemented and studied to eliminate these artefacts.

YI01.02 ID 67

Experimental validation of generating 4 Hz 4D-MRI from orthogonal cine-MRI on a 0.35 T MR scanner

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Introduction

Intrafractional tumor motion in MR-guided radiotherapy is assessed with 2D cine-MRI in clinical routine. With the lack of real-time 4D-MRI with sufficient spatio-temporal resolution, prior-information-based motion models are investigated to estimate the anatomy in 4D. The purpose of this study was to experimentally validate the propagation technique (PROP) by Paganelli et al. [1] on a 0.35 T MR scanner.

Materials and Methods

Four artificial nodules (2-4 cc) were injected in an ex vivo porcine lung, mounted in a phantom that allows the simulation of periodic and reproducible breathing motion. The phantom was scanned at 0.35 T while breathing at 7 cycles/min. A respiratory-correlated 4D-MRI with

35 phases and a resolution of 3.5×3.5×5 mm3 was reconstructed from cine-MRI, serving as ground truth 4D image (GT). Four series of orthogonal cine-MRI (4 coronal & 4 sagittal slices/s; alternating acquisition; bSSFP) intersecting each nodule were acquired over ten breathing cycles. Estimated 4D-MRI (EST) at 4 Hz were created using the PROP method [1] by extrapolating the deformation fields from b- spline deformable image registration of the 3D mid-exhale image extracted from GT to the orthogonal slices. The nodule positions in GT and EST were compared.

Results

The 3D centroid motion amplitudes of the nodules ranged from 7-18 mm on GT. Averaged over all series, the mean centroid differences over ten breathing cycles was (2.1±0.5) mm (±1σ) for nodules intersected by the orthogonal slices and (2.3±0.4) mm for the remaining nodules. Smaller differences were observed for nodules at small distance to either of the orthogonal slices.

Conclusions

Experimental results confirm the in silico results obtained by Paganelli et al. The PROP method is a simple and fast method that uses standard clinical MR-Linac sequences and can estimate the 4D anatomy at high temporal resolution with sub-voxel-size accuracy.

References

[1] Paganelli et al., J Med Imaging Radiat Oncol, 62.3 (2018).

YI01.03 ID 82

Influence of beam quality on magnetic field correction factors for ionization chambers in MRgRT

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Introduction

In the past, many authors have published experimental results for magnetic field correction factors for ionization chambers. These factors are mandatory for the measurement of absorbed dose in an MR-linac setup. Often, these experiments have been carried out in setups that combine a conventional 6 MV linac with an electromagnet. This study investigates whether experimental results based on these measurements are applicable for measurements at a 7 MV Elekta Unity MR-linac.

Materials and Methods

Full accelerator head models of an Elekta 6 MV accelerator and the 7 MV Elekta Unity MR-linac, including the cryostat, were created in BEAMnrc. Both models have been benchmarked experimentally [1,2]. An egs_chamber model of a PTW30013 ionization chamber that is described in detail in [1] was used to simulate the response of the ionization chamber under the influence of a magnetic field up to 1.5 T, in steps of 0.15 T, for both beam qualities. This was done for an orientation in which the secondary electrons are deflected to the stem of the ionization chamber.

Results and Conclusion

The largest difference of the magnetic field correction factors obtained for both beam qualities was found at a magnetic induction of 1.2 T. Here the magnetic field correction factors differ by 0.31(32) %, which is within the calculated uncertainty interval. At 1.5 T, a difference of 0.19(31) % was found.

For the given orientation, the influence of the change in beam quality between a conventional Elekta 6 MV linac and a 7 MV Elekta Unity MR-linac is of minor influence for the calculation of magnetic field correction factors within an uncertainty interval of about 0.3 %.

[1] Pojtinger et al. Phys Med Biol 2019;64(13) [2] Friedel et al. Med Phys 2019;46(11)

YI01.04 ID 51

Reduction of respiratory pancreas motion using an MRI and proton therapy compatible abdominal corset

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Objectives

An MRI- and particle therapy compatible patient-individualized abdominal corset was developed and its efficacy to reduce respiratory- induced pancreas motion was evaluated by orthogonal 2D-cine and 4D-MRI.

Patients and Methods

Nine patients (6 female; average age 72.9±9.6 years) with tumors of the pancreas (7), gallbladder (1), or liver (1) provided written informed consent to be scanned on a 3T MRI scanner (Philips Healthcare) by means of orthogonal 2D-cine and 4D-MRI, without and with a patient-individualized abdominal corset, respectively. A polyethylene (PE) abdominal corset (ORD Dresden GmbH) was customized based on an optical 3D-surface scan (Artec Eva®). For MR imaging the patients were positioned supine on a flat tabletop using an anterior coil holder to avoid compression of the chest wall. For 2D-cine MRI, coronal and sagittal slices were selected to image the pancreatic head. The 4D-MRI dataset was reconstructed by retrospectively resorting a multi-slice 2D acquisition into 10 respiratory phases. Pancreas motion was determined as center-of-mass displacement in three orthogonal directions (inferior-superior (IS), anterior-posterior (AP), left-right (LR)).

Results and Conclusion

MRI revealed predominant motion in IS direction, which was reduced by 42% ($p<0.05$) in both 2D-cine (5.0±3.7 mm without corset; 3.8±1.1 mm with corset) and 4D-MRI (8.6±3.7 mm without corset; 5.0±2.4 mm with corset) through the corset which furthermore reduced the motion variability by 40% ($p<0.01$). The corset had no effect on motion in AP and LR direction. This confirms earlier results obtained with a custom-made polyurethane corset [1]. However, the homogeneous material properties of PE allow the corset to be integrated in PT without increasing range uncertainties. Pancreas motion in IS direction can be significantly reduced in patients scheduled for PT by an individualized abdominal corset.

[1] Heerkens et al, Phys Imaging Radiat Oncol 2017; 2:7–10.

YI01.05 ID 30

Free-breathing motion compensated 3D T2-weighted turbo spin-echo MRI for body imaging

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Introduction

T2-weighted turbo spin-echo (TSE) remains the workhorse for MR based tumor delineation in radiotherapy. For abdominal tumors, 4D methods are an additional requirement to account for respiratory motion. To date, these 4D methods have only been described using 2D multi-slice acquisitions1. Here we present a 3D rewound hybrid cartesian spiral acquisition (rCASPR), in which data are acquired in

free-breathing and reconstructed into a mid-position while simultaneously providing 4D motion information.

Material and Methods

K-space is sampled using a rewound version of the golden angle CASPR trajectory. rCASPR maintains advantages of non-cartesian sampling, such as robustness to motion artefacts, while also maintaining benefits of cartesian sampling, such as compatibility with TSE.

Subsequently, we perform a two-step reconstruction, where we first estimate motion fields from a low-resolution ($4mm^3$), respiratory- sorted, 4D compressed sensing reconstruction. Second, the motion fields are directly incorporated in the iterative optimization to reconstruct a high-resolution ($1.5mm^3$) mid-position using motion compensated compressed sensing[2]. CASPR reconstructions were qualitatively compared to cartesian linear (reference) sampling in two volunteers with sequence parameters: (TE=225ms, TR=1s, FOV=$350mm^3$, scan time=250s).

Results and Conclusion

The motion compensated mid-position reconstruction considerably reduced motion-induced image artefacts and improved image sharpness compared to the reference scan. Important to note is the fact that the CASPR readout did not affect the image contrast compared to the reference method. In conclusion, free-breathing 4D T2-TSE imaging with direct mid-position reconstruction is feasible. We anticipate that this method can provide a general purpose mid-position reconstruction strategy that could improve tumor contouring and simultaneous motion quantification for abdominal radiotherapy treatment planning.

[1]Stemkens 2018

[2]Batchelor 2004

TOPIC YOUNG INVESTIGATOR 2021

YI02.01 ID 54

Quantitative investigation of dose accumulation error from intra-fraction motion for prostate cancer

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EBRT is increasingly moving towards MR-guided adaptive strategies that rely on accurate and precise dose reconstruction. For anatomies subject to biological motion during energy delivery, this requires reliable image registration and dose mapping methods for a motion compensated dose accumulation (MCDA). Using a systematic dose error analysis we assessed the influence of the most dominant sources of dose error to find if and how MCDA can be performed reliably.

We simulated the delivery of an 8 Gy fraction to a prostate under motion, using a clinical RT plan. Four motion patterns were created from a finite element model (FEM) of prostate displacement, qualitatively mimicking the patients observed motion, giving a gold standard and 11 MR-images. We evaluated the difference between the absorbed dose calculation based on the known FEM deformations and the results obtained by MR-based MCDA. We quantitatively assessed the dose error for 5 DIR algorithms (optical flow with an L2L1 and L2L2 norm and EVOlution with a smooth, incompressible and adaptive regularization [1]), using direct-dose mapping (DDM) and energy/mass transfer (EMT), for 4 MR-image resolutions from 1.6x1.6x1.0 mm3 to 6.5x6.5x3.9 mm3, and 5 SNR's from 12 to 3.

All compensation strategies considerably reduce errors in the estimated delivered dose. For large-scale biological motion such as the passage of a gas bubble, the dose error decreases up to a factor of 7 and 15 within the prostate and rectal wall, respectively. Moreover, MCDA did not introduce any relevant errors when only minimal motion is present and decreased errors even for the lower resolutions and SNR's considered. Using EMT for dose mapping has the largest influence on decreasing dose estimation errors. The results show that MCDA allows exploring intra-fraction treatment adaptions after anatomical changes and provide a guideline for the specifications for MRgRT workflows.

[1] C. Zachiu et al., Phys Med Biol (DOI: 10.1088/1361-6560/abad7d), 2020.

YI02.02 ID 32

Reduced white matter diffusion in glioblastoma patients after radiotherapy with photons and protons

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Introduction

Radio(chemo)therapy is standard in the (adjuvant) treatment of glioblastoma. Inevitably, brain tissue surrounding the tumor bed or residual tumor is also irradiated, which may lead to acute and late side-effects. Diffusion-weighted imaging (DWI) with magnetic resonance imaging (MRI) has been shown to be a sensitive method to detect early changes in the cerebral white matter after radiation. The aim of this work was to assess possible changes in the mean diffusivity (MD) of the white matter after radio(chemo)therapy using DWI and to compare these effects between patients treated with proton and photon irradiation.

Patients and Methods

70 patients diagnosed with glioblastoma underwent adjuvant radio(chemo)therapy with protons (n=20) or photons (n=50). MRI follow-up examinations were performed at three-monthly intervals and were evaluated until 33 months after the end of therapy. For all time points, MD maps were calculated and normal appearing white matter was segmented in T1-weighted MR images. Relative white matter MD changes between baseline and all follow-up visits were calculated in different dose regions.

Results

We observed a significant decrease of MD (mean -4,0%, range -0,8 – -7,9%, $p<0.05$) in white matter in areas, in which a dose of more than 20 Gy had been applied. The MD reduction was progressing with dose and time after radio(chemo)therapy. In patients treated with photons, significant reductions in white matter in the whole brain (mean -2,3%, range -0,9 – -3,1%, $p<0.05$) were seen at all time points. In proton patients, conversely, MD did not change significantly (mean -0,5%, range 0,5 – -2,4%).

Conclusion

The results show that irradiation leads to measurable changes in white matter and that treatment with protons reduces this effect due to a lower total dose in the surrounding white matter. Further investigations are needed to assess whether those MD changes correlate with known radiation induced side-effects.

YI02.03 ID 31

Planning Target Volume margin assessment for online adaptive MR-guided dose-escalation in rectal cancer.

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Introduction

MR-guided radiotherapy (RT) allows online target definition and replanning and has the potential to scale down conventional margins significantly. This may be of particular value in future organ sparing regimens where the primary tumor will be boosted to a high dose to obtain complete remission. This study aimed to assess the gross tumor volume to planning target volume (GTV-to-PTV) margin needed to cover tumor intrafraction motion during an MR-guided dose-escalation strategy in intermediate risk rectal cancer.

Materials and Methods

Fifteen patients were included with intermediate stage rectal cancer treated with neoadjuvant short-course RT, 5x5 Gy. Treatment was performed according to an online adaptive workflow on a 1.5 T MR-linac. Per patient, 26 3D T2 weighted MRI scans were made; one reference scan preceding treatment and 5 repeat scans during each treatment fraction (typically 40 min). For this study, the GTV was delineated on each MRI scan. Target coverage margins were assessed by isotropically expanding the reference GTV until more than 99% of the voxels of the sequential GTVs were covered.

Results

At a coverage probability threshold of 90%, the margins needed to cover inter- and intrafraction GTV motion were 20 mm, and 9 mm, indicating substantial inter- and intrafraction GTV motion. Analysis based on time intervals between scans showed that smaller margins were needed to cover the GTV as time intervals became shorter, with a 5 mm margin required for 15 minutes.

Conclusion

The shorter the treatment time, the smaller the margins needed to cover for movement of the GTV during a dose-escalation strategy for intermediate risk rectal cancer. When time intervals between replanning and the end of dose delivery could be reduced to 15 minutes, a 5 mm margin would be feasible.

YI02.04 ID 65

Development of anthropomorphic phantom materials for end-to-end testing in MR-guided ion therapy

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Objective

The use of MRI for online adaptive irradiation procedures in recently proposed MR-guided ion therapy (MRgIT) poses new demands on anthropomorphic phantoms for quality assurance and end-to-end tests, since conventional phantoms used in ion therapy are typically not visible in MRI. In this work, phantom materials with individually adjustable imaging contrast in CT and MRI at (0.35, 1.5 and 3.0 T) were developed. Furthermore, the ion range of these materials was investigated by comparing stopping power ratio (SPR) measurements with predictions based on single- and dual energy CT.

Material and Methods

Ni-DTPA and potassium chloride (KCl) doped agarose gels were used to create phantom materials with individually adjustable CT value as well as T1 and T2 times (MR contrast) at 0.35, 1.5 and 3.0 T. Using a multidimensional linear fit model a set of equations was developed describing the imaging parameters as a function of the Ni-DTPA, agarose and KCl concentration and vice versa. The SPR of nine specific soft tissue samples was acquired using 12C range measurements and compared with single- and dual energy CT based predictions using a clinical HLUT and acquired rel. electron densities and eff. atomic numbers [1], respectively.

Results and Conclusion

16 equations were established describing the required concentrations of Ni-DTPA, agarose and KCl to produce a given CT value as well as T1 and T2 time at 0.35, 1.5 or 3.0 T and vice versa. Furthermore, it was found, that a SECT-based SPR prediction overestimates the measured SPR by a mean of 2.3 ± 0.4 %, while a DECT-based prediction agrees well with the measurement with a mean deviation of 0.2 ± 0.3 %.

The presented materials having anthropomorphic CT and MR contrast in the soft tissue range are well suitable to develop anthropomorphic phantoms for end-to-end testing in MRgIT, if the ion ranges are predicted using DECT-based approaches.

[1] N. Hünemohr et al. 2014, doi: 10.1088/0031-9155/59/1/83

YI02.05 ID 11

Experimental investigation of a stopping proton beam in liquid water using MR imaging

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Introduction

To date, proton therapy is hampered by the lack of reliable in-vivo real-time feedback on the beam range, profile and energy deposition. So far, no technique enables the determination of beam effects on images also showing anatomical information in 2D/3D with high temporal and spatial resolution. The aim of this study is to demonstrate the possibility of visualizing a stopping proton beam in water using MR imaging.

Materials and Methods

An open 0.22 T MR scanner was combined with a static proton research beamline to acquire MR images during simultaneous proton beam irradiation. Proton beams with an energy of 190−225 MeV and current

of 3−64 nA impinged centrally on a 20 cm PMMA range modulator and were stopped in a water-filled phantom placed inside a dedicated knee MR receiver coil. A variety of different MR pulse sequences including T1- and T2-weighted Spin Echo (SE), Turbo Spin Echo, spoiled and unspoiled T1-weighted Gradient Echo (GE), inversion recovery gradient echo (IRGE), FLASH, Scout and time-of-flight (TOF) Angio were used. For each sequence, coronal images were acquired both with and without irradiation.

Results

The unspoiled GE sequence exhibited a hyper-intense central line artefact that showed a beam energy and current dependent twist under irradiation. The spoiled GE, IRGE, FLASH, Scout and TOF Angio sequences showed hyper- or hypo-intense signatures in the images that varied with the expected range and mimicked the shape of a 2D dose profile. The intensity of the effects depends on the beam current. The beam range determined from the MR images agrees to the expected range within a few millimeters. No beam induced signal changes were observed in the SE sequences.

Conclusion

A stopping proton beam in liquid water can be visualized with MRI. The observed signatures are beam energy and range as well as beam current and dose dependent. The underlying physical principles and the transferability to non-liquid materials needs further investigation.

YI02.06 ID 35

Bulk-density and deep learning synthetic CT for single-fraction neoadjuvant PBI on an MR-linac

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Objectives

A synthetic CT (sCT) is required for daily online plan optimization on an MR-linac. Yet, limited information is available on the accuracy of dose calculations on sCT for breast radiotherapy. The aim of this work was to evaluate dosimetric accuracy of treatment plans for single-fraction neoadjuvant partial breast irradiation (NA-PBI) on a 1.5T MR-linac calculated on a) bulk-density sCT mimicking the present MR-linac workflow and b) deep learning (DL) sCT generated from MRI.

Materials and Methods

For ten breast cancer patients we created three bulk-density sCTs of increasing complexity from the radiotherapy planning-CTs, using bulk-density for: 1) body, lungs, and GTV; 2) volumes in 1), chest wall, and ipsilateral breast; 3) volumes in 2) and ribs. Also, we created a DL sCT from a 1.5T MRI (mDIXON spoiled gradient echo). Single-fraction NA-PBI treatment plans (20 Gy to PTVGTV and 15 Gy to PTVCTV) for the MR-linac were optimized on each sCT and recalculated on the reference planning-CT. The Hounsfield Units (HU) of the sCTs were compared to the HU of the planning-CT using mean absolute error (MAE) and mean error (ME) inside the body. A dosimetric evaluation was performed by assessing mean absolute dose differences (DD) and mean DD (%) in the PTVs and gamma pass rate (2%/2mm criteria) using a 10% dose threshold.

Results

For the three bulk-density sCTs and the DL sCT we obtained the following results (presented as median among all patients for bulk- density 1/2/3/DL sCT): a MAE of 106/104/104/75 HU and ME of 8/9/6/28 HU, a mean absolute DD of 1.1/0.8/0.8/0.9% in the PTVGTVand 1.3/0.9/0.9/0.9% in the PTVCTV, a mean DD of 0.8/0.0/0.0/-0.4% in the PTVGTV and 1.1/0.1/0.1/-0.1% in the PTVCTV, and gamma pass rates of 98.9/98.9/98.7/99.4%.

Conclusion

Accurate dose calculations for single-fraction NA-PBI on an MR-linac could be performed on both bulk-density sCT and DL sCT. Balancing simplicity and accuracy, bulk-density method 2 is most favorable.

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TOPIC CLINICAL

P03.01 ID 8

MR-guided stereotactic body radiotherapy of liver tumors: Initial clinical experience

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Objectives

Stereotactic body radiation therapy (SBRT) is a treatment alternative for non-resectable liver metastases or hepatocellular carcinomas (HCC). Magnetic resonance (MR) guided SBRT has a high potential of improving treatment quality, allowing for tumoricidal irradiation doses whilst sparing organs at risk. However, data on treatment outcome and especially patient acceptance is still scarce.

Materials and Methods

We performed a subgroup analysis of an ongoing prospective observational study comprising patients with liver metastases or HCC. Patients were treated with ablative MR-guided SBRT at our MRIdian Linac between January 2019 and February 2020. Local control (LC) and overall survival (OS) analysis was performed using the Kaplan-Meier method. An in-house designed patient-reported outcome questionnaire was used to measure patients' experience with the MR-Linac treatment. Toxicity was evaluated using the CTCAE 5.0.

Results

Twenty patients (with n=18 metastases; n=2 HCC) received MR-guided SBRT for in total 26 malign liver lesions. Median biologically effective dose (BED at α/β=10) was 105.0Gy (range: 67.2-112.5Gy) and median planning target volume was 57.20mL (range: 17.4-445.0mL). Median treatment time was 39.0min (range: 26.0-67.0min). At 1-year, LC was 88.1% and OS was 84.0%. Gastrointestinal toxicity grade I° occurred in 30.0% and grade II° in 5.0% of the patients with no grade III° or higher toxicity. Overall treatment experience was rated positively, with items scoring MR-Linac staff's performance and items concerning the breath hold process being among the top positively rated elements. Worst scored items were treatment duration, positioning and low temperature.

Conclusion

MR-guided SBRT of liver tumors is a well-tolerated treatment modality. Initial results are promising with excellent local control and only mildest toxicity. Prospective studies are warranted to identify which patients profit most from this new versatile technology.

P03.02 ID 9

Stereotactic MRI-guided radiation therapy for Localized prostatE cancer – the SMILE protocol

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Introduction

For patients with treatment-naïve carcinoma of the prostate, hypofractionated irradiation becomes more and more popular. Due to the low α/β value of prostate cancer, increased single dose leading to a shortened treatment period seems to be safe and feasible. However, only few data is available for ultra-hypofractionation even though magnetic resonance (MR)-guided would be ideal for that treatment regime.

Patients and Methods

The SMILE trial is a prospective multicenter phase II trial exploring the safety and feasibility of primary hypofractionated irradiation of the prostate using MR-guided, adaptive radiotherapy. The study is designed to enroll 68 patients in 3 European centers. Patients will be treated with hypofractionated radiotherapy (37.5/ 7.5 Gy) on alternate days with a maximum overall treatment duration of 14 days. Primary objective of the SMILE trial is the assessment of the safety and feasibility of the study treatment on the basis of grade ≥ 2 early genitourinary (GU) toxicity and/ or treatment-related discontinuation of the irradiation. Secondary objectives are biochemical progression- free survival (bPFS), overall survival (OS), quality of life and toxicity.

Results and Conclusion

Since the introduction of MR-guided radiotherapy in 2014, several studies report on promising results due to MR-imaging and daily adaptive planning. This prospective phase II trial aims to evaluate the role of ultra-hypofractionated radiotherapy for patients with prostate carcinoma undergoing magnetic resonance-guided radiation therapy.

P03.03 ID 12

MR-guided adaptive stereotactic radiotherapy for hepatic metastases - the MAESTRO trial

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Introduction

Stereotactic body radiotherapy (SBRT) is an established local treatment for patients with hepatic oligometastasis. In many institutions, SBRT based on an internal target volume (ITV-SBRT) is the standard technique. Liver metastases often occur close to radiosensitive organs at risk (OARs), limiting the application of sufficiently high doses needed for optimal local control. MR-guided radiotherapy (MRgRT) is expected to highly improve SBRT of critically located liver metastases by offering superior soft-tissue contrast for enhanced target identification, gated dose delivery and the potential for daily real-time adaptive treatment. We hypothesize that MRgRT can be safely applied, is non-inferior to standard, state-of-the-art ITV-SBRT and enables SBRT of critically localized hepatic metastases.

Materials and Methods

This trial will be conducted as a prospective, randomized, three-armed phase II study in 82 patients with hepatic metastases (1-3 hepatic metastases confirmed by MRI, maximum diameter of metastasis ≤ 5cm (in case of 3 metastases: sum of diameters ≤ 12cm)). If a biologically effective dose (BED) of ≥ 100 Gy is achievable with ITV-SBRT, patients will be randomized to MRgRT or ITV-SBRT. Otherwise, patients will be treated with MRgRT.

Primary endpoint is any gastrointestinal or hepatobiliary toxicity ≥ CTCAE III°. MRgRT is expected to be non-inferior to ITV-SBRT. For each technique, the rate of metastases in which a BED of ≥ 100Gy can be achieved will be assessed. Further outcomes investigated are local control, progression-free survival, overall survival, quality of life as well as morphological and functional changes in MRI.

Results and Conclusion

MRgRT is highly cost- and labor-intensive. The MAESTRO trial therefore aims to provide initial evidence for the eminent clinical benefit of MR-guided, on-table adaptive and gated SBRT for dose escalation in critically located hepatic metastases adjacent to radiosensitive OARs.

P03.04 ID 33

SABR for infra-diaphragmatic soft tissue metastases: SOFT, a phase 2 study

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Objective

he emerging evidence of survival benefit after radical treatment of patients with oligometastatic disease (OMD) increases the need for safe ablative strategies for all metastatic sites. Data on stereotactic ablative radiotherapy (SABR) of abdominal non-liver soft tissue metastases is sparse. Proximity to the bowels makes SABR of these targets a high-risk procedure. SOFT is a prospective study exploring the toxicity and efficacy of MR-guided daily adapted SABR of infra-diaphragmatic soft tissue metastases in patients with OMD.

Materials and Methods

A total of sixty-one patients will be enrolled from three Danish radiotherapy centers. Dose levels of 45 Gy/3 fractions (F), 50 Gy/5 F or 60 Gy/8 F, prescribed to the GTV encompassing isodose, are available and applied depending on the tolerance of the surrounding OAR. The treatment is delivered on an MR-Linac. Patients with OMD (< 5 metastases in max. 3 organs) and patients with oligo-progressive disease (< 3 metastases), are eligible. Primary endpoint is cumulative grade ≥ 4 SABR related toxicity (CTCAE) within 12-months. Secondary endpoints are 1-year freedom from local progression, progression free survival, overall survival, time to progression outside the radiation field, patient-reported outcome, QoL assessment (EQ-5D-5L), and all CTCAE grade 1-3.

Results and Conclusion

The SOFT study aims to evaluate the feasibility, safety and efficacy of MR-guided SABR for infra-diaphragmatic soft tissue metastases and enable the introduction of a definitive treatment option for patients with oligometastatic soft tissue metastases.

The study opened in October 2019 and we expected the study to run for two years. The recruitment has exceeded our expectations and so far, fifty-two patients have been recruited. The protocol is open for inclusion from other national and international centers.

P03.05 ID 97

Synthetic CT for 2D and 3D patient positioning in head and neck radiotherapy

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Introduction

In an MRI-only workflow, synthetic CT data (sCT) and synthetic Digital Reconstructed radiographs (sDRR) originating from the sCT data replaces CT and DRR data. The accuracy of sCT based absorbed dose calculations has been previously evaluated, however the impact on the patient positioning has not yet been thoroughly investigated and to our knowledge never in the head and neck(H&N) region. Our aim of this work was to validate the use of sCT and sDRR for patient positioning in an MRI-only H&N workflow.

Materials and Methods

Fourteen data sets from CT, MRI, CBCT, orthogonal projections and sCT (MRI Planner) in the H&N region were used. The CT was deformably pre-registered to the MRI (Elastix, MICE) to mitigate differences due to different patient positioning in the planning process.

For positioning using 3D data, the CBCT were registered to the deformed CT (dCT) and sCT in six degrees of freedom with a rigid auto-registration algorithm and a threshold of 200-1700 HU (Eclipse, Varian).

For positioning using 2D data, the deformed DRRs (dDRR) and sDRRs were retrospectively manually registered to orthogonal projections in five degrees of freedom by six blinded observers (3 physicists, 3 radiotherapy technologists), resulting in a total of168 registrations (Eclipse, Varian).

The differences in translation and rotation around frontal, sagittal and longitudinal axis were evaluated between patient positioning using dCT and sCT, or dDRR and sDRR.

Results and Conclusion

The mean difference (± 1sd) in translation for 3D patient positioning were 0.1±0.5, 0.4±0.7 and -0.7±0.7 mm, and for rotation0.3±0.5º, 0.0±0.3º and 0.0±0.4º. The maximum difference was 2.1 mm and 1.3º.

The mean difference in translation for 2D patient positioning were -0.0±0.1 mm for all axis and 0.1±0.6º and -0.1±0.5º in rotation around frontal and sagittal axis, respectively. The maximum difference was 2.5 mm and 1.8º.

The sCT and sDRR data are suitable for patient positioning at treatment of H&N tumors.

TOPIC DOSIMETRY

P02.01 ID 103

Validation of charged particle transport algorithm in magnetic field in TOPAS Monte Carlo code

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Introduction

Reference dosimetry in magnetic field using ionization chamber is a real challenge since the absorbed dose and the detector response are disturbed. Monte Carlo (MC) particle transport simulation is an asset in reference dosimetry for dose calculations and determination of correction factors. In this contribution we present a validation of the MC code TOPAS for charged particle transport in magnetic field using a special Fano cavity test.

Material and Methods

TOPAS version 3.5 was used for the MC simulations. Customized C++ extensions for TOPAS were implemented to model the Fano test setup. It includes a cavity region with 1000 times less dense medium than the surrounding wall, with electrons being created uniformly and isotropically per mass unit in the geometry. The wall thickness was adapted for the different materials and energies tested, depending on the range of the initial electron kinetic energy in the wall. Transport parameters such as DRoverR and finalRange were adapted from previous studies using Geant4[1,2], optimizing the passing rate and computation time. The Fano test was performed for water, aluminum, PMMA and graphite materials, without and with 1.5 T magnetic field strength for electrons of 1, 3, 10, 30, 100 and 300 keV.

Results

Using the investigated parameters, TOPAS passes the Fano test in all materials and energies within 0.08% in the absence of magnetic field, and within 0.18% in the presence of the magnetic field. The largest deviation from the theoretical value in presence of magnetic field is 0.18±0.40% (2 std), with 300 keV electrons in aluminum with 1.5 T magnetic field.

Conclusion

TOPAS MC code shows its capability of accurate electron particle transport in magnetic field providing a reliable tool for MC simulations in the applications of MR-Linac and MRgPT. These results support using TOPAS for the development of reference dosimetry in MRgPT.

[1]O'Brien et al 2016 Med Phys 43: 4915
[2]Simiele and DeWerd 2018 Phys Med Biol 63: 235012

P02.02 ID 85

Experimental determination of the EPOM for ionization chambers in a 1.5 T MR-Linac

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Introduction

Dosimetry in MR-Linacs is challenging due to effects of the magnetic field on secondary electrons. Due to differences in effective path lengths and gyro radii in water and air, the dose measured in air-filled ionization chambers (IC) does not reproduce the actual dose. The aim of this work was to experimentally determine the effective point of measurement (EPOM) for different ICs to correct this geometrical deviation in measured profiles.

Materials and Methods

All measurements were performed using a MR-compatible water phantom (Beam Scan MR, PTW Freiburg) in a 1.5T MR Linac (Unity, Elekta AB). To determine the reference dose deposition in water, percentage depth dose (PDD) curves as well as cross profiles (in-/crossline) were measured using a

solid-state detector (Microdiamond 60019, PTW Freiburg) along the isocenter axis and in 10cm depth, respectively. PDDs and cross profiles were measured for two different ICs (31021/31010, PTW Freiburg) with a chamber radius of r=2.4/2.75mm in parallel and perpendicular orientation with respect to the magnetic field for radiation field sizes of 5x5 and 10x10cm^2. Each measurement was repeated four times.

The EPOM for each IC and orientation was determined by the average shift (ΔX, ΔY, ΔZ) needed to reach optimal agreement between measured profiles and reference data.

Results

The measured data showed that the EPOM of both ICs in parallel orientation to the magnetic field were shifted by (ΔX, ΔY, ΔZ)= (-1.2±0.2, 0±1, 0.21±0.3)mm and (-1.4±0.2, 0.76±1.2, 0.66±0.5)mm for PTW31021 and 31010, with respect to the reference point.

In case of a perpendicular alignment of the chamber axis and the magnetic field, the EPOM was determined as (ΔX, ΔY, ΔZ)= (0.5±0.4, 0.1±0.5, 1.6±0.7)mm and (0.79±0.5, 0.1±0.6, 1.73±0.5)mm for PTW31021 and 31010, respectively.

EPOMs were experimentally determined successfully for two ICs allowing accurate measurement of profiles in a 1.5T MR-Linac in the future.

Funding: DFG,

COI: Elekta, Philips, PTW.

P02.03 ID 27

Beam model validation of the MRIdian® Linac with the THALES 3D MR SCANNER.

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Introduction

The market introduction of the MR-Linac technology improves the quality of patient care via the real time imaging of the targeted PTVs. Conventional water phantoms with ferromagnetic material becomes prohibited due to the presence of the static magnetic field of MR-Linacs. To overcome this situation LAP introduces the MR-compatible water phantom THALES 3D MR SCANNER.

Material and Method

The design of the Water Phantom has been adapted to fit with the Bore shape of the MRIDian machine. The MR-Certification of the system is granted by an external laboratory. The electro-motorization of the Water Phantom is patented. The application software is based on web-browser technology. A central database is deployed on the user sites to permit the data sharing between multiple users. The software offers guided and semi-automated measurement processes as well as dedicated analysis tools to analyze Flattening Filter Free (FFF) beams. Data collection containing crosslines, inlines, diagonals and PDDs have been carried out for different beam setting conditions, containing various field sizes, measurement depths or SSD. Additional measurements focusing on off-axis beam deliveries have been carried out to further investigate the MLC accuracy. The effects of the magnetic field on the dosimetry measurements have been investigated including a comparison involving different types of detectors.

Results and Conclusion

The agreement between the measured data and the Treatment Planning System expectations of the Viewray system is found to be outstanding. Series of gamma evaluations have been performed on the different acquired datasets. The Gamma index for typical 1%, 1mm, distance to dose (DD) and distance to agreement (DTA), exhibit a success outcome greater than 95% for various beam setting configurations. The THALES 3D MR SCANNER solution appears as a precise, reliable, fast, and user-friendly solution to perform the beam model validation of the MRIdian machine.

P02.04 ID 34

A Monte Carlo study of proton dosimetry of Farmer-type ionization chambers in magnetic fields

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MR guided proton therapy is a topic of rising interest and developments on dosimetry will be necessary for clinical application. While the electron return effect (ERE) is expected to play a minor role in proton beams [1], the chamber response needs to be modeled in detail. The aim of this work is to investigate the chamber specific correction factors for dosimetry of protons in a magnetic field.

The response of three custom built Farmer type ionization chambers with varying cavity radius of 1 (R1), 3 (R3) and 6mm (R6) in magnetic fields are investigated by means of Monte Carlo simulations using TOPAS version 3.5. To account for changes in the chamber response alone, the magnetic field was only applied in the chamber volume, neglecting its impact on the proton deflection. Accurate modeling of the geometry was achieved by using the manufacturer information and µCTs. The chambers, placed in a water phantom at a depth of z=2g/cm2, were irradiated with mono-energetic proton sources of 150, 200 and 250MeV with magnetic field strengths varying from 0 to 1.5T, perpendicular to the beam and chamber. In addition, a bent electrode of 0.2mm was simulated to investigate the impact on the response in no magnetic field. Last, the correction factor fQ was calculated for each chamber.

The f_Q for the R3 chamber diverge at most by (0.563±0.196)% from values in the literature [2], indicating the accuracy of the simulations. The f_Q shows a rise with increasing radius and a decrease for higher energies. The bend electrode and the magnetic field change the energy deposition at most by (0.389±0.323)% and (0.26±0.18)%, respectively. Only about 6% of the dose is deposited by electrons with initial energy above 100 keV. For electrons lower than 100keV, the impact of the magnetic field was shown to be minor, explaining the unchanged chamber response in a magnetic field for proton beams.

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P02.05 ID 20

Non-isocentric positioning of the ArcCHECK system for Patient Specific QA on 0.35T MR-linac

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Introduction

The MRIdian, Viewray MR-linac provides magnetic resonance-guided and adapted radiation therapy. Thanks to this new tool, digestive tumors often surrounded by high sensitive organs at risk are mostly treated on this machine. Many of these tumors are lateralized, especially for liver. Nevertheless, because of the limited size of the tunnel of the MR-linac, the centering of the target volumes on the isocenter of the machine is not always possible.

In this context, we evaluated the use of the ArcCHECK (AC) system for non-isocentric and lateralized positioning for Patient Specific QA (PSQA). The lateral shifting of the AC is needed to maximize the detection of significant and relevant levels of dose. This positioning is not standard and not recommended by the manufacturer. Consequently, it has to be investigated and validated.

Material and Methods

An algorithm included in the AC analysis software allows to deduce the beam angle at any time of the irradiation. According to the angles detected, correction factors are applied to the signal measured with the AC diodes. The main issue by shifting laterally the AC is to impact the correct detection of the beam angles and corrupt the results with non-adapted correction factors.

For different lateral AC position, clinical plans have been tested in order to successively evaluate the beam angle detected versus the planned one, the difference of correction induced, the number of diode included in the analysis and the final impact on gamma index pass rate.

Results

The difference in the beam angle detection and the impact on the angular correction remain limited in quantity and in amplitude (error <5° inducing a difference of correction <1%). The shift induces a logical and important increase of the number of diodes includes in the gamma index analysis (up to +80%). Eventually, the pass rates of the gamma index are similar or better by shifting the AC.

Conclusion

The lateral use of the AC seems to be possible without impacting the angular correction. It makes the PSQA more relevant and representative of the treatment.

TOPIC FUNCTIONAL IMAGING

P06.01 ID 28

First T1ρ mapping results on a 1.5 T MR-linac

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Introduction

T1ρ is an MRI relaxation time constant which provides contrast that differs from T1 and T2. The contrast is determined by relaxation of the magnetization while being locked by a continuous RF pulse. As an additional contrast, T1ρ could be interesting for treatment response monitoring purposes. In this study, we implemented a T1ρ sequence on a 1.5T MR-linac system. We validated the sequence in a phantom and showed the feasibility of acquiring T1ρ maps in a rectal cancer patient.

Materials and Methods

A ΔB0 and B1 insensitive spin lock sequence was implemented on a Unity MR-linac (Elekta AB, Sweden). Six images with spin-lock times of 0, 5, 10, 20, 40, and 60 ms were acquired using a TSE readout. A spin-lock amplitude of B1 = 400 Hz was used. Due to hardware restrictions, short gaps of 0.6 ms were introduced after the excitation and around the refocusing pulses, and RF pulses exceeding 10 ms were interrupted with these gaps every 10 ms. To calculate T1ρ maps, a linear model was fitted voxel-wise to the log signal amplitude of the six T1ρ images using weighted least squares. A phantom with concentrations of 0, 2, 3, and 4% w/w agar in distilled water was used for quantitative validation of the sequence. A rectal cancer patient was scanned at each fraction during radiotherapy treatment (5x5 Gy) to determine in vivo feasibility.

Results

The average T1ρ in the phantom was 55, 35, and 27 ms for the tubes with 2, 3, and 4% agar, respectively. The T1ρ maps obtained from the rectal cancer patient showed good image quality without obvious artifacts. Median T1ρ values in the tumor and mesorectum were 81 and 84 ms on the first fraction and increased to 86 and 92 ms on the last fraction.

Conclusion

We have implemented a T1ρ mapping sequence on the Unity MR-linac. Values obtained from an agar phantom agree with values reported in literature, validating our sequence. In vivo images of a rectal cancer patient were obtained and changes in values were observed during radiotherapy.

P06.02 ID 21

Development of a 3D cine-MRI acquisition technique to quantify bowel motion in cancer patients

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Purpose

Patients with locally advanced gynecological cancer are treated with external beam radiotherapy and brachytherapy. As a consequence, a part of the bowel is irradiated, yielding risk of severe bowel toxicity. The exact motion and dosimetric effects are yet uncharted territories in radiotherapy (RT). Our aim was to develop a technique based on high quality 3D MRI movies to visualize and quantify bowel motion and apply it in a cohort of gynecological cancer patients.

Methods

We developed a MRI acquisition suitable for 3D motion quantification: a balanced turbo field echo sequence (TE = 1.39ms, TR = 2.8ms), acquiring images in 3.7 seconds (dynamic) with a 2.5mm isotropic resolution, with a field-of-view of 200x200x125mm^3. During a 10 minute scan 160 dynamics were acquired. Subsequent dynamics were deformably registered using a B-spline transformation model, resulting in 159 3D deformation vector fields (DVFs) per MRI set. From the 159 DVFs the average vector

length (AVL) was calculated per voxel to generate motion maps. In order to quantify bowel motion we introduced the concept of cumulative motion volume histogram (MVH) of the bowel bag volume. We acquired MVHs from 15 gynecological patients after giving informed consent for acquiring additional MRI sequences. Finally, interpatient variation of bowel motion was analyzed using MVH parameters M2cc, M10%, M50% and M90%.

Results

The AVL motion maps result in a visualization of areas with small and large movements. Interpatient variations were obtained from the MVHs. The mean M2cc, M10%, M50% and M90% were 8.2mm (range 4.7-13.6mm), 5.2mm (range 2.7-8.2mm), 2.5mm (range 1.2-5.3 mm) and 0.6mm (range 0.4-1.3mm) respectively over all patients.

Conclusion

We have developed a method to visualize and quantify bowel motion. This 3D cine-MRI based quantification tool and the concept of MVHs can be used in further studies to determine the effect of RT on bowel motion and consequently the dose to the bowel.

P06.03 ID 36

Accelerated non-Cartesian cine MRI reconstruction on CUDA capable architectures

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Introduction
The non-uniform fast Fourier transform (NFFT) requires the interpolation of non-uniformly sampled Fourier coefficients onto a Cartesian grid. The duration of this operation increases with data size, imposing strict limitations on the amount of MR data that can be reconstructed per unit time. Radially-acquired MR data has however, favorable properties for cine imaging that would allow for accelerated acquisitions for intrafractional tumor tracking on MR-linacs. One such mean to overcome this bottleneck is to exploit the highly parallelizable capabilities of Graphics Processing Units (GPUs).

Methods

The NFFT algorithm is optimized for non-Cartesian trajectories and multi-channel reconstruction through the use of parallel execution on CUDA capable architectures. Common bottlenecks in NFFT computing such as non-local access patterns and cache inefficiency are eliminated through the use of shared memory and high-performance stencil codes. The speed and accuracy were benchmarked against comparable GPU NFFT libraries on phantom data and in-vivo data acquired on a 7T Siemens Magnetom.

Results

It was observed that our NFFT algorithm is faster in reconstructing 32 channels than comparable libraries reconstruct 1 channel while maintaining a comparable image quality. The direct sampling method presented in our NFFT algorithm shows an isotropic sampling from the non-Cartesian trajectory onto the regular grid. The reconstruction of a 32-channel, 256 x 256 golden-angle radial phantom took 1.8ms on an Nvidia RTX 2080Ti.

Conclusions

There are many approaches to implementing the NFFT algorithm on GPU architectures, but we are commonly presented with either trajectory dependence, speed deficits, or accuracy loss. Combining highly optimized code for modern CUDA architectures to form a NFFT algorithm yields a combination that promises to solve the conflict of speed vs. accuracy while maintaining the flexibility of the trajectory choice.

P06.04 ID 53

Development of a hierarchical model of abdominal configuration from golden angle radial MRI

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Introduction

Breathing, antral contraction, and slow configuration changes all contribute to motion within the abdomen. A hierarchical motion model was developed, based on isolation of these abdominal motion sources from dynamic MR samples, and used to analyze such motions.

Patients and Methods

The model assigns a multidimensional set of motion states to each spoke acquired over 20min using a golden angle stack of spokes sequence. 21 breathing motion states are extracted and used to correct projections for breathing-induced deformations. Subsequently, 21 antral contraction states are extracted through PCA of rician-filtered temporal signals in the stomach volume, and 72 slow configuration states are determined from reconstructions at every 17 seconds using reconstructions of breathing motion-corrected projections. Deformations from each motion source are interpolated to the state of each spoke for motion estimations.

The model was evaluated using 20 example scans from 9 patients. 5 patients had 2 repeated scans and 3 patients had 3 repeated scans on different days. Motion frequencies and magnitudes were analyzed for the stomach, duodenum and bowel.

Results

An average of 12.0±3.5 cycles/min was observed for breathing motion, with poor reproducibility both within as well as between scan sessions for the same patient. Antral contraction frequency averaged 3.2±0.5 cycles/min. Intra-scan variation was more stable with average frequency differences of 0.1 cycles/min, compared to 0.3 cycles/min for inter-scan variations within the same patient.

Maximum motion magnitudes were 26.1, 26.3 and 33.9 mm for stomach, duodenum and bowel respectively, with antral contraction and slow configuration movements adding 6.6, 9.1 and 11.3 mm to those from breathing.

Future work will include application of the model to better estimate delivered dose, improve contrast by motion artifact removal and track tissues of critical interest for motion management during radiotherapy.

Sponsor NIHR01EB016079

P06.05 ID 40

MRI-Measured Quantitative Oxygen Sensors

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Objective

Clinical data shows that patients with hypoxic tumors have higher relapse and lower survival rates. Available and past oxygen sensing methods require an invasive step for each measurement or are qualitative and indirect. This has prevented hypoxia-targeting therapies, like radiation dose escalation, from being implemented clinically. Silicones, which have been shown to be safe in vivo, have MR relaxation times that correlate to tissue oxygen levels.[1] We report on the translation of a suite of custom silicone sensors for clinical use. We are currently evaluating one formulation in a clinical trial.

Material and Methods

Mixtures of silicone elastomer and silicone oil were heat cured to allow for elastomer crosslinking. Sensor relaxation times were evaluated using a 3 Tesla Siemens MRI.

Results and Conclusions

Silicone sensor shape and format can be customized based on the desired application. MRI acquisition parameters were selected such that the signal from the elastomer is substantially suppressed allowing the relaxation time to be obtained with a single exponential fit. Sensor relaxation time and oxygen sensitivity are functions of sensor formulation. Sensors have also been shown to be unaffected by exposure to radiation (tested up to 100 Gy). We present a comprehensive design and analysis of silicone sensors for clinical oxygen sensing applications. The highly customizable nature of these sensors enables the specific formulation and format utilized for a given clinical application to be based on application parameters including required sensitivity, mechanical performance, and data acquisition time.

This work is supported by a Bridge Project Grant and Frontier Research Grant. JT is supported by the Image Guided Therapy Center (NIH P41EB015898). GE is supported by the Koch Institute Quinquennial Cancer Research Fellowship and the KavanaughTranslational Innovation Fellowship.

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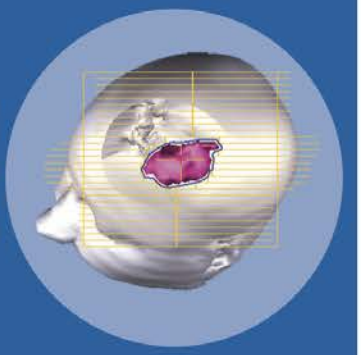

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TOPIC MR IMAGING IN RADIOTHERAPY

P04.01 ID 84

Measurement of B0 field variations with gantry position on an MR-linac system

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Introduction

Hybrid MRI-linac systems allow for concurrent radiotherapy and tumor tracking under MR guidance. Gantry rotation may however perturb the static field (B0) of the MR system which leads to artifacts and distortion in the images.

In this work, the B0 field dependency on the gantry position of a 0.35T ViewRay MRIdian system is measured, and a method for aprospective, 1st order correction is proposed.

Method

On the MRIdian, a 30cm spherical phantom was imaged. 3D B0 maps were acquired with the gantry at 12 angles, from which a linear approximation B0(x,y,z)~ax+by+cz+d was calculated [1]. From these coefficients, a linear correction could be calculated, which was used to update the shim setting of the MR system. After correction, a second B0 map was acquired for comparison.

To quantify the changes in the B0 uniformity pre and post correction, the RMSE and stdev for each B0 map was compared.

Results and Conclusions

It was observed from the B0 maps that there is a large dependency of B0 on the gantry position, with the average RMSE and stdev values over all gantry angles of the B0 map being (1.04, 0.43) µT. After correction, this was reduced to (0.04, 0.032) µT.

On the MRIdian system, prospective B0 correction is limited to 1st order only due to the shim hardware of the system. From the results, it can be seen that although the RMSE error of the mean of the B0 maps was reduced using this correction method, only a modest reduction in the mean of the stdev was observed. It is assumed that a greater improvement would occur if the correction were to be applied over a smaller ROI, as would most likely be the case in clinical practice. The next stage in this project would be to a full online implementation of this workflow.

This study shows that B0 is dependent on the gantry angle. The proposed method is able to quantify and prospectively correct for these errors, improving image quality of MR-guided tumor tracking sequences.

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P04.02 ID 57

ACR phantom comparison of coil setups for head and neck radiation therapy MRI simulation.

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Introduction

MRI for head and neck radiotherapy simulation necessitates non-standard receive coil configurations to accommodate thermoplastic masks applied during treatment, with minimal compromises in image quality compared to diagnostic coils. A novel arrangement of two UltraFlexLarge18 (UFL) coils was compared against a commercial (Qfix Insight) arrangement of two FlexLarge4 (FL4) coils relative to a standard diagnostic Head/Neck20 (HN) coil using the ACR MRI QA procedure.

Materials and Methods

The ACR large phantom was consecutively placed in the UFL, FL4 and HN coils in a 3T Siemens Vida and scanned using the ACR T1 and T2 series and three site-specific clinical sequences (T1 TSE, T2 SPAIR, STIR; TR/TE/TI: 616/9.3,4280/109, 4390/60/220 ms). Data analysis followed ACR guidelines, adding SNR estimations from slice 7. The procedure was performed as monthly coil QA for a year, yielding 10 common acceptable data points for all coil setups. For each sequence and obtained coil-dependent parameter the ratios UFL/HN and FL4/HN were formed. The resulting 20 and 30 ratio samples for the ACR and clinical sequences, respectively, were compared using a Wilcoxon rank-sum test.

Results

For the ACR sequences, high-contrast spatial resolution (HCSR), image intensity uniformity and low-contrast object detectability (LCOD) had equal medians for the UFL/HN and FL4/HN ratios, while SNR was statistically significantly higher (Z=-4.8,p=1.6E-6) and percent-signal ghosting (PSG) was lower (Z=4.5, p=6.7E-6) for FL4/HN than for UFL/HN. For the clinical sequences, HCSR showed again no statistically significant differences, but uniformity, LCOD and SNR were higher (Z=2.3, p=0.024; Z=4.3,p=1.5E-5; Z=6.6, p=3.0E-11) and ghosting was lower (Z=-2.1, p=0.038) for UFL/HN than for FL4/HN.

Conclusion

Although a commercial FL4 coil setup presented better image quality characteristics for the ACR series, the novel UFL coil setup outperformed the commercial one for clinically applied sequences.

P04.03 ID 5

Evaluating the image quality of PET-MR images acquired in the radiotherapy position

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Background

Positron Emission Tomography – Magnetic Resonance (PET-MR) scanners have great potential for improving radiotherapy with molecular PET combined with functional and anatomical MR [1]. Radiotherapy images need to be acquired in the radio therapy position. The aim of this study was to evaluate the impact of using a flat couch top and coil bridge on PET-MR image quality.

Materials and Methods

The American College of Radiologists MR and the National Electrical Manufacturer's Association PET image quality phantoms were imaged with a Signa PET-MR (GE Healthcare) in three set-ups: phantom on the PET-MR couch with anterior MR coil on it (diagnostic), phantom on a flat couch with anterior coil on it (couch), and phantom on the flat couch with anterior coil on a coilbridge (radiotherapy). Computed Tomography images of the flat couch and bridge were acquired for PET Attenuation Correction(AC).The MR images were assessed for low-contrast detectability and Signal-to-Noise Ratio (SNR). The PET images were reconstructed with and without the couch and coil bridge AC. The difference in background activity, PET SNR and contrast recovery was calculated.

Results and Conclusions

The SNR of the MR images was lower for the couch and radiotherapy set-ups, 89 ± 2% and 54 ± 1% of the diagnostic set-up respectively (mean ± sem). This resulted in fewer low-contrast objects detected, 22 ± 2 (radiotherapy) compared to 30 ± 1(couch) and 31 ± 1 (diagnostic). The radiotherapy setup resulted in a 12.3 ± 0.5% background activity loss, which reduced to 1.1± 0.8% when it was incorporated in the AC map. PET SNR was highest for the diagnostic setup, with the radiotherapy including AC map being not significantly different. There was no significant difference in PET contrast recovery between the setups. Acquiring PET-MR images in the radiotherapy position reduced PET and MR image quality. Including the radiotherapy hardware in ACimproves the PET result.

References

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P04.04 ID 41

Evidence of OAR dose reduction for anal and rectal cancer MR-only planning treatments

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Introduction

For anal and rectal cancers there is no direct evidence showing the benefit of MR-only planning to patient treatments in the literature. This study aims to assess the impact of MR-only planning on target volumes and treatment plan doses to organs at risk (OARs) for anal and rectal cancer patients when compared to a routine CT-simulation pathway.

Materials and Methods

46 patients (29 rectum and 17 anus, 24 male and 22 female) undergoing radical VMAT EBRT received CT and T2-SPACE MR simulation. For CT and MR, RT target volumes (TV) and organs were delineated and RT VMAT treatment plans were optimised following our routine clinical protocols (53.2Gy/28# for anus, 45Gy/25# for rectum) independently. The impact of dose boosting was also assessed (61.2Gy to GTV+0.5cm for anus and 55Gy to GTV+1cm for rectum). Differences in TV volume sand OAR doses in terms of Vx Gy (volume receiving x dose (Gy)) were assessed.

Results and Conclusions

GTV and primary PTV volumes reduced by 13 cc and 98 cc (anus) and 44 cc and 109 cc (rectum) respectively. The following OARs had statistically significant dose reductions vs. CT; for rectum; bladder, -5 % for V27-42.5 Gy, and uterus, -12 to -16 % for V27-42.5 Gy, and for anus; bladder, -4 % for V37.2 Gy, penile bulb, -8 to -11 % for V32-50.5 Gy, and genitalia, -4 % for V32-37.2 Gy. With GTV boosting, statistically significant dose reductions were also found for additional OARs including; sigmoid, -6 % for V45.8-52.3 Gy, small bowel, -4 % for V49.5-52.3 Gy, vagina, -14 % for V52.3 Gy, and penile bulb, -11% for V45Gy, (rectum) and vagina, -4 % for V58Gy (anus). Further OARs had dose reductions close to statistical significance for standard and boost plans.

Our findings provide evidence that MR-only planning for anal and rectal cancers results in statistically significant reductions in TV volumes and reduced doses to organs at risk. These OAR dose reductions may translate into less treatment related toxicity for patients.

P04.05 ID 88

Performance of deformable image registration for the integration of diagnostic MR images to treatment

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Introduction

In MRgRT, diagnostic MR images acquired at different field strengths and with different imaging contrasts can be included into treatment planning for an optimal delineation of the tumor and organs at risk. To be able to combine the information from those images, they have to be aligned to a single reference image acquired at the MRgRT device using rigid or deformable image registration (DIR). However, the performance of DIR algorithms highly depends on the applied sequences and therefore imaging contrasts of the diagnostic MR images. The aim of this study was to investigate the deformable image registration (DIR)performance of the Viewray MRIdian Linac system when registering images generated with different MR-devices (0.35, 1.5 and 3T) as well as different sequences.

Material and Methods

Images of two test subjects (male, 32 y and female, 25 y) were acquired at diagnostic 1.5 and 3T MR devices using a clinical TrueFISP and HASTE sequence, respectively. For the reference image, a TrueFISP sequence used in clinical routine was taken at a0.35T MRIdian Linac. Within the Viewray MRIdian treatment planning system, the images were registered to the reference image using the advanced registration mode.

Results and Conclusion

The direct DIR of the HASTE images resulted in clinically not acceptable results, while the DIR of the diagnostic TrueFISP images led to highly superior results that have been approved by a medical physicist and an experienced radiation oncologist. However, the deformation obtained during the TrueFISP registration process allowed the transformation of images acquired with other sequences such as HASTE. To enable the alignment of all diagnostic images acquired at higher field strengths, we therefore recommend the additional acquisition of a TrueFISP image with optimized sequence parameters for the registration process.

EP04.01 ID 7

MRI modality transfer using a generative adversarial network.

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Modern radiotherapy often requires multiple MRI scans of the same region with different modalities. As each modality shows a different contrast between the tissues, multiple scans achieve a better accuracy for delineating tumours and organs at risk. Unfortunately, the total examination time manifolds with the number of contrasts (modalities) and registering the sequences means extra working hours. Building on the recent achievements in Deep Learning with medical applications, this work aims to synthetically create any desired modality from a given sequence.

A generative adversarial network (GAN) based model was developed for spin echo sequences to transfer any modality to any other using the Echo and Repetition Time (TE and TR respectively) for the given protocol. The novel model architecture incorporates the signal equation for spin echo sequences, and hence the model inherently learns the unknown quantitative maps for proton density, T1 and T2 relaxation times. This grants the model the ability to reconstruct signal with any TE and TR combination.

Initial work involved training on multi-contrast datasets of paired images collected at Umeå University. The exciting results from the paired training show that any desired modality can be generated retrospectively for spin echo sequences if enough paired data is available for training. The quality of the results enticed for an expansion of the study to see if conditional GAN-based training could achieve the same results training only on unpaired data.

EP04.02 ID 73

Novel RT Planning Workflow for Breast MRI in Supine Setup

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Objectives

Supine is the preferred position for CT planning. However, diagnostic Breast MRI is typically performed in prone patient setup, which leads to mismatch and registration errors. The present work proposes a novel RT planning workflow for breast patients comprising free-breathing MRI measurements in supine position. The aim of this pilot study is to assess the workflow feasibility, which would allow future evaluation of deposited dose for free-breathing and DIBH treatments.

Methods

The study enrolled 5 female volunteers with varying breast sizes. For immobilization we used the indexed Qfix MR-Breastboard (Avondale, USA), a tabletop and a coil holder on a 1.5T scanner (MAGNETOM Sola). Both arms were positioned overhead and no external surrogates were needed for recording the respiratory phases. The 18-channel body array coil was positioned onto the volunteers without touching the volunteer. The integrated respiratory sensor in the 32-channel spine coil monitored the breathing pattern. Diagnostic T2w, T1w, T2w Tirm, DWI sequences and free-breathing 4D-self-gated MRI were used to describe OAR and breast motion.

Results

The whole patient setup took less than 5 minutes. Within 70 cm bore, an angulation of less than 30° for the arm holders lead to contact with the bore. No volunteer reported discomfort. Arms over head is the main criterion for reducing skin-coil distance for achieving high SNR. High clinical image quality was achieved for all contrasts. With large z-coverage e.g. from jugulum to liver, the axillar lymph nodes were clearly depicted. Motion of target volume and OAR i.e. heart are assessed within 7 phases supporting 4D capabilities of the planning system. We have demonstrated the first clinical Breast MRI workflow in supine treatment position which could be a perspective for lungs as well.

EP04.03 ID 80

Evaluation of B0 Susceptibility-Induced Geometric Distortion at Low-Field-Strength for MR in RT

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Objectives

Effective Radiation therapy relies on geometrically accurate images used for treatment planning. In MRI, magnetic field inhomogeneities and patient-induced B0 susceptibility, which is linearly dependent on the applied field strength[1], can lead to image distortion. This work evaluates geometric image integrity due to reduced B0 susceptibility at lower-field-strength MRI.

Materials and Methodes

Data was acquired in three volunteers (age: 66±4years, weight: 78±15kg) at 1.5T (MAGNETOM Sola, Siemens Healthcare, Erlangen, Germany) and a 0.55T prototype MRI scanner (Siemens Shenzhen Magnetic Resonance Ltd.,Shenzhen, China). At both field strengths, 3-D T2 SPACE images (voxel size = 1x1x1mm^3, FoV = 268x268x176mm^3) were acquired using high readout bandwidths, thus only minor distortions due to B0 field inhomogeneity are expected. Echo-planar diffusion-weighted imaging was performed, and all EPI parameters affecting distortion due to field inhomogeneity were matched between the two field strengths (voxel size = 1.4x1.4x4mm^3, acquisition matrix = 192x192x24, bandwidth = 766Hz/px, echo spacing = 1.53ms). Apparent diffusion coefficient (ADC) maps were calculated, and their mean distortion due to B0 field inhomogeneity compared to the T2 SPACE reference was assessed by non-rigid registration. B0 field maps were acquired, and we report mean maximal and minimal off-resonance values. The measurements at the two field strengths were performed directly one after another, with the same B0 shim settings.

Results and Conclusion

Smaller overall B0 field map variance was observed at 0.55T (min: -18±10Hz; max: 27±4Hz) compared to 1.5T (min: -40±8Hz; max: 56.3±9Hz) in an axial slice covering the optic nerve. In the same slice, mean ADC map distortion was 1.8±0.3mm at 0.55T and 4.6±0.3mm at 1.5T. Thus, imaging with less distortion due to B0 susceptibility is achievable at 0.55T compared to higher field strengths.

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Dosimetric impact of MR-CT registration inaccuracies in MR-based radiotherapy for brain

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Introduction

MR-CT registration inaccuracy typically is not considered in the determination of the CTV-PTV margin in MR-based radiotherapy (RT). For brain stereotactic RT (SRT), registration accuracy is most critical due to a small CTV-PTV margin (1-2 mm) and steep dose-gradients. Registration inaccuracies can originate from MR acquisition setup (treatment vs. diagnostic position) and registration method. An inadequate method or setup could degrade registration accuracy and sequentially treatment accuracy.

Materials and Methods

12 brain patients were measured at the 1.5T (Magnetom Sola, Siemens Healthineers) in both RT and diagnostic setup. Each patient received either intracranial SRT or conventional RT. The MR-images (T1w MPRAGE, 1 mm isotropic) were registered automatically to the planning CT (1x1x1mm3) using 3 different treatment planning systems (TPS). The clinical registration based on one of the systems including manual adjustments was used as ground truth. DVHs for PTV and brainstem for all registration methods and MR-acquisition setups were compared. Either $V_{80\%}$/$V_{95\%}$ were used as DVH metrics for PTV based on the prescription and D_{max} was used for brainstem.

Results

For 4 SRT patients prescribed to 80% isodose, the mean $V_{80\%}$(PTV) for automatic registrations across all TPS was between 84%-96% (clinical mean $V_{80\%}$=99.8%) and D_{max}(brainstem) deviated between -43%-9%. For 4 SRT patients prescribed to 95% isodose, mean $V_{95\%}$(PTV) varied between 79%-91% (clinical mean $V_{95\%}$=97.2%), with D_{max}(brainstem) deviation ranging between-20%-16%. Meanwhile, for 6 conventional RT patients, the mean $V_{95\%}$(PTV) varied between 85%-94%, with D_{max}(brainstem)deviating between -20%-40%. The various registration methods influenced the DVH significantly ($p<0.05$).

Conclusion

Registration inaccuracy due to an inadequate registration method can degrade the dosimetric accuracy in brain RT. Further dosimetric evaluation including the impact of different MR acquisition setups is ongoing

TOPIC MR GUIDED RADIOTHERAPY & TREATMENT PLANNING

P05.01 ID 113

Evaluation of Dosimetric Benefits of MR Guided Adaptive RT

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Objectives

To evaluate dosimetric benefits of on-line MR guided Adaptive RT (MRgART)

Patient and Methods

The adaptive workflow begins with a baseline plan on sim-MR image. For each treatment fraction, daily MR is acquired, fused with sim-MR, and the baseline plan recalculated. If OARs exceed dose tolerance, the treatment plan is re-optimized, validated and delivered (adaptive RT); else treatment proceeds unchanged (non-adaptive). Based on a retrospective review of 50 treatment fractions (PTV Rx: 40Gy/5 fractions), we evaluated inter-fractional position changes via OAR center-of-mass (COM) shifts and overlap indices (OI). To assess need for MRgART, three treatment plans were developed; P1: baseline plan on sim-MR (ignoring any anatomical change for the treatment course), P2: baseline plan computed on daily anatomy but not adapted; and P3: plan fully adapted for daily anatomy for each treatment. Average OAR doses (Dmean, Dmax) were compared via student t-test for stomach, duodenum, and both bowels (SB & LB).

Results

Significant positional changes in OARs near pancreas may occur due to respiration, cardiac motion and peristalsis. On daily MR, COM shifts for stomach, duodenum, SB & LB were, [mean (s.d.)] = 14(9), 5(3), 21(23) & 37(29) mm respectively. The corresponding OI were 0.83(0.09), 0.75(0.03), 0.55(0.21), & 0.67(0.25) respectively. If unaccounted, these shifts (P2 vs. P1) would have led to unacceptable increases in OAR doses with average % increase in (Dmean, Dmax) for stomach (24.8%, 13.2%), duodenum (12%, 17.9%), SB (37.4%, 7.7%), and LB (39.1%, 8.3%) ($p < 0.01$). With adaptive RT planning (P3), we were able to reduce all OAR doses below threshold. In our patient cohort, adapted treatment fractions were associated with large inter-fractional changes in OARs with both bowels showing the greatest variation based on COM shifts and OI.

Conclusion

MRgART for pancreas patients is effective in mitigating dose impact of daily anatomical changes.

P05.02 ID 70

Interfraction motion assessment of upper GI organs during MR-guided ablative SBRT treatment

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Objectives

Accurate assessment of inter-fraction motion of GI organs is essential to limit the doses to organs at risk. We quantified the interfraction deformations of upper GI organs in T2w MRI for locally advanced pancreatic cancer (LAPC) patients undergoing MR-guided ablative SBRT on Elekta Unity MR-linac using an in-house Large Deformation Diffeomorphic Metric Mapping(LDDMM) deformable registration framework.

Materials/Methods

Five LAPC patients underwent 5 fraction SBRT treatment to 50Gy using a pneumatic compression belt. The pneumatic pressure level was set in consultation with the patient to minimize GTV and adjacent

organ motion within 5mm. Daily online plan adaptation was performed using Elekta's Adapt-to-shape workflow using a T2w MR scan (TR/TE=1300/87ms, voxel size=1x1x2mm^3, FOV=450x450x125mm^3). Patients were asked to be NPO for 4 hours prior to treatment. Interfraction deformations were quantified for each direction (Left-Right [LR], Anterior-Posterior [AP], Superior-Inferior [SI]) using gradient magnitude of the Deformation Vector Fields (DVF) calculated from LDDMM between pre-treatment MRIs. The DVFs were fit to a B-spline to provide elasticity to the converging/diverging vectors resulting from large organ deformations. Registrations were assessed using Dice and Hausdorff distance (HD) calculated between the deformed and physician's contours.

Results

Average Dice and HD were: Stomach (0.95, 0.09mm), small bowel (0.82, 1.84mm), and large bowel (0.87, 0.61mm). Population average ranges (mean±SD) of interfraction deformation (mm) were: Stomach: LR=0-12.9 (2.5±0.7), AP=0-14.9 (3.0±1.3), SI=0-13.1 (3.5±2.1); Small and Large bowels: LR=0-21.8 (4.4±0.2), AP=0-22.5 (4.8±1.0), SI=0-22.1 (4.7±1.4) and LR=0-21.0 (4.7±1.7), AP=0-22.4 (5.0±1.0), SI=0-18.6 (4.4±0.9).

Conclusion

Our LDDMM registration was able to account for large deformations of upper GI organs greater than 2cm. The next step will be to apply the DVFs to estimate cumulative delivered doses.

P05.03 ID 23

MRgRT workflow development and recommendations for H&N treatment using the Elekta Unity MR-linac

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Introduction

The high-field Elekta Unity MR-linac (MRL) offers potential for MRgRT for head and neck (H&N) cancer patients. The integration of a diagnostic MR scanner, with exquisite soft-tissue contrast and functional imaging capabilities, with a RT treatment unit should enable more personalised treatment making H&N an ideal indication for treatment on the MRL. The MRL has two modes of operation. In Adapt-to-position (ATP) the field apertures of a reference plan are adapted according to the registration between the reference and daily images. In Adapt-to-shape (ATS) the reference image regions of interest (ROIs) are propagated tot he daily image on which a new plan is optimised. In this study we investigate the applicability of different treatment workflows for MRgRT for H&N cancer on the MRL and provide recommendations for use.

Materials and Methods

Patient alignment offsets of 1, 3, and 4mm in all directions were simulated in order to assess ATP dose recovery. Due to the time constraints of online treatment delivery, a simplified ATS workflow (ATS-lite) was investigated whereby all ROIs were rigidly propagated from the reference to daily image for optimisation. For the ATP and ATS-lite generated plans the PTV D95 and D98 (required to be >95% and >93% prescribed dose, respectively) and CTV D98 (>95% of prescribed dose) was assessed.

Results and Conclusion

ATP-generated plans were not able to reliably recover acceptable target coverage. For all simulated shifts the elective PTV D95 and D98 were 93% and 91% of prescription dose respectively with none of the ATP plans achieving required elective PTV dose. The average primary CTV D98 was 94% of prescribed dose with none of the ATP simulations achieving > 95%.For ATS-lite all plans achieved the required target coverage for both the primary and elective target volumes. In order to generate clinically acceptable H&N treatment plans for the MRL in a tolerable timeframe we recommend the novel ATS-lite workflow.

P05.04 ID 102

Respiratory motion mitigation using visual biofeedback on the Unity MR-linac

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Introduction

Intra-fractional tumor motion induced by respiration is a major source of uncertainty in thoracic and abdominal SBRT. The MR-linac has the potential to monitor the target position in real-time and gate the treatment delivery when motion exceeds pre-defined thresholds. However, this can lengthen the treatment significantly. In this study we investigate how visual biofeedback of the target location can guide the subject in assuming a respiratory pattern which could improve the treatment outcome.

Materials and Methods

Five healthy volunteers were scanned on a 1.5 T Unity MR-linac (Elekta AB, Stockholm, Sweden), wearing prism glasses to see an MR-compatible monitor mounted at the cranial bore opening. Sagittal 2D cine-MRI (T1-GRE, 4Hz, 2.5x2.5x10mm^3) was acquired continuously and deformably registered [1] to an end-exhale reference. The average shift of a 5cm ROI at the diaphragm was extracted. First, no biofeedback was provided. Second, the diaphragmatic motion was displayed as a rolling graph, and overlaid with an artificial end-exhale gating window of 5mm or 10mm. The subjects were instructed to stay within this window. Third, the window was set to encompass the full free-breathing motion envelope and then shifted 10mm up/down to simulate baseline motion. The latency was measured, the gating efficiency and residual motion (SD) were quantified, and the ability to accommodate the baseline shift was assessed.

Results

The end-to-end latency was 160+-7ms (91+-2ms imaging + 69+-6ms processing). Without biofeedback the gating efficiency was 35-39%/37-51% (5mm/10mm). Visual biofeedback improved this to 53-73%/75-95%, an average improvement of 26%/37%. The median (residual) motion was reduced from 8.5(6.2-15) mm to 2.0(1.3-2.1) mm. All subjects were able to adapt for cranial baseline shifts within 1-2 respiratory periods.

Conclusion

These results show that a visual biofeedback can guide a subject’s breathing to improve treatment efficiency.

[1] Zachiu (2015) PMB 60

P05.05 ID 52

Prototyping real-time adaptive treatments for IMRT/SBRT on the Elekta Unity MR-Linac

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Introduction

We report on a prototype implementation of a real-time adaptive software platform to demonstrate feasibility of intra-fraction real-time adaptive (RTA) radiotherapy on the Elekta Unity MR-Linac.

Materials and Methods

A prototype platform has been developed which enables low latency 3D+t motion modelling, deformable MLC tracking and dose accumulation. The patient motion model is based on a pre-treatment 4DMR and takes 2D cine MR acquired at ~5 Hz during beam-on as input to yield real-time 3D+t deformation volumes. The MLC tracking algorithms (rigid and deformable) uses the deformation to adapt the machine

settings through a research interface. The resulting machine settings, as read from the machine, and the deformation is input to the dose accumulation which is based on the clinical Monte Carlo algorithm taking the magnetic field into account. The dose accumulation provides the user with instant dosimetric feedback of the progress of the treatment and instant QA. The prototype has been used to simulate RTA treatments using both a Unity research tracking emulator and, for actual delivery, an Elekta Unity at the Uppsala University hospital. Tests have been performed with a prototype version of the Quasar deformable4D motion phantom from Modus QA and for a lung SBRT plan (healthy volunteer) from UMC Utrecht.

Results

The treatment simulations using the prototype system, proved successful delivery of RTA treatments. The patient motion modelling and MLC tracking were performed at 5Hz, and the dose accumulation at 2.5 Hz. The calculation time for the MLC tracking part of the workflow (motion modelling and MLC tracking) was determined to be < 50 ms. The total end-to-end latency, i.e. calculation time + overhead due to inter-process communication etc. was < 200ms (excluding k-space sampling and image reconstruction).

Conclusions

The successful prototype implementation shows the feasibility of delivering RTA treatments on the Elekta Unity MR-Linac.

EP05.01 ID 15

Comparison of Library of Plans and MR-Linac strategies for whole bladder RT based on MR-Linac data

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Introduction

Radiotherapy for bladder cancer is challenging due to constant changes in the bladder anatomy. CBCT-guided Library of Plans (LoP) deals with these challenges by selecting a plan from a pre-constructed set for each fraction. With the MR-Linac (MRL) the planning target volumes and plans are adapted based on the daily anatomy. The goal is to compare these strategies, based on clinical data obtained by an MRL.

Patients and Methods

Treatments for bladder patients were simulated using data from 25 MRL lymph node oligometastases treatments (125 fractions) with three MRI images at each fraction at 0, ~15 and ~30 min. Bladders were manually delineated on all MRIs and used to evaluate three strategies: 1) LoP, 2) present MRL workflow (MRL_{pres}) and 3) a hypothetical optimized MRL workflow (MRL_{opt}) with a shorter time between first image and end of fraction. Population based margins were determined for MRL_{pres} and MRL_{opt} which covers 100% of the bladder in 90% of the fractions. The volume of healthy tissue inside and the amount of bladder volume outside the PTV were evaluated on a post-treatment image (~15 min after the start for LoP and MRL_{opt}, and ~30 min for MRL_{pres}).

Results

Margins were 15, 15, 25, 13, 36 and 5 mm for MRL_{pres} and 10, 10, 11, 11, 17 and 4 mm for MRL_{opt} in left, right, anterior, posterior, cranial and caudal direction. The MRL_{pres} has a larger PTV and more healthy tissue inside the PTV (~75% more) than the LoP and MRL_{opt} strategy. In terms of target volume outside the PTV, the MRL_{opt} performs similarly to MRL_{pres} strategy (0.0 cc, 0–28 cc vs. 0cc, 0–98 cc; median, range; two-tailed Wilcoxon matched-pairs signed-rank test $p = 0.11$) but better than LoP strategy (0 cc, 0–48cc, $p < 0.01$).

Conclusion

LoP performs better than MRL_{pres}, but MRL_{opt} performs slightly better than LoP. The longer treatment times in MRL_{pres} overshadow the benefit of daily adapting. This might be counteracted in the future by intra-fraction plan adaptation.

EP05.03 ID 62

Treatment of patients with artificial hips on the Elekta Unity MR-Linac

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Introduction

Orthopaedic implants such as artificial hips cause signal voids and spatial distortion in MRI. The aim of this work was to determine the magnitude and spatial map of distortion, assess image quality, and develop a planning workflow for patient assessment of MR-Linac suitability.

Patients and Methods

3 patients (2 bladder, 1 oligomet in the ipsilateral pelvis) with single artificial hips were imaged on the MR-Linac under the PRIMER trial CCR4576, including the Treatment Session Manager (TSM) sequences used for the treatment workflow, B0 mapping and reverse readout TSM sequences (Chang et al, 1992). The B0 maps were assessed in conjunction with the imaging bandwidths to determine spatial distortion. Image quality was visually assessed with clinician input. IMRT treatment plans were generated in Monaco ensuring that beams do not enter the target through the implant (although can exit through).

Results

The B0 field distortions due to the presence of artificial hips are non-linear and extend out further than the near vicinity of the implant. However, the high bandwidth used for the Elekta TSM sequences restricts the spatial distortion. The B0 maps showed that the worst-case maximum field distortion in the bladder CTV was ~500Hz, corresponding to ~1mm displacement for the T2 3D Tra (2mins) sequence. Visual comparison of the reverse readout scans confirmed that distortion was undetectable for all 3 patients. IMRT plans created from distorted CTVs met all clinical goals based on CT defined CTVs, with acceptable dose distributions. However ghosting artefacts were visible and should be assessed to ensure ther eis no impact on target visualisation.

Conclusion

All patients referred for MR-Linac treatment require a pre-treatment MR-Linac planning scan acquiring the above sequences to assess potential distortion and image quality. If the distortion is shown to have minimal impact, then the online workflow should be based on a bone match registration.

EP05.04 ID 79

Evidence of high-quality, accurate and deliverable MR-guided stereotactic ablative radiotherapy

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Introduction

Access to MRgRT SABR in the UK is limited to privately insured patients and narrowly focused programs for NHS patients. Increasing availability requires evidence of benefit in patient outcomes. A first step to building this evidence base is demonstrating that high-quality, accurate and deliverable treatments are provided.

Patients and Methods

We report on daily adapted MRgRT SABR cases, including liver 15, pancreas 14, abdominal node 8, pelvic node 4, lung 2 and other 5. Each patient has a baseline treatment plan and for each fraction a predicted dose and a reoptimised plan.

Treatment plan quality is measured using plan metrics including prescription dose spillage and compared to acceptable values from national guidelines. Accurate delivery is assessed by improvement in PTV V100% and PTVHigh V95% coverage (percentage of the volume receiving 100% or 95% of the

prescription dose) achieved by adaption. Deliverability is reviewed via plan complexity metrics. These are compared to the patient specific QA (PSQA) pass-rate from ArcCheck fluence measurements.

Results

For baseline plans, dose conformity guidance was met in 91% and 99% of cases. For reoptimised plans, the rate of compliance with guidance more likely for larger PTV V100%.Daily plan adaptation improved PTV V100% coverage in 77% of fractions and PTVHigh V95% coverage in 93% of fractions. PTVV100% was improved by up to 31.4% (mean 3.5%, standard deviation 7.2%). The PTVHigh V95% was improved by up to 29.1% (mean 5.6%, standard deviation 6.3%). For all reoptimized plans the OAR doses were within tolerance or accepted as minor deviations. All baseline plans passed PSQA. A greater plan complexity is associated with a poorer PSQA pass-rate. The distribution of plan complexity metrics is the same for baseline and re-optimised plans.

Conclusion

MRgRT is shown to provide high-quality, accurate and deliverable treatments. This is a pre-requisite to providing evidence of benefit in terms of patient outcomes.

TOPIC MR GUIDED PARTICLE THERAPY

P07.01 ID 76

Determination of magnetic field correction factors for dosimetry in MR-integrated proton therapy

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Objectives

For the integration of magnetic resonance imaging (MRI) into proton therapy (PT), a 0.22 T MRI was installed at the pencil beam scanning beam line at OncoRay. As a next step, dosimetry in the magnetic field has to be established. This work aims to study the influence of the static field (B_0) of the MRI on ionisation chamber (IC) responses for proton beams through measurements and Monte Carlo (MC) simulations.

Materials and Methods

A Semiflex 0.3 and a PinPoint 3D IC were positioned in a water phantom placed in the MR imager isocenter. The absolute dose at five proton energies (70, 110, 150, 190,226.7 MeV) was measured within the entrance plateau of the depth-dose curve using a 10×10cm² homogeneous irradiation field. The correction factor kB was obtained by dividing the measured dose with/without B0.For the MC simulations, beam-commissioning data (depth-dose profiles in water, beam spot sizes in air) were used to create a MC beam model in TOPAS (1.5×10^5 particles). A 3D map of the scanner's magnetic field (MF) was calculated with COMSOL and used in the simulations to mimic the experimental setup.

Results

The MF correction factor kB showed systematic energy-dependent differences between dose readings with and without B0. For the Semiflex 0.3, kB was 0.9926, 0.9942, 0.9941, 0.9959and 1.0036 for 70, 110, 150, 190 and 226.7 MeV, respectively. For the same energies, kB for the PinPoint 3D was 0.9920, 0.9931, 0.9938, 0.9952 and 0.9969. For all energies, the standard deviations of kB were smaller than 0.002 for both ICs. MC simulations of the Semiflex 0.3response to 110 MeV showed no statistically significant B0 effect with kB of 0.997 (95% CI: 0.9893, 1.0049).

Conclusion

Measurements showed a small but significant influence of the MRI scanner's B_0 field on the IC response, which was beam energy-dependent. Further investigations should clarify the necessity of dosimetric correction factors for the MR-integrated PT.

P07.02 ID 92

An extension of the analytical treatment planning system matRad for MR-guided proton therapy

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Introduction

The potential of proton therapy (PT) is not fully exploited due to the need for considerable margins. With MR-guided PT (MRgPT) the targeting accuracy is expected to improve thanks to real-time anatomy imaging. Treatment planning systems (TPS) must account for changes in dose distribution due to the beam deflection caused by the magnetic field. Our aim is to extend the analytical TPS matRad for MRgPT treatment planning.

Methods

The Pencil Beam Algorithm (PBA) in matRad was extended to account for beam deflection and distortion of the dose distribution. To calculate the beam deflection the analytic model of Wolf and Bortfeld (2012) was implemented. The dose distribution was calculated with a double Gaussian dose profile and a

laterally asymmetric profile proposed by Padilla-Cabal et al. (2018) with parameters generated by fitting Monte Carlo (MC) simulations in a magnetic field from TOPAS v3.5. The accuracy of the extended PBA was evaluated for proton beams of 100, 160, and 210 MeV in a homogeneous water phantom with a uniform perpendicular field of 1.5 T.

Results

For all selected energies at 1.5 T, the lateral offset of the Bragg peak was predicted with an error below 0.25 mm at the depth of maximum dose. At the therapeutic range R_{80} the error was below 0.15 mm for 100 and 160 MeV and 0.7 mm for 210 MeV. The lateral dose profiles were evaluated at R_{80} for 1.5 T. For 210 MeV the double Gaussian profile deviated by more than 10% from MC results within the 50% lateral fall-off region. In contrast the asymmetric profile had no significant deviations from MC results up to a lateral fall-off of 1%. For 100 and 160 MeV both profiles had no significant deviations within the 10% fall-off region.

Conclusions

Results indicate that the extended PBA in matRad is feasible for fields up to 1.5 T in homogeneous geometries. An extension to handle heterogeneities is the topic of future research.

Wolf R and Bortfeld T. 2012 Phys Med Biol 57: 329

Padilla-Cabal F et al. 2018 Med Phys 45: 2195

P07.03 ID 104

Beam modeling of a proton pencil beam scanning beam line integrated with a low-field open MR scanner

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Objective

The integration of an MRI scanner into a proton beam line imposes challenges to the dose delivery, since the magnetic field (MF) of the scanner distorts the beams and hence the dose distribution [1]. This study aims to develop a Monte Carlo (MC)-based beam model of the pencil beam scanning nozzle in the OncoRay facility to accurately model the dose delivery in the presence of an open MR scanner.

Materials and Methods

Measurements of proton beam spot size in air at varying distance from the nozzle were used to model beam optics using the Geant4-based MC code TOPAS [2]. The beam energy and energy spread were obtained from the fit of depth-dose profiles measured in water. A 3D map of the magnetic fringe field of the 0.22 T (vertical field) open MR scanner was generated with COMSOL and used in TOPAS. The simulated beam deflection was compared to measurements 210 cm downstream of the beam isocenter. Horizontal spot scanning positions from 0 to 200 mm and energies of 70, 125 and 220 MeV were considered.

Results

The simulated spot sizes without MF agreed with experimental measurements within the experimental uncertainty up to100 cm downstream of the nozzle. With MF, spot deflections for the central spot differed from experimental values by 2.3 (70 MeV), 0.5 (125 MeV) and 2.4 (220 MeV) mm. For all spot positions, the mean error was 2.9%, 2.6% and 2.5% for the same energies. A systematic underestimation of the deflection was found with the error increasing with spot distances and lower energies. The largest error was 4.9% for 70 MeV and 195 mm spot.

Conclusions

Small deviations for the estimated beam deflection for central beam spots were observed. Further investigation is necessary to validate the beam model in the MF at 210 cm downstream and the 3D field map. Future work will include a detailed evaluation of beam deflection and changes in spot sizes in the MF.

References

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P07.04 ID 91

Fast Monte Carlo dose calculations in constant magnetic fields for MR-guided proton therapy

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Introduction

The development of a TPS for MR-guided proton therapy requires an efficient MC code for dose calculations that can handle the unique challenges imposed by the magnetic field. The aim of this work is to adapt MCsquare [1], a highly efficient MC code developed for proton therapy, to enable its use for treatment planning in magnetic fields.

Materials and Methods

The open-source code of MCsquare was extended to simulate MC transport of protons in an arbitrarily oriented magnetic field. Specifically, we implemented a correction of the movement direction of the protons based on the Lorentz force equation. The new algorithm was applied to calculate beam deflection and dose distributions in water for 100 and 200 MeV proton beams at 1.5 T. In total, 50 million histories were simulated per energy. The implementation was validated against results obtained with TOPASversion 3.5 [2].

The efficiency of the customized MC transport algorithm in MCsquare was benchmarked against simulations in the absence of magnetic fields.

Results

For 100 MeV, the beam deflection is 3.52±0.19 mm in MCsquare and 3.56±0.14mm in TOPAS. For 200 MeV, the deflection is 27.01±0.38 mm in MCsquare and 27.63±0.30 mm in TOPAS.

The computation time of MCsquare increased from 7.84e-6±1.92e-7 s/history to 8.75e-6±3.88e-8 s/history when adding the magnetic field for 100MeV and from 2.12e-5±2.80e-8 s/history to 2.13e-5±3.86e-7 s/history for 200MeV.

Conclusion

First results show good accuracy of the modeling of the proton deflection in magnetic fields caused by the Lorentz force. No substantial reduction of the efficiency of the MC transport is observed in magnetic fields. Future investigations will include extensive 3D analysis evaluation of the dose distribution in magnetic fields. This will allow the integration of the modified MCsquare code in a TPS for clinical treatment planning in MR-guided proton therapy.

[1] K. Souris et al 2016 Med Phys 43

[2] J. Perl et al 2012 Med Phys 39

P01.01 ID 47

Development of a phantom for adaptive end-to-end testing in magnetic resonance guided RT

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Objective

The introduction of magnetic resonance (MR) imaging in radiotherapy enhanced the complexity of the treatment workflow. New demands on the phantoms emerged by the characteristics of magnetic resonance guided radiotherapy (MRgRT), e.g. the generation of a strong MR signal. We present the first measurements in an in-house developed silicon phantom including air, water and bone structures.

Materials and Methods

The cuboid silicon phantom (19 cm x 23 cm x 17 cm) includes several cavities which can be left empty to simulate air bubbles, be filled either with water or with gypsum to simulate bone structures. On the central horizontal plane a frame for a radiochromic film was integrated, allowing a precise positioning of the film. An IMRT plan with 11 beams prescribing 3 Gy to the 65 % isodose line was calculated on the homogeneous silicon phantom, adapted to the phantom including air, water orgypsum and irradiated to simulate the adaptive workflow. The dose distribution was measured and compared to the calculated dose, applying a gamma evaluation criterion of 2 %/2 mm.

Results

The phantom generated enough MR signal to successfully perform adaptive end-to-end tests. The silicon showed a mean Hounsfield Unite (HU) of 252 and the gypsum 560 HU. The planned and measured dose distributions agreed for the first three measurements showing passing rates of 96.6%, 99.5% and 99.3%.

Conclusion

The in-house developed phantom including different materials is suited to test the adaptive workflow. The 2d dose distributions showed a high dosimetric and geometric precision

P01.03 ID 66

Physiological targeting features of a 4D deformable tumor phantom for MR/CT IGRT QA

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Introduction

Achieving realistic real-time adaptive MRgRT requires benchmarking tools for tracking and compensation of complex organ/tumor motion and deformation. Such tools should allow for multimodality imaging co-registration of physiological features with sufficient contrast. Previously, a prototype 4D motion phantom insert, capable of repetitive physiological deformation was implemented with basic targeting features. This work evaluates the introduction of physiological, heterogenous targeting features and highlights the importance of material selection.

Materials and Methods

The 4D deformable tumor model consisted of a tissue housing made from a low density open-cell polyurethane foam submerged in aqueous medium doped with $MnCl_2$. An ellipsoid tumor cavity (30 mm x 40 mm), offset by 7.5 mm from the housing centroid in the radial direction and marked by ceramic vertex fiducials (5 mm) was filled with either silicone or polyurethane rubber. Vascular structures made of either silicone, PTFE, PEEK, nylon, polyester, or polypropylene were explored within the tumor and housing. Additional heterogenous tumor structures were implemented with PTFE balls, polyester mesh, cotton balls, and polystyrene foam. Materials were evaluated based on MR and CT contrasts, viscoelastic deformation, and ease of preparation.

Results and Conclusions

Silicone rubbers are more favorable than polyurethane rubbers due to inherent MR signal, higher CT contrast, and favorable casting properties for the addition of physiological features; however, a larger chemical shift was observed in the silicone rubber (5.0 ppm vs. 3.5 ppm). The nylon string, representing vasculature, showed good contrast from the polyurethane housing on MR. PTFE balls showed good CT contrast for imbedded tumor tracking. Future work includes investigation of the influence of the rubber selection on deformable motion profiles, and implementation of tethered structures for edge detection and tracking on MRgRT systems.

P01.04 ID 4

Using CBCT for Dosimetric Quality Assurance of MR-Only Radiotherapy

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Introduction

Magnetic Resonance (MR)-only radiotherapy is now being used clinically for prostate cancer using commercial synthetic Computed Tomography (sCT) algorithms for dose calculations (1). sCT images have been evaluated against CT for dose accuracy, however patients in clinical MR-only pathways will not have a CT, so a different method of dosimetric Quality Assurance (QA) will be required. The first fraction Cone Beam CT (CBCT) has been proposed for QA of MR-only radiotherapy (2), but to our knowledge has not been evaluated clinically. The aim of this study was to evaluate the clinical use of CBCT for dosimetric QA of MR-only radiotherapy.

Materials and Methods

40 patients treated with MR-only prostate radiotherapy were included, divided into two cohorts. The first cohort (20 patients) received a back-up CT scan whilst the second did not. All patients were planned and treated using a sCT generated by MriPlanner (Spectronic Medical, Sweden) and received daily CBCT imaging (Varian Medical Systems, USA). Treatment verification was done by MR-CBCT soft-tissue matching. The treatment plan was recalculated on the first fraction CBCT using the soft-tissue match in RayStation (RaySearch Laboratories, Sweden) and the doses compared. For cohort 1 the sCT was also rigidly registered to the sCTback-up CT, the plan recalculated and the doses compared.

Results and Conclusion

Mean sCT-CBCT dose differences across both cohorts were small, -0.7 ± 0.1% (min -2.3%, max 0.6%). The CBCT underestimated the sCT dose in 36/40 patients. Mean gamma pass rate was (1%/1mm) 85 ± 1% (75%, 94%) and (2%/2mm) 95.6 ± 0.6% (85.4%,99.7%). For cohort 1 sCT-CBCT dose differences correlated with sCT-CT dose differences (r = 0.79, p In conclusion, CBCT seems a promising method of dosimetric QA for MR-only radiotherapy, with dose differences and gamma pass rates showing good agreement with gold standard CT.

References

1. Bird D et al., Int J Radiat Oncol. 2019 105(3).
2. Palmér E et al., J Appl

P01.02 ID 29

Patient-specific QA of geometric accuracy in MRI-based RT planning

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Introduction

Stereotactic radiosurgery/radiotherapy requires high spatial accuracy. While distortions caused by MRI system imperfections and chemical shift can be determined in phantoms, local susceptibility-induced distortions must be measured on a patient-specific basis. The goal of this study is to present an efficient and robust workflow for patient-specific QA of geometric accuracy.

Methods

10 patients who underwent clinical MRI for brain SRS planning were included in this study. All MRI scans were performed on a 3T scanner (MAGNETOM Vida, Siemens Healthcare, Erlangen, Germany). Local susceptibility-induced off-resonance frequency was measured using a 3D multi-echo GRE sequence: TE 2.44/4.66/7.16 ms, resolution 2.3 x 2.3 x 3 mm^3, FOV 300 x 300 x 270 mm^3, scan time 1 min. The GRE scan was performed under the same shimming condition as the primary planning scan. Off-resonance frequency was converted into distortion (mm) using: distortion = (off-resonance frequency)/(readout pixel bandwidth)*(pixel size). In this equation, bandwidth and pixel size were sequence parameters used in the primary planning scan (i.e. 240 Hz/pixel and 1.0 mm in our clinical post-contrast MPRAGE protocol).

Results

Automated inline processing provided off-resonance frequency maps free of phase alias or fat offset. Maximum off-resonance frequency of 188±52 Hz (mean±std among patients) was observed in the frontal lobe near the sinuses, indicating maximum distortion of 0.78±0.22 mm in the post-contrast MPRAGE scan. The variation range of off-resonance frequency throughout the cranium was 305±57 Hz, indicating worst-scenario alignment error of 1.27±0.24 mm. This workflow for geometric distortion evaluation is potentially compatible with other standard MRI protocols. Off-resonance maps saved as DICOMs could be used, on a patient-specific basis, to facilitate protocol optimization, determine patient eligibility for MR-only treatment planning, and estimate MR to CT registration uncertainties.

P01.05 ID 87

Quantification and reduction of susceptibility artefacts for a quality assurance phantom in MRgRT

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In this work, an in-house developed phantom that is being used in MRgRT for the quantification of isocentre-alignment between MR and treatment device was further optimized. As it holds a metallic sphere for radiation attenuation, susceptibility-induced artefacts occur leading to image distortions within the MR Images. The extent of susceptibility-induced distortions was investigated and susceptibility adjustment of the water-filling was performed by dissolving salts to reduce such artefacts.

The cubic phantom is printed in 3D including a grid for positioning in MRI. The radiation isocentre is defined by the centre of a metallic sphere's attenuation at the centre of the phantom measured on radiochromic films attached to the beam exit side. The attenuation of three different spheres (materials containing mainly copper, lead or tungsten) was measured at a Viewray MRIdianLinac and MRI measurements were acquired using clinical TrueFISP and TSE sequences at 0.35T and 1.5T. Additionally, the spheres' susceptibilities were measured using a magnetometer. Accordingly, a suitable salt for susceptibility adjustment of the water-filling was defined [1] ($CuSO_4$, $MgSO_4$) and MR measurements with different salt concentrations were performed. The extent of the susceptibility artefacts were calculated using distortion maps [2].

The tungsten sphere (volume susceptibility $\chi = (94.3 \pm 0.45)\ 10^{-6}$ (SI units)) had the highest attenuation (15 % higher compared to surrounding water) of the three investigated spheres. The maximum distortions were calculated for all sphere-salt combinations, which validated a trend of decreasing values with increasing salt concentration. For the tungsten sphere best results were achieved using a 50g/l (200 g/l) $CuSO_4$ solution leading to an artefact reduction by around 36 % (29 %) at 0.35T(1.5T).

[1] Kuchel et al., doi: 10.1002/cmr.a.10066
[2] Emmerich et al., doi: 10.1002/mp.12785

TOPIC MCS / RADIOMICS / DATA SCIENCE

P08.01 ID 105

Decomposition-based framework for prediction of radiotherapy response from longitudinal DW-MRI data

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Objective

DW-MRI is a promising tool for evaluation of tumor therapy response due to its ability to detect changes in local diffusion that occurs as a result of cellular damage. With the implementation of the hybrid MRI-Linear accelerator (MR-Linac) machine it has become feasible to collect this information during the entire radiotherapy (RT) course. This enables collection of longitudinal measurements and thus provides a conceptually new opportunity in the search for biomarkers. The aim of this work is to propose a processing framework for extraction of prognostic information from longitudinal DW-MRI data using a novel decomposition technique, and test this for stratification of RT response.

Method

In a prospective pilot study, DW-MRI brain scans were acquired on each day of a 10 fraction (total dose 30 Gy) whole brain RT regimen with a 1 T MRI scanner for a cohort of 16 patients with 31 metastases in total. The developed framework consists of an initial decomposition of the data using an extension of the non-negative matrix factorization (NMF), the monotonous slope (ms)NMF. Second, a transformation from voxel-maps to tumor-specific features using descriptive statistics, and a robust fit across days to capture temporal changes of these. Finally, a logistic regression with an integrated feature selection in a stratified k-fold cross-validation process was used for tumor stratification. A follow-up scan 2-3 mos post treatment was used for true labelling of the tumors (8 non-responders, 22 responders). The performance was reported using the balanced accuracy (due to class imbalance) and the AUC.

Results

The balanced accuracy of the prediction was 69 % and the AUC was 0.7.

Conclusion

A novel decomposition-based processing framework for prediction of radiotherapy response from longitudinal DW-MRI measurements was demonstrated in a small patient cohort. Large DW-MRI data sets are easily acquired with the MR-Linac and are expected to be used in further testing of the framework.

P08.02 ID 48

Influence of the magnetic field on the effective point of measurement of ionization chambers

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Introduction

Detector used for dose measurements in the presence of the magnetic field at an MR-linac may be subjected to a change of its effective point of measurement (EPOM) due to the deflection of secondary electrons by the Lorentz force. As a result, a lateral EPOM displacement has been suggested in magnetic field, in addition to the typical shift towards the source. In this study, the EPOM of cylindrical ionization chambers in magnetic field have been assessed systematically.

Materials and Methods

The EPOM of three ionization chambers (Farmer 30013, Semiflex 3D 31021 and PinPoint 3D 31022, all from PTW Freiburg) were investigated using a 10 x 10 cm^2 field and 6 MV photon beam for four configurations (chamber's axis pointing from the stem to the tip): (i) chamber's axis anti-parallel (axial) to beam's axis (+z) and magnetic field (+x), (ii) chamber's axis (+x) perpendicular (radial) to beam's axis and parallel to magnetic field (+x), (iii and iv) chamber's axis perpendicular (+y) to both the beam's axis and magnetic field (+x and -x). Simulations were performed with EGSnrc using the eemf-macro (EMSTEP = 0.2). A previously developed user-code was used to score the coordinates of the entry points of all secondary electrons crossing the sensitive volume. The EPOM shift in each direction (Δx, Δy and Δz) was computed as the energy deposited-weighted sum of the coordinate shifts of all registered entry points. Additionally, the Δz-shift was obtained by comparisons of simulated percentage depth dose distributions.

Results and Conclusion

The EPOM shifts in the source directions of all investigated chambers are reduced in the presence of magnetic field. For example, Δz of the Farmer chamber positioned radially is reduced from 0.43r (0 T) to 0.22r (1.5 T). The results obtained from both methods show good consistency. Additionally, a lateral shift of the EPOM (Δx and Δy) opposing the preferential direction of the Lorentz force that increases with magnetic field can be observed.

P08.03 ID 25

Delta Radiomics analysis in pancreatic cancer patients treated using MR-guided Radiotherapy

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Background

Aim of this study was to investigate the potential of delta radiomics in predicting local control for patients affected by locally advanced pancreatic cancer (LAPC) and treated using low field Magnetic Resonance guided Radiotherapy (MRgRT).

Methods

A total of 35 patients from two institutions were enrolled in this study: a 0.35 Tesla T2*/T1 MR image was acquired for each case during simulation and on each treatment fraction, prior to treatment delivery. Patients enrolled received different dose schedules: 35, 40 or 50 Gy in 5 fx or 67.5 Gy in 15 fx, based on the clinical situation of the patient at the time of diagnosis. Physical dose was converted in biologically effective dose (BED) to compensate for different MRgRT schemes and Gross Tumour Volume (GTV) was delineated on MR images acquired at BED level equal to 20, 40 and 60 Gy. Morphological, statistical and textural features were extracted considering GTV as region of interest and delta radiomics features were calculated with respect the corresponding values calculated at simulation. The performance of the delta features in predicting the local control one year after the end of MRgRT (1yLC) was investigated in terms of Wilcoxon Mann Whitney test and area under receiver operating characteristic (ROC) curve.

Results

1yLC was observed in 20/35 (57%) patients. A total of 644 features were calculated for each patient: the most significant feature in predicting 1yLC was the variation of the cluster shade calculated at BED=40Gy, reporting a p-value of 0.005 and an area under ROC curve (AUC) of 0.78 (0.61-0.94 as confidence interval). This feature has showed a sensitivity of 85% and a specificity of 67% in identifying patients with 1yLC.

Conclusion

Delta radiomics analysis on low field MR images might play a promising role in the 1yLC prediction for LAPC patients. Further studies including external validation dataset and larger cohort of patients are recommended to confirm the validity of this preliminary e

P08.05 ID 81

Segmentation-oriented Generative Adversarial Network for Synthetic-CT in MR-only Treatment Planning

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Introduction

Treatment planning in radiotherapy usually relies on accurate geometry and electron/mass-density information provided by CT images. However, due to the superior soft tissue contrast, MRI is often used for the delineation of tumors and organs at risk in radiotherapy. Using a single modality for treatment planning has great benefits, including reduced registration errors. To enable MR-only workflow, we propose a segmentation-oriented generative adversarial network (GAN) for accurate synthetic-CT generation.

Materials and Methods

A convolutional neural network is first trained to segment the input MR images into 3 classes: background, soft tissue and bone. Then the segmentation results are concatenated with the original MR input and used as the input and condition for a conditional-WGAN[1,2]. In this way, the segmentation labels can guide the training of GAN by offering clues on the tissue type of each pixel to reduce intensity error in image synthesis. Experiments were performed using paired pelvic MR and CT images (9059 2D slices of 76 subjects for training, 580 2D slices of 5 subjects for testing). In- and Opposed-phase MR Dixon images were acquired with Dixon-imaging protocol. Planning CT images were registered to the MR images using deformable registration.

Results and Conclusion

Compared with conditional-GAN, the proposed method reaches a higher fidelity in both intensity and geometry. Better MAE for soft tissue (17.05 HU) and bone (65.57 HU) are achieved, while better Dice (99.91%) and ASSD (0.078 mm) between the body boundary of the synthetic CT and input MR are reached. The concepts and information presented in this abstract/paper are based on research results that are not commercially available. Future availability cannot be guaranteed

Reference

[1] Isola, Phillip, et al. "Image-to-image

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