1

MRI-Guided Focal HDR Brachytherapy as Monotherapy for Prostate Cancer: Early Feasibility and Quality of Life Results

Lisa Joseph[1,2], Peter Chung[1,2], Joelle Helou[1,2], Andrew Bayley[1,2], Charles Catton[1,2], Padraig Warde[1,2], Bernadeth Lao[1], Alexandra Rink[1], Akbar Beiki-Ardakani[1], Jette Borg[1], Robert Weersink[1], Alejandro Berlin[1,2], (1) Princess Margaret Cancer Centre, Toronto, ON, (2) University of Toronto, Toronto, ON

Purpose: Brachytherapy (BT) is a highly effective treatment for localized PCa, traditionally being delivered to the whole gland. In recent years, there has been growing interest in focal treatment modalities (e.g., cryotherapy, HIFU), seeking to improve normal-tissue preservation, therefore resulting in reduced adverse effects compared to whole gland approaches. However, focal BT approaches remain underexplored in the high dose-rate (HDR) monotherapy setting. Herein, we evaluate and report the preliminary results of our focal HDR BT study for localized prostate cancer, enabled by our unique MRI-only workflow. **Materials and methods:** This is a prospective feasibility study. Main eligibility criteria were histologically proven low- and favorable intermediate-risk prostate cancer, with < 2 distinct lesions on mpMRI involving no more than a third of the whole prostate, prostate gland size < 80 c, and IPSS < 18. All patients were treated with MR-guided HDR BT to a dose of 33–36 Gy to tumor-PTV alone, in 2 separate sessions 7–14 days apart. The GTV was defined using mpMRI (T2-w, DWI, and DCE sequences). CTV margin expansion (7 mm craniocaudal and 5 mm in all other directions) within prostate boundaries. PTV margins of 2 mm craniocaudally were then applied. No patient received neoadjuvant ADT. Patients were followed up with regular PSA, mpMRI was performed at 12 and 24 months after BT, including MR-guided prostate biopsies after a minimum 2 yr to assess local control. Toxicity and quality-of-life (QOL) were measured using Common Terminology Criteria for Adverse Events (v4) and Expanded Prostate Cancer Index Composite (EPIC-26) respectively. **Results:** A total of 8 patients (median age 68, range 63–79) have been treated to date, and followed for a median of 13.9 months (0.8–24.8). Median PSA pre-treatment was 5.94 ng/mL (2.84–9.98). One patient had Gleason 3 + 3, and the remainder had Gleason 3 + 4 disease on diagnostic systematic biopsies. Between 6-9 BT catheters were used per implant. Median PTV volume was 7.3 cc (6–15.2). Median D95 to PTV was 18.7 Gy (16.6–20.6), corresponding with a D99 to GTV of 21.84 Gy (18.9–28.9). Median D2 cc to rectum was 8 Gy (6.2–10.2), D0.5 cc to bladder and urethra were 5.9 Gy (3.9–12) and 9.1 Gy (4.6–12.1) respectively. There were no Grade 3/4 adverse events within a month following procedure. There was a statistically significant decline in EPIC GU domain sum scores at 1 month ($P = 0.0074$) and sexual domain at 12 months ($P = 0.0065$). However, there were no significant differences in GU, GI and sexual domain scores at any other timepoint compared to baseline. A minimally important difference of > 10 points in EPIC sum scores compared to baseline were only recorded by 2 patients in the sexual domain at 6 and 12 months. **Conclusions:** MR-guided focal HDR brachytherapy is feasible, allowing the delivery of highly ablative doses to mpMRI-defined tumors with lower doses to surrounding OAR compared to conventional whole-gland HDR monotherapy. Preliminary toxicity and patient-reported outcome measures are encouraging. Further follow-up is required to evaluate the long-term oncologic, toxicity and patient-reported outcomes of this unique MR-guided HDR BT focal approach.

2

MRI-Based Quantitative Oxygen Sensors for Guiding High Dose-Rate Brachytherapy

Gregory Ekchian, Massachusetts Institute of Technology, Cambridge, MA

Purpose: Hypoxic tumors are resistant to radiation and chemotherapy. Tumor hypoxia is a poor prognostic factor and has been observed in cancers including cervical,[1] prostate,[2] and head and neck.[3] Localized radiation dose escalation to low-oxygen sub-volumes is a compelling approach to overcome hypoxia-induced radiation resistance. MR-based high dose-rate brachytherapy (HDR-brachy) provides a means to achieve this dose escalation while still adhering to normal tissue constraints. Hypoxia-targeting therapies have been of limited clinical utility because available oxygen sensing methods are qualitative and provide low sensitivity. We report on the development and validation of a novel quantitative and MR-based oxygen sensor for use during our upcoming clinical trial in HDR-brachy treatment of cervical cancer. **Materials and methods:** The presented work is in support of an early feasibility trial in ten patients with locally advanced cervical cancer. Our upcoming, IRB-approved, trial will take place during MR-guided catheter placement for HDR-brachy at Brigham and Women's Hospital. Early feasibility trials are used to guide the further development of a technology and occur before device design has been finalized. Depots of oxygen-sensitive silicone were placed in the tip of a modified HDR-brachy catheter. The oxygen-sensitive portion of the device is a proprietary combination of an implant grade liquid silicone oil and silicone elastomer.[4] Sensor performance was evaluated in a 3T MRI scanner (Siemens Verio). Oxygen-sensitive T_1 relaxation measurements of the silicone were made using an inversion recovery turbo spin echo pulse sequence. **Results:** The sensor was shown to have MR contrast against an aqueous background, enabling locating the sensor during clinical MRI scans. The T_1 relaxation time of the sensor was measured under conditions of 21% (ambient) and 0% (hypoxic) oxygen to mimic insertion and equilibration to the hypoxic environment. The T_1 relaxation times under these conditions were statistically significant ($P < 0.001$, n = 6). This sensor design meets the requirements of a device to be used in this early feasibility trial. **Conclusions:** The primary aim of our upcoming clinical trial is the insertion, measurement, and removal of the sensor within the constraints of the current clinical workflow. MR-based silicone oxygen sensors promise to be a viable method of measuring tumor oxygen content. We will use the results of our early feasibility trial to finalize our next generation sensor for broader use cases and with enhanced performance metrics, such as increased sensitivity and more flexible form factors.

References

1. Hockel M, Schlenger K, Aral B, Mitze M, Schaffer U, Vaupel P. Association between tumor hypoxia and malignant progression in advanced cancer of the uterine cervix. *Cancer Res.* 1996;**56**:4509–4515.
2. Milosevic M, Warde P, Ménard C, et al. Tumor hypoxia predicts biochemical failure following radiotherapy for clinically localized prostate cancer. *Clin Cancer Res*. 2012;**18**:2108–2114.
3. Janssen HL, Haustermans KM, Balm AJ, Begg AC. Hypoxia in head and neck cancer: how much, how important? *Head Neck.* 2005;**27**:622–638. https://doi.org/10.1002/hed.20223.
4. Liu VH, Vassiliou CC, Imaad SM, Cima MJ. Solid MRI contrast agents for long-term, quantitative *in vivo* oxygen sensing. *Proc Natl Acad Sci USA*. 2014;**111**:6588–6593. https://doi.org/10.1073/pnas.1400015111

3

Changes In Apparent Diffusion Coefficient (ADC) In Serial Weekly MRI During Radiotherapy In Patients With Head and Neck Cancer: Preliminary Results From Predict-HN Study

Sweet Ping Ng[1], Carlos Cardenas[2], Houda Bahig[3], Baher Elgohari[2], Amy Moreno[2], Shalin Shah[2], Adam Garden[2], Jack Phan[2], G Brandon Gunn[2], Steven Frank[2], David Rosenthal[2], William Morrison[2], JiHong Wang[2], Clifton Fuller[2], (1) Peter MacCallum Cancer Centre, Melbourne, AU, (2) The University of Texas MD Anderson Cancer Center, Houston, TX, (3) Centre Hospitalier de l'Université de Montréal, Montreal, QC

Purpose: To quantify change in apparent diffusion coefficient (ADC) of primary tumor on weekly magnetic resonance imaging (MRI) obtained during radiotherapy in patients with mucosal head and neck squamous cell carcinoma. **Materials and methods:** Patients with localized mucosal head and neck squamous cell carcinomas undergoing definitive radiotherapy were enrolled on the prospective IRB-approved PREDICT-HN study. Pre-treatment and weekly in-treatment MRIs were obtained in radiotherapy treatment position. T1-weighted, T2-weighted and DWI sequences were obtained on 1.5 T Siemens MRI. ADC maps were generated. Primary gross tumor volume (GTV) was contoured on T2-weighted MRI. GTV volume and ADC parameters were recorded. Patient, tumor and treatment characteristics were documented. As GTV decreases over time and measurements of ADC may be inaccurate, ADC values of pre-treatment GTV area across the serial MRI

were used for analysis. Longitudinal changes in ADC values were analysed using mixed models. **Results:** A total of 36 patients completed the study. The median age was 58.5 yr (range: 41–81 yr) and 33 were males. The predominant primary site of disease was tonsil (42%), followed by base of tongue (28%). Twenty-three (64%) had p16/HPV-positive disease. The median dose/fractionation delivered was 6996 cGy in 33 fractions. Twenty-three (64%) received volumetric modulated arc therapy (VMAT) and 13 had intensity modulated proton therapy (IMPT). Thirty patients (83%) received concurrent chemotherapy. The median pre-treatment GTV volume was 14.1 cc (range: 1.3–44.9 cc). Overall, there was significant decrease in GTV volume in week 4 of treatment (median of 81% decrease in size). The median ADC for pre-treatment GTV was 92 (range 16–1796). Throughout treatment, there was a significant rise across 25th–75th percentiles of ADC values ($P < 0.0001$). At 2- to 3-month post-treatment evaluation, 35 patients had complete response and 1 had partial response at the primary site on imaging. For the patient who had partial response, there was an initial rise in ADC values in weeks 1 to 4 but in weeks 5 and 6, the ADC values decreased to similar values as weeks 2 and 3. **Conclusions:** Preliminary results from this study showed that ADC changes significantly during radiotherapy. Further follow up is required to determine if changes in ADC during radiotherapy predicts for subsequent local failures.

4

Initial Clinical Experience Using 4D-MRI Based MR-Guided Online Adaptive SBRT on A High Field MR-Linac

Eric Paulson[1], William Hall[1], X. Allen Li[1], Michael Straza[1], Beth Erickson[1], Christopher Schultz[1], Nikolai Mickevicius[1], Xinfeng Chen[1], Ergun Ahunbay[1], (1) Medical College of Wisconsin, Milwaukee, WI

Purpose: MR-guided radiotherapy offers unique potential to safely escalate radiotherapy doses to mobile tumors. We describe here our first-in-man experience treating patients with abdominal tumors using a 1.5 T MR-Linac. **Materials and methods:** Four patients with abdominal tumors were treated with MR-guided online adaptive SBRT (MRgOASBRT) on a 1.5 T Elekta Unity MR-Linac. Pre-beam images were acquired using a 3D golden angle radial stack of stars sequence (275% spoke density, TE: 3.9 ms, TR: 6.8 ms, flip angle: 30°, 50 partitions). Immediately after acquisition, raw k-space data were transferred to a 96 core, 256 GB RAM Linux workstation positioned within the local MR-Linac network. Motion averaged, mid-position, and respiratory binned images were reconstructed using CG-SENSE or XD-GRASP. All images were corrected for gradient nonlinearity distortions prior to export to delineation and treatment planning systems for recontouring and plan adaptation. Both adapt-to-position and adapt-to-shape workflows were utilized. A parallel contouring strategy employing one therapist, physicist, and physician was employed in the adapt-to-shape workflow to reduce time-to-treat and chance of errors. Briefly, truncated structure sets from the reference plan were derived for physicians (targets and deforming OARs within 2 cm radius of PTV), physicists (external contour, bone, and air), and therapists (non-deforming OARs listed in IMRT constraints). The truncated structure sets were rigidly transferred to daily motion averaged or mid-position MR images. Team members contoured in parallel using a commercial delineation system. After contouring, the truncated structure sets were concatenated into a single structure set, approved by the physician, and then sent to a treatment planning system for plan adaptation. Completion of each task in the MR-gOART workflow was time stamped in a checklist for each fraction. Quantitative IVIM and T2 mapping was performed during plan adaptation. Real-time motion monitoring was performed during beam-on. Post-treatment verification images were obtained for dose reconstruction and accumulation. **Results:** The use of motion-averaged images was found to be acceptable for patients with small motions (<0.8 cm). Patients with larger motions required mid-position images which took slightly longer to reconstruct. Two patients were treated with the adapt-to-position workflow; two patients were treated with the adapt-to-shape workflow. All team members were comfortable contouring. The parallel contouring strategy was compatible with the vendor-provided adapt-to-shape workflow. The average recontouring time with the parallel workflow was 9 min. The average total time for an MR-gOART SBRT fraction was 49 min. Dose reconstructed on post-treatment images revealed no inconsistencies. For one patient, the accumulated dose to GI structures was sufficiently below the reference plan dose, which permitted administration of an additional treatment fraction. **Conclusions:** Our initial clinical experience using 4D-MRI based MRgOASBRT on a high field MR-Linac was a success, wtih all patients tolerating treatments. Contouring in parallel maximized utilization of human resources, reduced the pressure felt by one team member holding up the plan adaptation process, and gave each team member sufficient time to concentrate on their specific role and check each other's work. The high-performance computer architecture used for 4D-MRI also facilitates clinical use of other advanced MRI techniques (e.g., MR fingerprinting).

5

Clinical Dosimetric Benefit of the First 1.5T MR-Linac SBRT Treatments of Lymph Node Oligometastases Compared to Conventional CBCT-Linac Treatment

Dennis Winkel[1], Gijsbert Bol[1], Anita Werensteijn-Honingh[1], Martijn Intven[1], Wietse Eppinga[1], Jochem Hes[1], Louk Snoeren[1], Bas Raaymakers[1], Ina Jürgenliemk-Schulz[1], Petra Kroon[1], (1) UMC Utrecht, Utrecht, NL

Purpose: In August 2018 clinical treatment with the 1.5 T MR-linac system (Unity, Elekta AB, Stockholm, Sweden) commenced in our clinic. This system makes it possible to acquire daily magnetic resonance imaging (MRI) directly before and during each treatment session. The good soft tissue contrast allows for online adaptive radiotherapy treatment, as has been performed for stereotactic body radiotherapy (SBRT) of lymph node oligometastases. The purpose of this study was to compare clinical dosimetric outcomes of online adaptive radiotherapy treatment with the CBCT-linac VMAT back-up plans. **Materials and methods:** Dosimetric evaluation was performed for the first nine patients who have undergone SBRT of single lymph node oligometastases on the 1.5 T MR-linac with a prescribed dose of 5 × 7 Gy prescribed to 95% of the PTV with a 3 mm PTV margin. For each patient, a seven-beam IMRT pre-treatment plan was created using Monaco TPS (Elekta AB, Stockholm, Sweden), taking into account the presence of the 1.5T magnetic field. Beam angles were selected dependent on whether the target was located in the left or right side of the body. Additionally, a CBCT-linac VMAT back-up plan was created for each patient with a PTV margin of 3 or 8 mm, depending on target visibility during CBCT simulation. During each treatment session, a daily MRI was acquired. Contours were automatically deformed and, when necessary, adapted by a radiation oncologist. Based on the daily MRI and the adapted contours, a completely new treatment plan was generated using segment shape and weight optimization. The clinically delivered plans were compared with the VMAT CBCT-linac back-up plans, calculated on the daily MRI and contours, for all 45 fractions. For these plans, online position correction was simulated by placing the plan isocenter in the center of the PTV. The PTV coverage was compared and all plans were evaluated using clinical dose criteria: PTV $V_{35Gy} > 95\%$, PTV $D_{0.1cc} < 47.25$ Gy, ureter $D_{max} < 40$ Gy, bladder $V_{38Gy} < 0.5$ cc, bowel bag, rectum and sigmoid $V_{32Gy} < 0.5$ cc, nerve root $D_{max} < 35$ Gy and sacral plexus $V_{32Gy} < 0.1$ cc. **Results:** The clinically delivered 1.5 T MR-linac plans showed a significantly higher target coverage ($P < 0.01$, Wilcoxon matched-pairs signed rank test) with a median PTV V_{35Gy} of 99.9% [91%–100%] compared to a median PTV V_{35Gy} of 95.1% [86%–100%] for the CBCT-linac VMAT back-up plans evaluated on the daily anatomy. For the MR-linac and CBCT-linac all dose criteria were met for 35 out of 45 (78%) and 13 out of 45 (29%) fractions, respectively. The ten plans that did not meet all criteria on the MR-linac had organs at risk present very close to the PTV. In six of these plans, PTV coverage was slightly below criteria [V_{35Gy} 91%–94%]. Small violations of organ at risk constraints occurred for 7 MR-linac and 12 CBCT-fractions with a maximum of 2 Gy or 0.2 cc. **Conclusions:** Dosimetric evaluation of the first clinical SBRT treatments of lymph node oligometastases on the 1.5 T MR-linac yields beneficial DVH-parameters compared to conventional CBCT-linac treatment. The clinically delivered MR-linac plans yielded significantly higher PTV coverage and less unplanned violations of dose constraints for organs at risk.

6

Rapid and Accurate Automatic Contouring of Quantitative Diffusion-Weighted MRI Using A Deep Convolutional Neural Network

Oliver Gurney-Champion[1], Jennifer Kieselmann[1], Kee Wong[2], Kevin Harrington[1], Uwe Oelfke[1], (1) The Institute of Cancer Research and The Royal Marsden NHS Foundation Trust, London, UK, (2) The Royal Marsden NHS Foundation Trust, London, UK

Purpose: With the clinical introduction of the MR-Linac, daily treatment response monitoring with quantitative imaging, such as diffusion-weighted imaging (DWI), is feasible. However, retrieving the quantitative parameters for certain pathologies requires contouring regions of interest. Daily contouring adds a significant load to the clinical workflow. Furthermore, day-to-day

variation in the contours causes an additional uncertainty in response detection, especially when contouring is done rapidly and by different clinicians.

Therefore, we trained a deep convolutional neural network that automatically and systematically contours involved lymph nodes on DWI images of head and neck cancer patients for rapid automated daily assessment of apparent diffusion coefficient (ADC) and, ultimately, treatment response monitoring, throughout treatment. **Materials and methods: Data:** DWI images (field of view: 200 × 200 × 40 mm, 2 × 2 × 2 mm resolution, b = 50, 400 and 800 s/mm^2) were obtained from 48 patients[1] with a total of 58 involved lymph nodes, taken at baseline (48 patients), throughout neo-adjuvant chemotherapy (3 weeks: 18 patients; 6 weeks: 16 patients) and throughout radiotherapy (1 week: 33 patients; 2 weeks: 19 patients).

A radiation oncologist delineated the lymph nodes on the b = 50 s/mm^2 images, with help of a T2-weighted image, a post-contrast image and the b = 800 s/mm^2 DWI image.

We envision a clinical workflow in which a clinician can receive contours and ADC information by selecting a lymph node (mouse click) in the MRI. In this workflow, a bounding box (64 × 64 × 32 voxels) is placed centered at the selected voxel and used as input for the U-net. We used a 10-fold data-augmentation, consisting of different voxels selected for centralizing as well as mirroring images in right–left. **Network:** We implemented a 3D U-net in python using Keras and Tensorflow (Dice loss function; 30% dropout; batch normalisation; 64 base features; 4 pooling layers; 22 convolutional layers; learning rate: 2e-4; 100 epochs). We added a voxel-wise bias-layer[2] before each convolution. Training was done on the b = 50 s/mm^2 DWI image. An automated post-processing toolkit was developed to select the central lymph node of interest. **Evaluation:** We evaluated the performance using 8-fold cross-validation and calculating the Dice coefficient (1 means full overlap; 0 is no overlap) and absolute change in median ADC (measure used for detecting treatment response assessment; 0% is best) between the manual and the learnt contours for the patients at baseline and throughout radiotherapy. **Results:** We successfully trained the U-net. The Dice coefficient was on average 0.83 (0.83, 0.84 and 0.83) and the median ADC had a mean absolute change of 2.8% (3.0%, 2.5% and 2.7) compared to the expert (@baseline, 1 week RT and 2 weeks RT, respectively). These numbers are in the range of interobserver variation. **Conclusions:** Our network was able to contour DWI images and assess ADC values at high accuracy. We believe our network will be essential for clinical workflows in which treatment response is being assessed regularly, by reducing interobserver variability with more systematic contours, and reducing workload. We are interested in testing the algorithm on similar datasets from different institutions.

1. Wong, et al. EJNMMI; 2017.:
2. Dalca, et al. IEEE-CVPR; 2018.:

7

Implementation of MRI-Only Planning and Treatment for Accelerated Partial Breast Irradiation

Areti Marko, H. Michael Gach, Olga Green, Imran Zoberi, Maria Thomas, Justin Park, Washington University in St. Louis-School of Medicine, Saint Louis, MO

Purpose: Conventional RT planning requires the use of a CT simulation to provide relative electron density information for dose calculation. MRI is used as a secondary simulation that provides superior soft tissue contrast and target delineation compared to CT. However, it is preferable to minimize the number of simulations for the patient. Some MRI systems generate synthetic CTs that provide the electron density information for planning purposes. If an MRI unit does not have this capability, the use of bulk density overrides is still an option.

The purpose of this study is to determine if the use of bulk density overrides on an MRI dataset is comparable to the use of CT for Accelerated Partial Breast Irradiation (APBI) treatment planning, with the goal of eventually forgoing a CT simulation. **Materials and methods:** Retrospective analyses were performed for three cases of APBI that were originally planned with MRI only and then replanned with CT primary and MRI for cavity delineation. Bulk density overrides for cavity, lung, breast, heart, and skin were used for dose calculation. Coverage, hotspots, isodose lines, and DVH were reviewed to evaluate plan quality. Daily alignment comparisons were done to determine practicality. **Results:** Three patients were evaluated with dose calculations using the same optimization parameters in the MRI/CT fusion plan and the electron density information derived from the density overrides. D_{95} for the PTV calculated in the MRI-only plans varied by less than 1% from that calculated in the clinical plan. Similar agreement was observed in the other calculated metrics (D_{100} and D_{max}). Disagreements of greater than 1% arose from dose differences of <1 Gy, where discrepancies were largely inconsequential. The 3D gamma index comparing the clinical and proposed dose distributions yielded passing rates equal to or greater than 98% for all patients using a 2%/2 mm criterion. **Conclusion:** The future of radiation oncology will include the use of MRI as a primary image set. If an MRI unit is readily available in a clinic, clinicians can move forward with delineation and planning on MRI images for APBI with confidence in the bulk density overrides, and without the use of CT for electron density information. Trials are undergoing at our institution. This new process for MRI-only planning reduces the number of scans the patient undergoes and eliminates the need for image fusion, thus making the planning process more efficient.

8

Tumour Dynamics Assessment and Machine Learning Based Contour Propagation for Post-Operative MRI Based Adaptive Glioblastoma Radiotherapy

James Stewart, Sten Myrehaug, Young Lee, Chia-Lin Tseng, Hany Soliman, Jason Xie, Mikki Campbell, Angus Lau, Arjun Sahgal, Mark Ruschin, Sunnybrook Odette Cancer Centre, Toronto, ON

Purpose: Online magnetic resonance image (MRI) guided radiotherapy of glioblastoma is an encouraging approach to maximize the benefit of advanced radiotherapy techniques. However, the implementation of such methods is challenged by poor knowledge of tumour temporal dynamics and the difficulty of incorporating the imaging and planning requirements in a clinically realizable workflow. The goal of this study was twofold: to quantify tumour volume, position, and shape using serial MRIs, and evaluate a machine learning based algorithm to propagate gross tumour volume (GTV) contours from planning to successive imaging timepoints. **Materials and methods:** Twenty post-operative glioblastoma patients were prospectively imaged with Gadolinium-enhanced T1-weighted MRI at planning (Fx0), fractions 10 (Fx10) and 20 (Fx20) of radiotherapy, and one most post-radiotherapy (P1M). After manual delineation of the GTV, the following were quantified: GTV volume (TV), three-dimensional GTV centroid (CENT), and volume deviation from the planning GTV (DEV). For GTVs at Fx10, Fx20, and P1M, DEV is the proportion of the GTV outside the Fx0 GTV. GTV propagation from Fx0 to subsequent timepoints was performed using three methods: rigid cross-correlation (RIGID), deformable registration based on normalized mean squared difference and local cross-correlation (DEF), and machine learning using multiple atlases developed from all previous timepoints in conjunction with a random forest voxel classifier (ML). The propagations were compared to the manually contoured GTV using Dice similarity coefficient (DSC) and Hausdorff distance (HD) metrics. **Results:** The TV at Fx0 ranged from 4.5 to 72.0 cc (median 25.7 cc) and changed by ranges of −46.1 to +37.9% at Fx10, −52.2 to +29.2% at Fx20, and −62.5 to +94.9% at P1M (negative and positive values indicate GTV regression and growth, respectively). The majority of GTVs regressed; the median TV at the same timepoints was −21.2, −20.1, and −32.1%. Relative to Fx0, CENT varied by as much as (5.5, 5.5, 8.0) mm along the (left-right, anterior-posterior, superior-inferior) directions. CENT also showed a propensity to move towards the surgical incision. For left sided GTVs (n = 9), CENT moved to the left by a median 0.6, 1.2, and 0.5 mm at Fx10, Fx20, and P1M, respectively. Similarly, for right sided GTVs (n = 9), CENT moved to the right by 0.5, 1.3, and 1.7 mm. Median DEV across all patients was 11.1, 12.3, and 12.8% at Fx10, Fx20, and P1M, respectively, but reached as high as 32.4, 41.5, and 55.4% in individual patients. Propagation based on rigid registration was inadequate to capture these changes; for the RIGID method, median DSC and HD at (Fx10, Fx20, P1M) was (0.79, 0.71, 0.67) and (8.84, 9.81, 11.21) mm, respectively. The DEF method improved this agreement to (0.88, 0.85, 0.82) and (7.56, 9.51, 11.21) mm with the ML technique further increasing these results to (0.88, 0.90, 0.88) and (7.56, 7.56, 6.94) mm. **Conclusions:** Glioblastoma tumour dynamics during radiotherapy are variable among a patient cohort and frequent soft tissue imaging is necessary to ensure the robustness of inventive radiotherapy strategies. The machine learning based propagation method presented here will help maximize the benefit of these image intensive methods.

9

Multi-Modality Deformable Image Registration for External-Beam Radiotherapy and Brachytherapy Dose Accumulation

Aran Kim[1], Michelle Tremblay[1], Stina Svensson[2], Minna Wedenberg[2], Peter Chung[1], Tim Craig[1], Tony Tadic[1], Alejandro Berlin[1], Michael Velec[1],
(1) Princess Margaret Cancer Centre, Toronto, ON, (2) RaySearch Laboratories, Stockholm, SE

Purpose: MR-based radiotherapy planning is increasingly being used in clinic, often in conjunction with co-registered CT imaging. Deformable CT to MR registration is challenging due to large anatomic changes between acquisitions and differences in image intensities. External-beam radiotherapy (EBRT) plus brachytherapy (BT) boosts for prostate patients are planned on CT and MR images at our institution, respectively, requiring deformable registration for accumulation of total planned doses. The purpose of this work is to evaluate multi-modality deformable registration between CT and MR and identify the technique to perform accurate dose accumulation between EBRT and BT. **Materials and methods:** Initial testing was performed on 20 patients with prostate fiducial markers who underwent MR with normal rectum (i.e., not empty) and a repeat MR with an endorectal coil, for a prior study. Three DIR algorithms were evaluated in a treatment planning system (RayStation v6, RaySearch Laboratories): hybrid contour/intensity-based, contour only-based, and biomechanical-based algorithms. Registration accuracy was quantified as the mean surface distance-to-agreement (DTA) between rigid vs DIR-mapped contours of the prostate, rectum, and bladder. Internal prostate accuracy was also quantified using the residual 3D distance of the fiducial markers. Subsequent DIR validation was performed for 14 patients treated on a trial of whole gland BT (HDR 15 Gy, 1 fraction) followed by EBRT without fiducial markers (VMAT, 37.5 Gy, 15 fractions). BT was planned on MR with an endorectal coil and empty bladder and EBRT was planned on CT with empty rectum and full bladder. Each distribution had voxel-by-voxel linear-quadratic corrections to radiobiologically equivalent doses in 2 Gy fractions (EQD2) prior to deformation and accumulation. **Results:** On the initial MR to MR data, the mean DTA was sub-millimeter for the prostate and bladder surfaces for all 3 algorithms, while the rectum was 1.4 ± 0.5, 0.5 ± 0.2 and 1.6 ± 0.5 mm for the hybrid, contour-only and biomechanical DIR respectively. The internal prostate accuracy was 4.1 ± 1.4, 2.7 ± 0.7 and 2.2 ± 0.7 mm for the hybrid, contour-only and biomechanical DIR respectively. Given the larger errors, hybrid DIR was eliminated from further testing. On the MR to CT data, the mean DTA was sub-millimeter for the prostate and bladder while the rectum was 1.2 ± 0.4 mm with biomechanical DIR vs 3.3 ± 4.0 mm with contour-based DIR. Therefore, using the best overall performing algorithm (biomechanical DIR) the mean accumulated total EBRT plus BT doses in EQD2 were 87.3 ± 13.0 Gy for at least 99% of prostate volume, 22.6 ± 5.1 Gy for at most 50% of bladder volume, and 23.0 ± 7.6 Gy for at most 50% of rectum volume. **Conclusions:** Substantial anatomic variability between EBRT and BT images, particularly the rectum, is challenging for DIR. A biomechanical-based algorithm performed the best overall for CT to MR registration at organ surfaces and internal landmarks, both of which are necessary for accurate accumulation of dose. This technique is a critical step towards developing a pipeline between EBRT and BT. Potential clinical applications include unified adaptive planning strategies between CT and MR images and unveil total accumulated dose-response relationships for tumor control and toxicity.

10

Predictive Value of ADC Before Chemoradiotherapy for Survival in Esophageal Cancer

Keiichi Jingu, Maiko Kozumi, Takaya Yamamoto, Rei Umezawa, Noriyoshi Takahashi, Tohoku University Graduate School of Medicine, Sendai, JP

Purpose: To evaluate correlations between results of definitive chemoradiotherapy (dCRT) in esophageal squamous cell carcinoma and histogram-derived apparent diffusion coefficient (ADC) parameters on diffusion-weighted MR images. **Materials and methods:** The eligibility criteria were (a) oesophageal SCC histologically proven by upper endoscopic biopsy, (b) clinical stage T3 or 4 defined on primary staging chest and abdominal CT scans, (c) no prior chemotherapy, radiotherapy or surgical treatment, (d) no distant metastasis and (e) no other active cancer. Forty consecutive patients (36 men, 4 women; mean age, 68.4 yr; age range, 51–88 yr) with esophageal squamous cell carcinoma who were treated by dCRT in our institution between September 2012 and October 2015 were included in this prospective study. All patients received chemotherapy concurrently during definitive radiotherapy. MR examination at 3 T was performed 1–3 days prior to dCRT. Readout-segmented echo-planar diffusion imaging was used to acquire ADC maps. All region of interest (ROI) placement on DWI with b = 50 s/mm^2 was decided by the two readers referring to the outline of the tumor that showed intermediate to high intensity with esophageal wall thickening on T2-weighted images. Each ROI was placed to cover the entire primary lesion without the lumen in multiple slices (in cranio-caudal direction also) and was transferred to the corresponding ADC map. Pre- and post-treatment CT examinations were performed. Histogram parameters (mean, 10th, 25th, 50th, 75th, 90th percentiles, skewness and kurtosis) of ADC values were compared with post-treatment disease status based on RECIST, tumor regression ratio and survival. **Results:** The median follow-up period of survivors was 46 months (range, 2–74 months). The mean values of the largest tumour diameter on pre- and post-treatment CT images were 32.0 ± 8.9 mm and 21.1 ± 8.6 mm, respectively ($P < 0.001$). Post-treatment status was CR in 15 patients (37.5%), PR in 16 patients (40%) and SD in 9 patients (22.5%). No patient was categorized as PD. The mean tumour regression ratio was 34.4 ± 18.9%. The mean 50th percentile ADC values were $(1.39 \pm 0.27) \times 10^{-3}$ mm^2/s in patients with CR or PR and $(1.35 \pm 0.18) \times 10^{-3}$ mm^2/s in those with SD ($P = 0.61$). None of the ADC parameters was significantly correlated with post-treatment status (Spearman's ρ = -0.19–0.14, P = 0.22–0.47) or tumor regression ratio (Spearman's $\rho = -0.045$–0.18, p = 0.26–0.96). There was also no significant correlation between any of the patients' characteristic data (sex, age and clinical T stage) and treatment response. However, there was a significant difference in overall survival between the lower arm (< median) and the upper arm (≧median) of the mean ADC parameter (4-yr, 18% vs 52%, log-rank test; $P = 0.025$). **Conclusions:** Our results suggest that pre-treatment ADC parameters obtained from readout-segmented echo-planar DWI are not correlated with tumor response after dCRT; however, mean ADC before dCRT could predict overall survival of patients with esophageal squamous cell carcinoma.

11

Cardiac MRI Left Ventricular Mapping of LEft-Sided Breast Cancer Patients Treated with Tangential Radiotherapy Alone

Simon Tang[1], James Otton[1], Eng-Siew Koh[1], Robba Rai[1], Geoffrey Delaney[1], David Tran[1], Liza Thomas[2], Lois Holloway[1], Gary Liney[1], (1) University of New South Wales Kensington, Sydney, AU, (2) University of Sydney, Sydney, AU

Purpose: Acute and subacute cardiac pathological changes following radiotherapy (RT) include inflammation, decreased capillary density and early myocardial fibrosis. Using a novel quantitative cardiac MRI technique, this study aimed to determine if T1/T2 and extracellular volume maps could detect early cardiac changes in the myocardium in breast cancer patients treated with tangential breast radiation alone. **Materials and methods:** Twenty-three female left sided breast cancer patients [median age 59 (38–76)] were recruited October 2015 and October 2016. Three cardiac MRI scans were obtained, a baseline scan 2–3 days before adjuvant RT, 6 weeks and 12 months post RT. No patients received chemotherapy. All patients except one received 42.4 Gy in 16 daily fractions. A clinical modified look locker inversion sequence was used to acquire short axis T1 maps, pre and 15 min post administration of gadolinium – based contrast agent (Gadovist) as well as T2 maps at 3T. Extracellular volume (ECV) was derived from pre and post contrast T1 maps. Two independent T1/T2 map segmentations of the left ventricle (LV) were performed in cvi42 and averaged for analysis. Standard cardiac parameters were acquired from single breath-hold (SSFP) cine acquisitions of the cardiac short axis. Paired *t*-testing was performed between baseline T1/T2 and ECV values, and 6 week, and 12 month values. A $P < 0.05$ was considered statistically significant. Radiotherapy doses were to the whole heart, regions and segments according to the American Heart Association 16 segment model were recorded. **Results:** Average mean heart dose was 2.6 Gy. The basal, mid and apical regions of the left ventricle received an average mean dose of 1.7 Gy, 3.9 and 16.3 Gy respectively. Regionally, a significant increase in T2 relaxation was noted at 12 months in the mid region of the left ventricle (42.6 vs 44.4 ms $P = 0.03$). Segmentally, at 6 weeks post RT segment 12 (43.5 vs 42.1 ms $P = 0.02$) had a significant reduction in T2 relaxation and segments 5 (28.3 vs 27.2% $P = 0.2$), 9 (29.1 vs 27.6% $P = 0.01$) and 10 (28.7 vs 27.1% $P = 0.01$) had significant reductions in ECV values. At 12 months, segment 11 demonstrated an increase in both T1 (1192.4 vs 1218.0 ms $P = 0.03$) and T2 (41.7 vs 44.1 ms $P < 0.01$) relaxation, with segment 10 (42.0 vs 43.7 ms $P = 0.03$) demonstrating an increase in T2 relaxation only. An increase was seen in myocardial mass at 6 weeks (102.7 vs 108.9 g $P = 0.05$) and 12 months (102.7 vs 109.2 g

$P = 0.05$) post RT when compared with baseline. There were no associated changes in LV end diastolic and end systolic volumes. **Conclusion:** Preliminary results from this small study indicate isolated T2 signal changes involving the mid region at 6 weeks post RT, and discrete segmental changes involving the basal inferolateral, mid inferoseptal, inferior and inferolateral segments, associated with an increase in myocardial mass. Further studies are required to verify this pattern of change following tangential left breast irradiation and to determine their correlation with subsequent cardiac events.

12

Pretreatment ADC Shows No Added Value for the Prediction of Local Recurrences in Head and Neck Squamous Cell Carcinoma

Marielle E. P. Philippens, Juliette Driessen, Jeanine Vasmel, Remco de Bree, Chris H. J. Terhaard, University Medical Center Utrecht, Utrecht, NL

Purpose: In head and neck squamous cell carcinoma, pretreatment identification of radio-insensitive tumors would affect treatment planning. ADC has been reported to be a predictor of local recurrence. However, correction for known clinical parameters such as tumor volume has rarely been performed. The aim of this study is to find the added value of ADC to tumor volume in predicting local recurrence. **Material and methods:** This retrospective cohort study included 217 patients with T2–T4 oral cavity, oropharyngeal, laryngeal or hypopharyngeal squamous cell carcinoma. All patients were treated with (chemo) radiotherapy, prior to treatment an MRI examination was performed. The tumor delineation procedure was semi-automatic. First, a seed point was placed in the tumor on the axial DW-MRI with the highest available b value (800 or b1000 s/mm^2) and with a maximum intensity threshold of 50% the tumor was segmented. The delineation was transferred to the ADC map and high intensity areas at the edges of the segmentation were manually removed. The variables obtained from this segmentation were median ADC and total volume. The predictive effect of the variables on local recurrence was analyzed in univariable and multivariable regression. **Results:** Univariate analysis showed no significant correlation between tumor ADC and local control within 3 yr after (chemo)radiotherapy. However, tumor volume was predictive for local recurrence. Multivariable cox regression including ADC and volume showed that tumor volume was an independent predictor of local recurrence with a hazard ratio of 1.032 (CI95% 1.020–1.044). ADC was not an independent predictor of local recurrence. **Conclusion:** ADC has no added value in predicting local control in patients with HNSCC. Tumor volume, however, is predictive of recurrence.

13

Cardiac Substructure Segmentation with Deep Learning for Improved Cardiac Sparing

Eric Morris[1], Ahmed Ghanem[1], Ming Dong[2], Hajar Emami[2], Milan Pantelic[1], Eleanor Walker[1], Carri Glide-Hurst1, (1) Henry Ford Cancer Institute, Detroit, MI, (2) Wayne State University, Detroit, MI

Purpose: Radiation dose to sensitive cardiac substructures is related to radiation-induced heart disease. However, substructures are not currently considered in radiation therapy (RT) treatment planning due to their poor visualization on computed tomography simulation (CT-SIM) datasets, whereas magnetic resonance imaging (MRI) provides exceptional soft tissue contrast in the heart. Currently available auto-segmentation and atlas-based methods are limited in the segmentation of small, complex structures such as the coronary arteries. This work presents a novel deep learning pipeline that incorporates MRI/CT information into deep learning for the generation of high quality, efficient cardiac substructure segmentations and compares it to our previously developed multi-atlas segmentation method. **Materials and methods:** Thirty-two left-sided whole-breast cancer patients underwent cardiac T2 MRI and CT-SIM scans in an Institutional Review Board approved study. A rigid cardiac-confined MR to CT registration was performed to enable a radiation oncologist to delineate 12 cardiac substructures (chambers, great vessels, coronary arteries, etc.) as ground-truth. Paired MRI and CT data were placed into separate image channels along with indexed ground-truth images for 25 patients to train a 3-dimensional Neural Network (3D U-Net) using all substructures simultaneously. The network was trained using the entire 3D image (batch size = 1). To manage the different image features among substructures, a Dice-weighted multiclass loss function was utilized. Deep supervision was implemented by adding segmentation layers in the localization pathway and then applying an elementwise summation to generate the final segmentation. Data augmentation (scaling, rotation, flipping, and translation) was used to prevent overfitting and results were compared pre/post augmentation. Network testing was conducted using 11 test patient CTs (7 unique patients). Comparisons of network predictions to ground-truth delineations were completed using Dice similarity coefficient (DSC) and mean distance to agreement (MDA). **Results:** The model stabilized in ~17 h after 200 epochs (training error < 0.001). Data augmentation increased DSC ~5% across all substructures. Deep learning provided accurate segmentations for the chambers (DSC = 0.87 ± 0.3), great vessels (DSC = 0.85 ± 0.3), and pulmonary veins (DSC = 0.71 ± 0.3). DSCs for the left anterior descending artery, right coronary artery, and left main coronary artery (LMCA) were 0.52 ± 0.04, 0.51 ± 0.05, and 0.35 ± 0.07, respectively. MDA across all 12 substructures was <2.0 mm (MDA 1.51 ± 0.5 mm) with an MDA in the great vessels of 1.11 ± 0.2 mm. Compared to our previously developed multi-atlas method, DSC agreement to ground-truth increased 9%–11% for the superior/inferior vena cava and pulmonary vein, 3%–7% for chambers, and 23%–35% for the coronary arteries. On average, MDA also improved by ~1.4 mm with deep learning. For four test CTs, our trained U-Net yielded LMCA contours, whereas our previous atlas-based model failed to produce any segmentation. Substructure contour generation takes ~5 s (<1% of multi-atlas segmentation time). **Conclusions:** These promising preliminary results suggest our novel deep learning application offers major efficiency and accuracy gains for cardiac substructure segmentation over previously published multi-atlas results, using only non-contrast CT inputs. Future work involves further refinement of coronary artery segmentation using conditional random fields and expanding the patient cohort. Coupled with robust margin design, improved cardiac sparing in treatment planning can be realized.

14

Clinical Evaluation of a Prototype Receiver Coil Custom Designed for MR Simulation of Immobilized Patients

James Balter, Dinank Gupta, Michelle Kim, James Hayman, Karen Vineberg, Yue Cao, University of Michigan, Ann Arbor, MI

Purpose: A prototype RF receiver coil, designed for use primarily with a commercial immobilization system for frameless stereotactic radiosurgical precision treatments, was evaluated using phantom and clinical measurements. **Materials and methods:** The ACR MRI phantom was scanned on a 3T scanner with this coil. Image-based measurements were evaluated, and SNR compared to values from the uniform region scanned using two commercially available coils: (a) a standard Head/Neck 20 Channel Coil and (b) a combination of an 18-channel surface coil placed anterior to the phantom with 4 channels of a posterior spine coil (RTcombo) routinely used for scanning immobilized patients in the clinic.

Under an Institutional Review Board approved protocol, human images were acquired for 8 patients immobilized for intracranial stereotactic treatments with the intent of supporting MR-only simulation. Standard T1-weighted post-contrast, T2 FLAIR, diffusion weighted (using an echo planar sequence), and T1 VIBE Dixon images in support of synthetic CT generation for MRI-only treatment planning and positioning support were acquired.

Diffusion weighted images (at b = 0) were analyzed to estimate the relative signal to background ratio and compared to reasonably comparable information from other subjects scanned under different research protocols using the 20 channel coil.

Synthetic CT image volumes were generated, using a U-net architecture trained on 6500 MR-CT image pairs, from T1-weighted (in-phase) images acquired using a Dixon VIBE sequence. These images were compared to simulation CT scans acquired for radiosurgical treatment planning for intensity similarity, accuracy of dose calculation, and accuracy of alignment to Cone Beam CT (CBCT) scans used for patient positioning. **Results:** The prototype coil passed all ACR phantom test criteria. SNR, measured in the center of the uniform section of the phantom, was 88.5, 89.9 and 44.4 for the prototype, 20-channel and RTcombo coils, respectively.

Images were qualitatively reviewed by a physician specializing in intracranial treatment and deemed to be potentially noisier than those acquired on other patients using the 20 channel coil, but of sufficient quality for clinical use nonetheless. DWI analysis showed higher signal to background ratio for the prototype coil (20.7) vs the 20 channel coil (15.6).

The synthetic CT image volumes compared well with simulation CT scans, with average Mean Absolute Error values of 4.7, 180.5 and 5.7 HU in regions of brain parenchyma, skull, and ventricles. Treatment plan comparisons showed dose differences of 2.3 ± 0.9% of the mean dose to the planning target volumes, comparable to differences seen with synthetic CT scans generated on patients with the RTcombo coils. Alignment with CBCT yielded a mean difference between CT and Synthetic CT of 0.1 mm (standard

deviation of 0.3 mm) across all patients. **Conclusions:** Tests performed on a dedicated coil in support of MR-only simulation for immobilized radiosurgery patients demonstrate image quality comparable to commercial general purpose coils for clinical use. Synthetic CT images generated using this coil are similarly of sufficient quality to support MR-only treatment planning and image guided patient positioning for radiosurgery.

(Supported by NIH R01EB016079 and QFIX).

15

Lung Volume Effect on Thoracic CT-MR Deformation in MR-Guided Radiotherapy (MRGRT) with a Swine Model

Kathryn Mittauer, Mattison Flakus, Antonia Wuschner, Jessica Miller, Michael Lawless, Michael Bassetti, Jennifer Meudt, Dhanansayan Shanmuganayagam, John Bayouth, University of Wisconsin, Madison, WI

Purpose: MR-guided radiotherapy (MRgRT) utilizes deformable image registration (DIR) for electron density mapping through deforming the simulation CT to simulation MR frame of reference during initial plan creation. We have quantified the effect of lung volume change from CT to MR on the accuracy of electron density deformation in a swine model, Wisconsin Miniature Swine™ (WMS™). **Materials and methods:** Five WMS™ underwent a stereotactic MR-guided online adaptive radiotherapy (SMART) course of 60 Gy in 5 fractions to the lung on a clinical MRgRT system. Prior to each MRgRT fraction, the WMS™ underwent three CT scans: maximum inspiration breath hold (MIBH) CT (CT_{MIBH}), maximum exhalation breath hold (MEBH) CT (CT_{MEBH}), and a 4DCT. All scans were acquired under a fixed total lung capacity using an anesthesia ventilator for respective MIBH and MEBH maneuvers. In this study, to evaluate the impact of lung volume change on the accuracy of CT-MR DIR, extreme breath hold maneuvers (MIBH vs MEBH) were evaluated. CT_{MIBH} and CT_{MEBH} scans for one fraction, of each of the five WMS, were retrospectively imported into a clinical MRgRT treatment planning system and deformed to the daily MR frame of reference, acquired under MIBH (MR_{MIBH}). The MRgRT vendor-provided DIR algorithm used was an inverse consistent, free-form multi-modality deformation with a similarity metric of mutual information and regularization term proportional to the Jacobian of the deformation vector field.

The DIR accuracy of CT_{MIBH}-MR_{MIBH} and CT_{MEBH}-MR_{MIBH} was assessed in three methods: (a) calculation of the mutual information (MI) between the deformed CT_{MIBH} and CT_{MEBH} with respect to the MR_{MIBH}, (b) mean absolute error (MAE) in the electron density of the Hounsfield unit (HU) of the lung as segmented on the MR_{MIBH} and reported with respect to the deformed CT_{MIBH} and $CT_{MEBH,}$ (c) 3D gamma analysis (3% dose difference/3 mm distance to agreement) of the SMART IMRT dose distribution calculated with the deformed electron density of the CT_{MIBH} vs CT_{MEBH}. **Results:** In total, ten CT-MR deformations were assessed among the five WMS. Lung volume differences from CT_{MIBH} to MR_{MIBH} was -490.5 ± 258.9 ml and from CT_{MEBH} to MR_{MIBH} was $+1021.8 \pm 211.8$ ml. No difference was observed for the MI between CT_{MIBH}-MR_{MIBH} and CT_{MEBH}-MR_{MIBH} (0.73 vs 0.76, $P = 0.6256$). The lung MAE (N = 10 ROIs) was 37.9 ± 34.9 HU for CT_{MIBH}–MR_{MIBH} and 299.9 ± 37.2 HU for CT_{MEBH}–MR_{MIBH} ($P < 0.0001$). Comparing the dose distributions resulting from difference in electron density between the deformed CT_{MIBH} and CT_{MEBH}, the gamma passing rate was $90.66 \pm 8.67\%$. Greatest differences in deformation (MAE > 295 HU) and mean PTV dose difference (>8.5%) resulted with tidal volume differences from CT to MR was >1093 ml (n = 3 cases). **Conclusions:** At extreme breath hold maneuvers, reduced CT-MR deformation accuracy was observed ($P < 0.0001$). Specifically, when the tidal volume differs by greater than 1000 ml, clinically acceptable CT-MR deformations are seen, and therefore tidal volume mismatch between CT-MR of greater than 1000 ml should be avoided. Future work will quantify the precise tidal volume through the 4DCT phases at which clinically unacceptable deformations and dose differences result.

16

Cross-Modality Deep Learning: Contouring of MRI Data from Annotated CTS Only

Jennifer Kieselmann[1], Oliver Gurney-Champion[1], Brian Hin[1], Simeon Nill[1], Clifton Fuller[2], Uwe Oelfke[1], (1) The Institute of Cancer Research and The Royal Marsden NHS Foundation, London, UK, (2) MD Anderson Cancer Center, Houston, TX

Purpose: The clinical introduction of MR-guided RT systems enables daily treatment adaptations. To fully utilise benefits from daily adaptations, daily delineation of volumes of interest (VOI) is required. This time-consuming process, known to be subject to large inter-expert variabilities (IEV), would benefit from automation. Therefore, we aim to automate delineation of VOIs using a deep convolutional neural network (CNN). Due to a lack of annotated training data, only few studies on using CNNs to segment VOIs on MR images have been reported. A general approach to tackle the lack of training data is to augment data with random rotations and translations. However, these simple methods do not capture large variabilities existing in the full population of patients' anatomies. Furthermore, this is only feasible if there is already sufficient annotated data available and both annotation and training need to be repeated for every novel MR contrast setting. In this study we solve these shortcomings by exploiting the wealth of publicly available annotated head and neck (H&N) CT images and generating synthetic MR images via an image style transfer network, instead. We then use these synthetic MR images to train a 2D CNN to automatically delineate the parotid glands on real MR data. **Materials and methods:** Imaging data consisted of a CT and an MR database of H&N patients. The MR database contained 27 T2-weighted pre-treatment images ($256 \times 256 \times 30$ voxels of $1 \times 1 \times 4$ mm^3; 3T scanner) acquired at the MD Anderson Cancer Center (Houston, USA). The CT database contained 202 CT images from the Cancer Imaging Archive and MICCAI H&N segmentation challenge. Each database included manual contours of the parotids. We performed contrast stretching for both CT and MR images and mapped intensities to a common range. The unpaired CT and MR images were then fed into a 2D CycleGAN network to generate synthetic MR images for each of the 202 CT images. Annotations of the synthetic MR images were generated by propagating the CT contours. We consequently selected synthetic MR axial slices to train a 2D CNN using the U-Net architecture. Prediction was performed on the 27 3D real MRIs. Performance was evaluated by calculating the Dice similarity coefficient (DSC) and mean surface distance (MSD) between manual and auto-generated contours and compared to the pairwise IEV between 3 observers. **Results:** With an average DSC of 0.76 ± 0.07 and an average MSD of 2.57 ± 0.91 mm, the accuracy was close to the MR IEV of 0.84 ± 0.06 (DSC) and 1.50 ± 0.77 mm (MSD), respectively. **Conclusions:** This technique of cross-modality learning can be of great value for segmentation problems where not a lot of annotated training data is available. We anticipate using this method with any small MR training dataset to generate synthetic MR images of the same type via image style transfer from CT images. Furthermore, as this technique allows for fast adaptation of annotated datasets from one imaging modality to another, it could prove to be useful for translating between large varieties of MRI contrasts due to differences in imaging protocols within and between institutions.

17

The Effect of Magnetic Field on Dose Distribution of HDR CO-60 and IR-192 Sources

Hassan Ali Nedaie, Tehran University of Medical Sciences, Tehran, IR

Purpose: MR-linac machines are being developed for image-guided radiation therapy, but the magnetic field of such machines could affect dose distributions. The purpose of this work was to evaluate the effect of MR magnetic field on HDR Co-60, Ir-192 sources dose distribution when are used in the MR-linac bunker at the presence of 1.5 T magnetic field. **Materials and method:** HDR brachytherapy sources Co-60 and Ir-192 were simulated in the Geant4 Monte Carlo code in the presence of a homogenous magnetic field of 1.5 T which is used in the MR- linac machine. The correct physical dimensions of the seeds were acquired from the website and other dosimetric parameters also calculated by Monte Carlo code. The magnetic field was applied both perpendicularly and parallel to the longitudinal axis of the seeds. A $15 \times 15 \times 15$ cm grid comprising small voxels of uniform 1 mm resolution in each direction was used for dose scoring in a water phantom. Calculated isodose distributions were compared. All the isodose lines were normalized to the delivered dose to a 1 cm away from the transverse axis. **Results:** The results have shown that in the presence of a magnetic field when the magnetic field is applied transversely and perpendicularly, the dose profile distribution in the water phantom unaffected in all planes for both sources. **Conclusion:** The presence of a homogenous 1.5 T magnetic field for both HDR sources do not affect the profile dose distribution at both transverse and perpendicular plane. These results show that one could use the HDR machine in the same room of MR-linac machine and use concurrent MR imaging for accurate treatment.

18

Implementing an Adaptive MRI Guided Radiation Therapy Program Using A Phantom and Volunteers

Eenas Omari, John Roeske, Tamer Refaat, Anil Sethi, Loyola University Chicago, Maywood, IL

Purpose: Implementing an online MRI guided adaptive radiotherapy (MRIgART) program requires commissioning of the adaptive process by a qualified medical physicist (QMP). This includes the verification of both the treatment planning system (TPS) and the treatment delivery system (TDS). In this work, we implement a two-phase approach. The First is by QMP commissioning using a phantom and the second phase is using volunteers with the help of team members involved in the adaptive workflow, including: radiation oncologists (RO), medical dosimetrists (CMD), radiation therapists (RT), and QMP. This approach increases efficiency of the verification process while simultaneously providing training for members involved, causing a smoother implementation of the clinical workflow. **Materials and methods:** Phantom- and volunteers were used to commission. For the phantom based approach, a cylindrical phantom with a multi-plug ion chamber plus was used. The phantom was CT and MRI simulated. The commissioning process was divided into the verification of (a) the treatment planning system (TPS), and (b) the treatment delivery system (TDS). A plan was generated including all parameters required for adapting; this included verifying contours, Boolean operations, correct electron density override assignment, and appropriate settings. The phantom was then set-up to verify the TDS and the adaptive work flow was tested. We then implemented a team approach to verifying the ART workflow using volunteers. MRI simulations were performed by the RT and images were imported into the TPS by a CMD. For TPS verification, PTV and OARs were respectively drawn by RO and CMD. Bulk electron density assignment were used. The CMD also created optimization structure with Boolean operations to reduce contouring time on the machine. Clinically acceptable plans were generated by the CMD and reviewed by the QMP. The RO then reviewed the final plan prior to approving for delivery. Patient specific plan QA was performed by the QMP. The TDS verification was performed by simulating a patient treatment. For each volunteer; set-up positioning, image acquisition and registration were performed by the RT and reviewed by the RO. A CMD edited OAR structures followed by RO review. The QMP applied density overrides and Boolean operations. The dose was then re-calculated on the daily images by the QMP. The RO reviewed the plan and made a decision on whether to re-optimize. The QMP performed the optimization and a secondary check using a Monte Carlo based algorithm. Following the online treatment process. Offline quality assurance was performed by the QMP. **Results:** The volunteer approach for commissioning took 2.5 times longer than the phantom based approach. However, the volunteer commissioning time was halved with a team-based approach. Team members gained more confidence and were better prepared to start the MRgART program. **Conclusion:** Efficiency was increased with the volunteer team approach to commission MRgART opposed to QMP alone verification. This method also served as training for all individuals involved in the adaptive workflow. Patients treated with MRgRT will also benefit from this approach due to more efficient clinical work-flow.

19

Treatment Response on MR During Radiotherapy in Patients with Head and Neck Squamous Cell Carcinoma

Boris Peltenburg, Marielle Philippens, Remco de Bree, Chris Terhaard, University Medical Centre Utrecht, Utrecht, NL

Purpose: In head and neck radiotherapy, early recognition of patients with poor response to treatment is important and might allow for treatment modification. Conventionally, tumor volume changes are used to assess treatment response. Recently, apparent diffusion coefficient (ADC) determined by diffusion weighted magnetic resonance imaging (DW-MRI) has been introduced as a prognostic factor in patients with head and neck squamous cell carcinoma Aim: To follow treatment response on DWI and T2 weighted images of head and neck tumors. **Material and methods:** Twenty-five patients with stage II, III or IV head and neck squamous cell carcinoma were included in the PREDICT study. Three patients had HPV positive tumors. Treatment consisted of radiotherapy with or without concurrent chemotherapy. All patients underwent MRI prior to and during week 2, 3, 4 and 5 of the radiotherapy treatment. Imaging was obtained with the patient positioned in the radiotherapy mask. Tumor delineation was performed on T2 weighted images for the baseline MRI and each subsequent MRI. Volume changes were determined using these delineations. The ADC changes in 20 patients were determined by delineating the baseline ADC map b = 800 s/mm^2 images using a semi-automatic method. This delineation was copied to the corresponding ADC map and ADC maps of subsequent weeks. Median ADC values for each available delineation were extracted. A follow up of at least 3 months was available for all patients. **Results:** During (chemo)radiotherapy tumors generally reduce in size with each passing week. On average the tumors were only 50% of their original size at the end of the third week of treatment. However due to the treatment effects, tumors are increasingly harder to differentiate from nonmalignant tissues in the treatment area. At the end of the fifth week only 25% of the original tumor volume was visible on T2. In one patient the tumor visibly increased in size from the third week onward. This patient had a local recurrence within 3 months after treatment. In total four patients had a recurrence. ADC generally increases during therapy. The fractional change in median ADC between the baseline and third week of treatment (fΔADC3) was on average 1.25. A cutoff of 32% increase in ADC at week 3 resulted in a sensitivity of 100% and specificity of 81%. **Conclusion:** During (chemo)radiotherapy, T2 images can be used to measure tumor volume. Generally, tumors decrease in size during treatment. A large increase at week 3 however, might predict a recurrence of tumor.

20

An IPEM International Audit of MRI Use for External Beam Radiotherapy Treatment Planning

Richard Speight[1], Maria A. Schmidt[2], Gary Liney[3], Robert Johnstone[4], Cynthia L Eccles[5], Michael Dubec[5], Ben George[6], Ann Henry[1], Tufve Nyholm[7], Faisal Mahmood[8], Juha Korhonen Kymenlaakso[9], Rick Sims[10], Rob H.N. Tijssen[11], Hazel McCallum[12], (1) Leeds Teaching Hospitals NHS Trust, Leeds, UK, (2) Royal Marsden NHS Foundation Trust and Institute of Cancer Research, London, UK, (3) Ingham Institute for Applied Medical Research & Liverpool Hospital, Sydney, AU, (4) Guy's and St. Thomas' NHS Foundation Trust, London, UK, (5) The Christie NHS Foundation, University of Manchester, Manchester, UK, (6) University of Oxford, Oxford, UK, (7) Umea University, Umea, SE, (8) Odense University Hospital and University of Southern Denmark, Odense, GER, (9) Central Hospital and Aalto University, Kotka, FI, (10) Auckland Radiation Oncology, Auckland, NZ, (11) University Medical Center Utrecht, Utrecht, NL, (12) Newcastle upon Tyne Hospitals NHS Foundation Trust, Newcastle, UK

Background: Despite documented benefits of MRI integration in external beam radiotherapy (EBRT) treatment planning pathways, routine uptake varies globally. Challenges cited include financial, technical and knowledge-based barriers. **Objectives:** To assess the current international landscape of MRI in EBRT use, to understand how MRI is used/managed and to identify barriers to its routine implementation in EBRT. **Materials and methods:** A six-section survey was developed by a multi-disciplinary IPEM working-party exploring: MRI access; MRI use; MRI to CT registration; commissioning/QA/safety; workflow/ staffing/education; and future applications. The survey was distributed in 10 countries by a 'local champion' ensuring it reached academic/non-academic clinical radiotherapy centres. **Results:** This abstract reports on the first six countries in which the audit has been closed, namely the UK (UK), Denmark (DK), Finland (FN), Sweden (SE), the Netherlands (NL) and New Zealand (NZ). Of 129 centres surveyed, 111 responded (86%). Both DK/FN had 100% response rates from 8 and 13 centres respectively; NZ/SE had the lowest response rate at 67% (6 of 9 centres responding each).

The UK reported the lowest access (69% of centres). Of the reported MRI access most centres used either dedicated radiotherapy MRI scanners (>80% DK/SE) or radiology MRI scanners (>80% NL/UK/FN/NZ). 3 T scanners were used in >80% of SE/NL centres, whilst in other counties >70% have access to 1.5 T systems.

Variation in the use of auxiliary equipment for MRI in EBRT planning was reported. Lasers/flat MRI couch-top were used in >80% of DK/SE centres, but <50% of centres in the UK/NZ. Patient groups undergoing MRI for EBRT varied locally and internationally. Routine MRI was used most commonly for brain radiotherapy in 38%–83% of centres, prostate (11%–100%), rectum/anus (0%–75%) and gynaecological (10%–75%). There was a clear lack of consensus with respect to the imaging sequences used in EBRT.

Commissioning and quality assurance of image registration and MRI systems varied greatly, as did staffing models and training given to different staff groups. Barriers to using MRI routinely for EBRT included a lack of local

knowledge/support/clinical interest in DK/SE and a lack of MRI access in UK/FN/NZ/NL.

Looking forward, whilst only 17%–50% of centres are planning for a new MRI scanner dedicated for EBRT, 36%–77% of centres intend to use functional MRI in the next five years. MRI-only EBRT planning is currently employ in a limited number of sites in NL/DK/SE/FN and is expected to be used in >50% of centres in the NL/SE/DK/FN and <35% in UK/NZ in the next five years. DK/UK/NL have begun to implement MRI-Linac into RT practice, and the expected 5 year uptake varies from <35% (UK/FN/SE/NZ) to 75% (DK). **Conclusions:** Considering the use of MRI in EBRT in six countries, variations in equipment/QA /staffing models have been identified. These are likely due to differences in funding as well as knowledge gaps. There is a lack of consensus or guidelines in the literature. Results from this survey will be used to produce guidance aimed at establishing best practice. Despite challenges, significant interest remains in increasing MRI in EBRT over the next 5 yr.

21

A Dosimetric Study of MR-Directed Simultaneous Integrated Boost to Intraprostatic GTV Using Stereotactic Body Radiotherapy in Localized Prostate Cancer

Astrid Billfalk-Kelly, Ning-Ning Lu, Vickie Kong, Alejandro Berlin, Tim Craig, Joelle Helou, Peter Chung, University of Toronto, Toronto, ON

Purpose: To assess the dosimetric feasibility of SIB using multiparametric MR (mpMR)-directed stereotactic body radiotherapy. **Background:** Presence of MR-visible prostate cancer tumors have been reported to be associated with reduced disease control rates after conventional external beam radiotherapy. Ultra-hypofractionated radiotherapy (i.e., stereotactic body radiotherapy [SBRT]) may render improved disease control but long-term toxicity data is still limited, particularly for higher dose per fraction (>8 Gy). Simultaneous integrated boost (SIB) may maximize use of the optimal therapeutic index, by allowing higher dose escalation to the gross tumor, while limiting dose to healthy tissues and subsequent risk of toxicity. **Methods and Materials:** Ten patients were selected within a cohort of prostate cancer cases treated with whole gland SBRT and focal HDR (high dose rate) brachytherapy boost. Patients included had T1-3aN0M0, Gleason score ≤8, PSA level ≤20 ng/ml, visible PIRADS 4–5 lesion on MRI (>5 mm and <1/3 of gland involved).

Patients underwent insertion of 3 gold fiducial markers and rectal spacer prior to radiotherapy, and had mpMR/CT simulation. 3 T mpMR (T2w, DWI, DCE and 3D-CISS sequences) with and without endorectal coil were acquired. Images were co-registered using the fiducial markers.

GTV boost was contoured on mpMRI (T2w/DWI/DCE) and mapped onto CT using deformable image registration (Raystation v 6.1). A 5 mm PTV_-boost margin was used in all directions, except laterally where 3 mm was used. Single arc VMAT 36.25 Gy in 5 fractions to the prostate only vs 36.25 Gy in 5 fractions to the whole prostate plus SIB up to 50 Gy were prescribed.

Planning objectives were PTV D98% ≥ 34.4 Gy and CTV D95% ≥ 40 Gy; additional objective of PTV_boost D99% ≥ 47.5 Gy for SIB; rectum D20% ≤ 29 Gy and D1cc ≤ 36 Gy; penile bulb D50 < 29.5 Gy, bladder D40 < 18.1 Gy and D10cc < 37Gy, and urethra D50 < 42 Gy. **Results:** The median GTV_boost volume was 1.63 cm^3 (0.3–6.3). Five of the lesions were in the posterior peripheral zone, but due to the rectal spacer the median distance on axial slices from the prostate to the rectum was 1.7 cm (range 1.1–3.6), 1.1 cm (0.9–1.3), and 0.95 cm (0–1.5) at the top, mid-gland and apex respectively.

All dose constraints were met in both planning strategies. The median urethra D50 changed from 4166 cGy (4001–4234) to 4325 cGy (4129–5022) $P = 0.010633$, but the other constraint changes were not statistically significant; rectal D20 and D1cc changed from 756 cGy (421–1417) to 896 cGy (478–2397) $P = 0.31$ and 2637 cGy (1650–3048) to 2737 cGy (1881–3445), $P = 0.54$, respectively, bladder D40 177 cGy (117–1807) to 204 cGy (128–1723) $P = 0.37$, D10 cc 2980 cGy (2040–3563) – 3047 (2068–3655) $P = 0.78$, and the median the median penile bulb 307 cGy (209–1731) to 303 (218–1907) $P = 0.996$. **Conclusions:** Dose escalation was feasible with MR directed SIB to 50 Gy in this unique cohort of patients with rectal spacers without exceeding the OAR dose constraints designed for SBRT whole gland. This may allow selected dose escalation in the ultra-hypofractionated setting while minimizing toxicity, which will be the subject of a MR-directed S(I)BRT pilot study.

22

Dosimetric Feasibility of An MR-Linac System for Image-Guided Cranial Radiosurgery

Jochen Cammin[1], Gage Redler[2], Martha Malin[2], Tynan Stevens[2], Olga Green[1], Sasa Mutic[1], Bulent Aydogan[2], (1) Washington University in St. Louis, St. Louis, MO, (2) University of Chicago, Chicago, IL

Purpose: Cranial lesions can often be treated successfully with radiosurgery using platforms like GammaKnife, CyberKnife, or C-arm linacs. These systems offer only x-ray-based on-board imaging with poor lesion visibility and require fusion of pre-treatment CT and MRI from separate scanners. Image-fusions between MRI and planning CT for target delineation and on-board x-ray imaging during patient setup add additional uncertainties. MR-linacs offer high-contrast imaging of the brain within the same unit as the treatment delivery. Integrated online-adaptation enables on-the-fly adjustments in response to changes in lesion size or shape. In this work, we demonstrate that a MR-linac system with double-focused, double-stacked MLCs is capable of delivering high-precision dose distributions with steep dose gradients as needed for cranial radiosurgery. **Materials and methods:** Coplanar treatment plans prescribing 20 Gy in 1 fraction were created for a conventional C-arm linac and the ViewRay MR-linac using an anthropomorphic head phantom and spherical targets with diameters ranging from 0.6 to 2.5 cm (volumes 0.11 cc to 8.18 cc). The MR-linac plans used 11 equally spaced, coplanar IMRT fields with (Dmax = 25 Gy) or without a maximum dose constraint. The C-arm linac plans used either 11 coplanar fixed 3D conformal beams or 5 non-coplanar dynamic conformal arcs. Clinical planning objectives focused on conformity index (CI) and normal brain V12 Gy. Dosimetric fidelity between planned and delivered dose was verified for two plans using an anthropomorphic head phantom with embedded radiochromic EBT3 film and a QA phantom with a diode array and MR-compatible ion chamber. Agreement was assessed using the Gamma metric for the measurements with film and the diode array. **Results:** The MR-linac SRS plans were found to be clinically acceptable and comparable to conventional linac VMAT plans. Conformality of the C-arm linac plans was marginally better than the MR-linac plans ($P = 0.05$). The normal brain V12 Gy was comparable between C-arm and MR-linac plans ($P = 0.06$). The MR-linac plan conformality improved (average CI of X vs Y) when no max dose constraint was used in the optimizer at the cost of increased heterogeneity (average Dmax of 30 vs 25 Gy). Comparisons between planned and delivered dose showed agreement within 1.3% using a point-dose measurement with an ion chamber, >93% agreement with the diode array, and >99% agreement with film (both with a Gamma criterion of 2%/2 mm). **Conclusions:** Coplanar MR-linac plans achieve normal brain V12 Gy values similar to conventional C-arm linac plans and can be used for lesion sizes up to 2.2 diameter (5.5 cc volume) without violating the V12 Gy < 8.5 cc constraint to avoid symptomatic brain necrosis (Minniti et al. Rad.Onc. 2011, 6:48). Dose conformality was comparable with values averaging CI = 1.08 for lesions of diameter 0.8 cm or larger. Quality assurance measurements using ion chamber, film, and a diode-array demonstrated passing rates between planned and delivered doses at the level of current clinical standards. The results suggest that MR-linac based cranial SRS is feasible with the added advantages of improved lesion visibility from on-line MR images and the potential for a sim-and-treat workflow using the online adaptive capabilities of the MR-linac platform.

23

Deformable Dose Reconstruction for A Hybrid Cone Beam CT-MRI Guided Adaptive Radiotherapy Workflow

Michael Velec, Tony Tadic, Jason Xie, Joanne Moseley, Tirth Patel, Michael Milosevic, Anthony Fyles, Kathy Han, Jennifer Croke, Princess Margaret Cancer Centre, Toronto, ON

Purpose: Women with cervix cancer can exhibit unpredictable organ deformation and tumor response during radiotherapy that is challenging to visualize with cone-beam CT (CBCT), and barrier to the application of highly-conformal treatment plans. Therefore, a novel platform combining a CBCT-equipped linear accelerator and 1.5 T MR-on-rails was recently implemented for daily guidance. The aim was to develop a dose reconstruction workflow to evaluate the dosimetric impact of organ deformation and adaptive re-planning interventions using cervix cancer as a proof-of-concept. **Materials and methods:** Patients received 45 Gy/25 fractions using volumetric modulated arc therapy (VMAT) consistent with EMBRACE II, margins accounting for bladder filling plus 7 mm and daily pre-treatment CBCT. Daily post

treatment axial T2w MRI acquired in the same patient position, was reviewed offline for geometric-only assessment of tumor motion. To reconstruct the actual delivered doses, scripts were developed to automatically retrieve, apply density corrections and perform dose calculations on all CBCTs in the treatment planning system. Daily MRIs were rigidly registered to the corresponding CBCT is the treatment position. The primary target CTV and normal tissues were delineated by an expert clinician first on all CBCTs, then MRIs. The CBCT contours were used to guide hybrid deformable image registration in order to map and accumulate the daily CBCT doses on the planning CT. Dose calculation accuracy on CBCT is within 3%. Deformable registration accuracy at contoured structures was previously quantified as 2–3 mm on average, and visually verified in this study. Deviations in dose-volume metrics ≥5% vs planning were considered to be clinically significant and reported. **Results:** Two cervix patients have been treated prospectively to date. The daily MR-defined CTVs were 16.6 cc (26%) smaller on average than corresponding CBCTs ($P < 0.01$). Patient 1 had no remarkable organ motion on daily CBCT or MRI (acquired for 8/25 fractions) that warranted adaptive re-planning. Post-treatment dose reconstruction using CBCT confirmed no significant dose deviations >5%. Patient 2 had substantial bladder and rectum deformations causing displacement of the uterine fundus on daily CBCT. On review of MRI (acquired for 17/25 fractions), geometric miss of CTV and potentially the GTV was presumed and adaptive re-plan was initiated on fraction 19. Post-treatment dose reconstruction using CBCT resulted in a 5% decrease in minimum CTV dose (in the uterine fundus, but not GTV) and 13% increase in rectum V40 relative to the initial plan. There were no dose deviations >5% relative to the re-plan or overall composite plan, confirming the adaptation strategy. **Conclusions:** A dose reconstruction workflow was developed for cervix patients treated on a hybrid CBCT-MRI guidance protocol. Integrating this dosimetric information into clinical practice will aid clinicians in adaptive re-planning decisions. Owing to the improved soft-tissue visualization, MRI-only workflows are being developed for more precise adaptation strategies, including more accurate dose reconstruction, and the integration with MR-guided brachytherapy.

24

Dosimetric Feasibility of Utilizing the Viewray MR-Linac System for Image Guided Spine SBRT

Gage Redler[1], Tynan Stevens[1], Jochen Cammin[2], Martha Malin[1], Olga Green[2], Sasa Mutic[2], Bulent Aydogan[1], (1) University of Chicago, Chicago, IL, (2) Washington University in St. Louis, St. Louis, MO

Purpose: Radiation therapy plays an integral role in the management of various paraspinal diseases, providing palliation, avoidance of bone fractures, and/or relief from neurological symptoms. Ablative doses using SBRT in spine achieves favorable outcomes compared to conventional doses/fractionation and facilitates re-treatment and/or dose escalation. The spinal cord is the principle dose limiting organ-at-risk (OAR) for such treatments, requiring precise immobilization/localization. Therefore, image guidance is paramount to successful spine SBRT. However, x-ray imaging utilizing bony anatomy as a surrogate may be insufficient when using margins of ~1 mm. MRI offers the potential to directly visualize the dose-limiting cord and the ViewRay MR-Linac combines this potential with the necessary dosimetric capabilities, utilizing a 6FFF treatment beam and double-focused, double-stacked MLCs. This work demonstrates the capability of this system to accurately deliver high-precision dose distributions necessary to ablate paraspinal disease while avoiding damage to the cord. **Materials and methods:** This work consisted of a planning study, in which 8 spine SBRT patients previously treated using VMAT were re-planned using fixed-field IMRT on the ViewRay MR-Linac. These plans were assessed for feasibility via a phantom study and dosimetric verification using Gafchromic film, an MR-compatible ionization chamber, and a commercial MR-compatible diode array QA phantom. The patients selected represented a variety of clinical cases with PTV volumes of varying geometric complexity (volumes from 25.8 to 160.3 cc; disease extent from vertebral body only to nearly fully wrapped around spinal canal). Clinical planning objectives were used when re-planning these cases, with OAR tolerances from AAPM TG101 and ideal PTV coverage of $V_{100\%} > 95\%$ (sacrificed as necessary to respect OAR constraints). Prescribed doses were 30 Gy in 3 fractions (n = 6), 50 Gy in 5 fractions (n = 1), and 30 Gy in 5 fractions with a sub-volume boost to 40 Gy (n = 1). A 1 mm margin on the true cord was used for the cord planning organ-at-risk volume (PRV). **Results:** All ViewRay plans were found to achieve clinical goals and were comparable to conventional linac VMAT plans. The most dramatic differences were increased entrance dose, decreased conformality (conformity index of 1.28 ± 0.06 vs 1.06 ± 0.06), and increased heterogeneity (D_{max} of $134 \pm 3\%$ vs $120 \pm 2\%$) for the MR-linac plans vs. conventional linac plans, respectively. However, the MR-linac plans exhibited improved cord sparing (cord D_{max} of 16.1 ± 2.7 Gy vs 19.5 ± 1.6 Gy; cord PRV D_{max} of 20.0 ± 2.6 Gy vs 24.5 ± 2.0 Gy). Delivery time was longer for the MR-linac but clinically acceptable (14.39 ± 1.26 min vs 9.57 ± 1.19 min). Ionization chamber measurements were found to agree with planned dose to within 2.5%. Film and diode array measurements demonstrated accurate/precise delivery of high dose gradients between PTV and cord, with overall gamma passing rates of >95% (3%/3 mm). **Conclusions:** The ViewRay MR-Linac platform provides necessary dosimetric capabilities to feasibly deliver doses with the necessary spatial gradients for spine SBRT. This has been verified via planning of 8 clinical spine SBRT cases followed by rigorous delivery verification in phantoms using film, diodes, and an ionization chamber. This suggests that real-time visualization of the dose limiting spinal cord during spine SBRT delivery may be feasible, enabling cord-based gating, reduced PTV margins, and/or eventual dose escalation.

25

On the Development of Reference Dosimetry Service in MRI Guided Radiotherapy

Ilias Billas[1], Hugo Bouchard[2], Uwe Oelfke[3], Simon Duane[1], (1) National Physical Laboratory, Teddington, UK, (2) Université de Montréal, Montreal, QC, (3) The Institute of Cancer Research, Sutton, National Physical Laboratory, Teddington, UK

Purpose: Reference dosimetry in conventional radiotherapy machines is commonly performed with ionisation chambers. In practice, secondary chambers are calibrated against primary standards of absorbed dose to water (such as ionometry, water calorimeter, graphite calorimeter, etc.) and then used to calibrate the output of radiotherapy machines. In the presence of a B-field, charged particles are influenced by the Lorentz force which strongly modifies the dose response of the ionisation chamber, making it challenging to perform beam output measurements in MR-Linacs. In such systems, there are still no protocols that can provide traceability for reference dosimetry. The aim of this work is to adapt existing protocols for reference dosimetry and evaluate the use of the magnetic field correction factor, k_{QB}, in MR guided Radiotherapy. **Materials and methods:** We have performed reference dosimetry measurements at different hospitals/institutions and different Elekta Unity MR-Linacs. At each visit, waterproof ionisation chambers were cross-calibrated directly in the MR-Linac, in terms of absorbed dose to water traceable to the NPL (National Physical Laboratory) primary standard, by using NPL alanine/EPR as a transfer standard. The alanine was corrected for the effect of the B-field. Absorbed dose measurements were performed in water, at the machine iso-centre, with a 10×10 cm^2 radiation field and at a depth of 10 g/cm (and 20 g/cm to determine $TPR_{20/10}$ beam quality). The chamber signal was corrected to standard environmental conditions (20°C and 1013.25 mbar). The gantry angle was either 0^o or 90^o with the detector long axis orientated parallel or perpendicular. With respect to the B-field, detectors were orientated either parallel, anti-parallel or perpendicular. **Results:** The results of this study have shown that the stability of the Elekta Unity and the setup repeatability are 0.1% or better. The $TPR_{20/10}$ between the Elekta Unity machines was ranging from 0.696 to 0.703 for 0 T and 0.694 to 0.701 for 1.5 T. On average, the $TPR_{20/10}$ was found to be 0.699 ± 0.003 and 0.698 ± 0.003 for 0 and 1.5 T, respectively. Magnetic field correction factors were determined at different Unity systems and found to be 0.995 with a standard deviation of 0.006 (PTW/30013) and 0.999 with a standard deviation of 0.004 (IBA/FC65-G). The absorbed dose to water calibration coefficients, ND_w, based on the alanine measurements at the MR-Linac have a standard uncertainty of 1%. **Conclusions:** In this work, we performed reference dosimetry measurements at different Unity MR-Linac systems and various hospitals/institutions. Traceability to an existing primary standard was achieved using alanine dosimetry calibrated with NPL's primary standard graphite calorimeter in a conventional Elekta Linac. This work demonstrates the feasibility of using alanine to transfer absorbed dose standards from conventional Linacs to MR-Linacs. Results of our investigations to date would be consistent with the adoption of a chamber type-dependent k_{QB} correction, for chamber types PTW/30013 and IBA/FC65-G, for Elekta Unity systems.

26

Pre-Trained Recurrent Inference Machines for Reconstructing Data from the MR-Linac

Kai Lønning[1], Tessa Lindt[1], Matthan Caan[2], Jan-Jakob Sonke[1], (1) Dutch Cancer Institute, Amsterdam, NL, (2) Universitair Medische Centra, Amsterdam, NL

Purpose: Fast imaging is necessary to maximize the efficiency of MRI guided Radiotherapy (MRgRT). Compressed sensing (CS) can speed up the acquisition process by requiring less samples, but reconstruction tends to be slow. Recurrent Inference Machines (RIM) can reconstruct data 10 times faster than CS, and have been shown to generalize well to data distributions not encountered during training.[1] We show that they can be directly applied to data from the MR-linac after training on an unrelated dataset. **Materials and methods:** T1-weighted brain scans were acquired from 10 healthy subjects on a 3 T Philips Ingenia scanner at 1.0 mm. These scans were retrospectively under sampled in k-space using a Gaussian distribution favoring lower frequencies. Each datapoint was generated using a subsampling factor randomly drawn in the range 4×–10×, before given as input to train the network.

For evaluation, a total of 5 scans were made of the pelvis, and head and neck region on the Elekta Unity (Elekta AB, Stockholm, Sweden) MR-linac: 2.0 mm T1-weighted TFE and T2-weighted TSE acquisitions for each of the two regions, in addition to a 1.0 mm T2-weighted TSE acquisition of the head and neck. The data were fully sampled, and then retrospectively under sampled using acceleration factors ranging from 4× to 24× (equivalent scan times: 90–15 s). For comparison, we made the same reconstructions using compressed sensing (CS).[2] **Results:** Using the structural similarity as a quality metric, the RIM decreases from 0.9 to 0.8 for acceleration factors 12×–24×, as opposed to 0.8 to 0.7 for CS. The improvement is greater for acceleration factors 4×–12×, where the RIM achieves scores between 0.97 and 0.9, whereas CS ranges from 0.9 to 0.7.

The RIM reconstructions have a sharp look, with little loss of detail up to 8× acceleration, with blurring becoming pronounced at 12× acceleration. At higher acceleration factors there is serious loss of detail, although the contours of major organs are still clear. **Conclusion:** We have shown that once trained on brain scans from a separate scanner, RIMs can be directly reapplied to pelvis and head and neck scans from the MR-Linac. The level of acceleration depends on the diagnostical goal, but we consider reconstructions with acceleration factors 10×–12× and 8×–10× for respectively T2-weighted TSE and T1-weighted TFE scans to be of sufficient quality for most applications. In conclusion, RIMs produce fast reconstructions with sufficient quality even for a scan time of 30 s at large FOV, making them excellent candidates for fast MRgRT.

References

1. Lønning, MedIA 2019.
2. Lustig, Magn. Reson. Med. 2007.

27

Quantifying the Variability of Respiratory Motion Using Multiphasic 4D-MRI

Martin Fast, Tessa van de Lindt, Georgios Sotiropoulos, Christoph Schneider, Jan-Jakob Sonke, The Netherlands Cancer Institute, Amsterdam, NL

Purpose: 4D-MRI is considered increasingly important in guiding radiotherapy for patients with thoracic or abdominal lesions. One characteristic of retrospectively sorted 4D-MRIs is that the natural variability of respiratory motion is averaged into a single unified respiratory cycle. Given the typical 4D-MRI acquisition time of several minutes, and the inter-fractional respiratory variation, there is a risk that the 4D respiratory model is not appropriate for the entire course of treatment. In this study, we develop multiphasic 4D-MRI for radiotherapy guidance with each 4D-MRI representing a characteristic respiratory mode. **Materials and methods:** We previously developed a self-sorted 4D-MRI method based on a multi-slice coronal TSE sequence. To facilitate the 4D-MRI reconstruction, all 2D images are rigidly registered to the diaphragm in a 3D reference image extracted from the unsorted 2D images. Normalizing and concatenating the registration shift vectors in cranial-caudal direction generates a self-sorting signal, which is then used to perform amplitude binning. For this study we acquired 4D-MRI data from 5 healthy volunteers on the Unity MR-linac (Elekta AB, Stockholm, Sweden) under an IRB-approved study protocol. During the 16 min image acquisition, a stack of 25 coronal slices (2 × 2 × 5 mm voxel size) was repeatedly acquired (120×). Following the extraction of the self-sorting signal, we identified the end-inhale positions by applying a Hilbert transform. All images acquired between two subsequent end-inhale positions were then assigned to the same respiratory cycle. For each respiratory cycle, we calculated the mean and SD of respiratory motion. The motion parameters were then converted into dimensionless z-scores. Subsequently we applied k-means clustering to partition the motion parameter distribution into characteristic respiratory modes. During optimisation the squared Euclidian distance to the cluster centres was minimised. The optimal number of clusters (k) was determined by iteratively incrementing k as long as all of the resulting clusters had more than 25% of the original image data. The 4D-MRI reconstruction was then repeated for each characteristic respiratory mode. The respiratory characteristics of the resulting 4D-MRIs were quantified by rigidly registering all respiratory phases to the end-exhale phase of the original 4D-MRI using a registration mask on the diaphragm. **Results:** Mean and SD of respiratory motion as extracted from the self-sorting signal could be best described by 2 (for 2 volunteers) or 3 (for 3 volunteers) characteristic respiratory modes. When comparing the time-weighted diaphragm position between original 4D-MRIs and the 4D-MRIs based on the characteristic respiratory modes, the median (min, max) difference was 0.0 (−0.5,0.5) mm (LR), 1.2 (−0.6,3.9) mm (CC), and −0.5 (−2.6,0.6) mm (AP). For all volunteers and 4D-MRIs, the time-weighted std.-dev. of respiratory motion was 0.5 (0.1,1.1) mm (LR), 4.4 (2.8,7.4) mm (CC), and 2.2 (0.5,3.4) mm (AP). The difference in time-weighted SD between original 4D-MRIs and the 4D-MRIs based on the characteristic respiratory modes was −5 (−25,19) % (CC) and 14 (−43,85) % (AP). **Conclusions:** Multiphasic 4D-MRI is a novel technique that can retrospectively identify variability in respiratory amplitude and time-weighted anatomical position. In the healthy volunteers, we detected considerable respiratory variability during the image acquisition duration.

28

Magnetic Resonance Signature Matching (MRSIGMA) for Real-Time Volumetric Motion Tracking

Li Feng, Ricardo Otazo, Memorial Sloan Kettering Cancer Center, New York, NY

Purpose: The recently introduced MR-Linac system, which combines an MRI scanner and a linear accelerator, holds significant promise for adaptive treatment of moving organs, such as the lung, pancreas and liver. However, even with the latest MRI acquisition and reconstruction techniques, tracking volumetric motion in real-time with a high spatial and temporal resolution is still challenging. The purpose of this work is to develop a novel real-time 4D MRI technique called MR SIGnature MAtching (MRSIGMA) with an imaging latency (acquisition time + reconstruction time) lower than 500 ms. **Materials and methods:** MRSIGMA general idea: MRSIGMA consists of two steps: (a) offline learning of a database of 3D respiratory motion states and corresponding motion signatures; and (b) online matching of high-temporal resolution signature-only data with a pre-learned motion state/signature database entry. Offline learning employs motion navigation and motion-resolved imaging over multiple motion cycles (e.g., respiratory cycles) to create a database of high spatial resolution 3D motion states and corresponding unique motion signatures. A key point in MRSIGMA is that the acquisition of signature data must be very fast (<200 ms). During the online matching step, only high temporal resolution signature data are acquired, and the 3D motion state whose signature best matches the real-time data is selected for a given time point with low latency. **Implementation:** MSIGMA was implemented using stack-of-stars 3D golden-angle radial sampling. For the offline learning step, motion signatures were generated using projection profiles along the z dimension extracted directly from the MR raw data, and a database of high-resolution 3D motion states were reconstructed from continuously acquired data over multiple motion cycles using a motion-resolved compressed sensing reconstruction technique called XD-GRASP. Online matching was performed by acquiring, extracting and matching signature data only. **Evaluation:** Two 3D liver MR datasets previously acquired using a stack-of-stars 3D golden-angle sequence (matrix size = 256 × 256 × 35, FOV = 320 × 320 × 216 mm^3, scan time = 178 s) were used to test the MRSIGMA framework. For each data, a total of 1000 spokes were acquired. Offline learning was performed using the first 900 spokes to reconstruct a 4D respiratory-resolved image database using XD-GRASP, resulting in 10 motion states spanning from expiration to inspiration. Online matching was performed with the last 100 spokes to generate 100 3D images from the pre-learned database using the online matching algorithm, leading to a temporal resolution of 0.178 s/3D volume. **Results:** The total latency of creating each

3D online image was ~330 ms, including acquisition of signature (~178 ms) and matching with the corresponding signature in the database (~150 ms). High temporal-resolution x-z projections, generated from online signature data, were used for validation. The motion displacement in the MRSIGMA real-time 4D image was well-correlated with the underlying true pattern (23.51 ± 9.84 vs 24.35 ± 10.89 pixels, $R^2 = 0.925$). **Conclusions:** MRSIGMA enables volumetric motion tracking in real-time by performing all time-consuming data acquisition and image reconstruction tasks during the offline learning step and leaving simple and rapid tasks for online matching step, resulting in very low latencies that can potentially be applied for adaptive treatment planning using the MR-Linac system.

29

The Influence of the Linear Accelerator of A 1.5 T MR-Linac on Diffusion Imaging During Radiation Treatment

Ernst Kooreman, Petra van Houdt, Vivian van Pelt, Marlies Nowee, Uulke van der Heide, The Netherlands Cancer Institute, Amsterdam, NL

Background: MR-linacs are hybrid machines that enable MR imaging of a patient during radiation treatment. As a result, the design is such that the linac is positioned close to the magnetic field of the MRI. The linac includes magnetic components which can cause magnetic interference. This can reduce the B_0 field homogeneity causing imaging artifacts. The influence of the position of the linac on the B_0 homogeneity was characterized previously, but only in static conditions. During treatment delivery, the linac rotates around the patient and the multileaf collimator is constantly adjusted. It is conceivable that these movements influence the magnetic field, especially because active shimming of the B_0 field is typically done once before acquisition. **Objectives:** We investigated both in a phantom and in patients whether the moving linac has influence on the quantitative values of apparent diffusion coefficient (ADC) maps. **Materials and methods:** Six patients were imaged in a test-retest setting during two consecutive fractions. Each measurement consisted of a T2-weighted anatomical image, and two diffusion acquisitions. One was acquired before, and the other during radiation treatment. An echo planar imaging (EPI) acquisition was utilized for the diffusion weighted images with the following parameters: TE/TR = 54/3201 ms, b-values 0, 30, 150, 500 s/mm^2, acquired voxel size of 3 mm isotropic, and a FOV of $430 \times 430 \times 60$ mm^3. The images with b-values of 150 and 500 s/mm^2 were used to calculate the ADC map.

ROIs were drawn in healthy prostate and tumor, from which the mean ADC values were compared using a mixed effect model with the patients as a random effect, and tumor, gantry rotation, and test/retest time point as fixed effects.

Additionally, the QIBA diffusion phantom was scanned during three modes of operation: with a static gantry, with a stepping gantry, and with a continuously rotating gantry. The mean value of a ROI in the central tube was compared to the phantom reference value of 1109 mm^2/s. **Results:** The mean ADC value of the test data of the healthy prostate was $1316 \pm 61 \times 10^{-6}$ mm^2/s when the gantry was inactive. The only significant fixed effect was between tumor and healthy prostate, where the effect size of tumor was $-201 \pm 70 \times 10^{-6}$ mm^2/s with respect to healthy prostate. The effect of a moving gantry was not significant, as was the effect of the retest measurement. Both effects were of the same order of magnitude: $-20 \pm 31 \times 10^{-6}$ mm^2/s and $-13 \pm 31 \times 10^{-6}$ mm^2/s, respectively. The phantom ROI mean and standard deviations were $-1112 \pm 58 \times 10^{-6}$ mm^2/s for the static gantry, $1101 \pm 68 \times 10^{-6}$ mm^2/s for the stepping gantry, and $1117 \pm 71 \times 10^{-6}$ mm^2/s for the continuously rotating gantry. **Conclusions:** Our data show no influence of the rotating gantry on quantitative ADC values of the phantom. In the patients, a clear difference in ADC between tumor and healthy prostate ROI mean values was found, which corresponds to previously published values for this set of b-values. We found no significant effect of the rotating linac on ADC values in patients, which implies that in a clinical setting ADC maps can be acquired during radiation treatment with negligible influence on the measured quantitative values.

30

Quantitative Imaging for Prediction of Local, Regional and Distant Failure in Locally Advanced Head and Neck Cancers

Yue Cao, Madhava Aryal, Peter Hawkins, Choonik Lee, Pin Li, Matt Schipper, Christina Chapman, Dawn Owen, Alek Dragovic, Michelle Mierzwa, University of Michigan, Ann Arbor, MI

Purpose: To investigate multi-modality quantitative imaging (QI) metrics of MRI and PET for prediction of local, regional and distant failure (LF, RF and DF) in locally advanced poor diagnosis head and neck cancers (HNC). **Materials and methods:** 54 (31 p16+) patients with poor prognosis HNCs who were enrolled in an IRB approved adaptive chemoradiation therapy trial (CRT) were analyzed. MRI-derived blood volume (BV) and apparent diffusion coefficient (ADC) images were obtained pre-CRT and after 10 Fx of RT (2 week). The low BV subvolume (<7.6 ml/100 g), mean BV, mean ADC, and low ADC subvolume (<1.2 um^2/ms) in primary and nodal gross tumor volumes (GTVs) and their changes at 2 week were calculated. The mean/max standard uptake value (SUV), metabolic tumor volume of 50% of maximum SUV (MTV_{50}), and total lesion glycolysis (TLG) were calculated from pre-treatment FDG PET. These QI metrics were compared for differences between p16− and p16+ tumors, between tumors with LRF and with no evidence disease (NED), and between ones from the patients with DF and with NED by Students' *t* test. Cox proportional hazards model and Kaplan Meier (KM) analysis were used to test QI metrics for prediction of LRF and DF free survival (LRFFS and DFFS, respectively). **Results:** The p16− primary tumors had significantly greater mean ADCs pre-RT (1.48 ± 0.05 (SEM) um^2/ms), and significantly less percentage increases at 2-week ($10.0\% \pm 1.2\%$) than p16+ ones (1.34 ± 0.04 um^2/ms and $21.2\% \pm 3.0\%$, $P = 0.04$ and $P = 0.004$, respectively), supporting a hypothesis of a large stroma-tumor ratio in p16− tumors. 24 patients had local, regional and distant failure at the analysis (12-month median follow-up). The p16− primary and nodal tumors with LF or RF (n = 14) had significantly greater mean ADCs pre-RT and at 2-week than ones from the patients with NED ($P = 0.002$ and 0.01, respectively). Both Cox model and KM analysis showed that mean ADC in primary tumor pre-RT and p16 status interacted significantly and predicted for LRFFS ($P < 0.003$). In addition, Cox model identified a sum of all nodal gross tumor volumes (GTVs) at 2 week ($P = 0.04$), a change in a sum of all nodal GTVs 2 week vs preRT ($P = 0.008$), a mean value of SUV over all nodal MTV_{50}s ($P = 0.04$), and a sum of TLGs over all nodal MTV_{50}s preRT ($P = 0.01$) as a significant predictor for LRFFS when the p16 status was included as a co-variate. Cox model identified a mean value of BV in primary tumors at 2 week, a sum of all nodal GTVs at 2 week, a sum of all nodal low BV subvolumes at 2 week, a mean SUV over all nodal MTV_{50}s pre-CRT, and a sum of TLG over all nodal MTVs pre-CRT as a significant predictor for DFFS after considering T4/N3 staging. When analyzing tumors treated by standard care only, primary and nodal tumors with large low mean BV at 2 week were associated with LF ($P = 0.01$) and DF ($P \leq 0.03$), respectively. **Conclusion:** Heterogeneity nature of pathology, site and progression type in HN cancers requires multi-modality imaging for prediction of types of failure in order to identify patients who are benefited for different intensified treatment strategies.

31

Quantifying the Effects of Respiratory Variability on 4D-MRI Guided Mid-Position Liver SBRT

Tessa van de Lindt, Martin Fast, Jochem Kaas, Wouter van den Wollenberg, Uulke van der Heide, Jan-Jakob Sonke, Netherlands Cancer Institute — Antoni van Leeuwenhoek Ziekenhuis, Amsterdam, NL

Purpose: The MR-linac facilitates direct localization of liver lesions, which are not visible on CBCT. A 4D-MRI guided mid-position (midP) treatment on the MR-Linac will provide a markerless free-breathing treatment, improving patient comfort and treatment efficiency. In this study, we investigated geometric and dosimetric robustness of 4D-MRI guided midP liver SBRT in the presence of respiratory variability. **Materials and methods:** Experiments were performed on the Unity MR-linac (Elekta AB, Stockholm, Sweden) using the QUASAR MRI^{4D} Motion Phantom (Modus Medical Devices Inc., London ON, Canada). The phantom consisted of a water-filled thorax, with a moving cylindrical gel-filled insert positioned 10 cm to the right of the center to mimic the liver. The cylinder contained a Modus proof-of-concept beta testing film-cassette for dosimetry, with a spherical target of 30 mm diameter. The phantom performed 12 CC-motion trajectories, derived from respiratory self-sorting 4D-MRI signals of 4 patients with liver metastases,

containing regular to very irregular motion patterns. The respiratory signals were processed to all have the same midP and fit the 40 mm phantom range. For each trajectory, a coronal 4D-MRI was acquired (multi-2D TSE, 25 slices, $2 \times 2 \times 2$ mm^3, 30 repeats). During 4D-reconstruction, the self-sorting signal was extracted and the 2D-images were sorted in 10 amplitude bins. An MRI scan of the phantom in midP was acquired and density overrides were applied to create a pseudo-CT. A step-and-shoot IMRT plan (15 beams, 3×20 Gy, non-isotropic CTV-PTV expansion of 8-11 mm) was created in Monaco v5.4. The dose and dose-rate were reduced with a factor 4 to match the dynamic film range without affecting the motion interplay. One treatment fraction was delivered to the static phantom in midP and per motion trajectory. The 4D-MRI self-sorting signal was compared to the phantom input. All 4D-MRI phases were rigidly registered to the midP-MRI on the target to determine the time-weighted average CC-displacement (i.e., midP). The delivered dose to the static phantom and planned dose were compared by calculating the local gamma pass rate at 3%/2 mm. Additionally, dose-area histograms (DAH) for the GTV were compared between all delivered dose distributions and the planned dose. Since target delineation uncertainty is one of the main contributors to the treatment margin in liver SBRT, we isotropically expanded the GTV by 7.5 mm to create a dose evaluation structure (GTV_{TD}). The GTV_{TD} D95% was compared to evaluate the effect of motion blurring. **Results:** The mean±SD Pearson's correlation coefficient between the self-sorting 4D-MRI signals and the phantom input was 0.98 ± 0.01. The average midP accuracy determined by the 4D-MRI was 0.2 ± 0.1 mm (LR), 0.5 ± 0.4 mm (CC) and 0.4 ± 0.1 mm (AP). The gamma pass rate of the static delivery with respect to the planned dose was 96.6%. The DAH-analysis showed differences in GTV D98%, D50%, D2% and GTV_{TD} D95% of -0.58 Gy, -0.17 Gy, 0.14 Gy and -0.30 Gy, for a fraction of 20 Gy. Mean $\pm$ SD differences between moving delivery and planned dose were -0.23 ± 0.38 Gy, -0.21 ± 0.08 Gy, 0.35 ± 0.21 Gy and -0.45 ± 0.4 Gy. **Conclusions:** Robustness of 4D-MRI guided midP liver SBRT in the presence respiratory variability was experimentally validated with a motion phantom. Dose coverage of the GTV and GTV_{TD} was excellent for all investigated motion trajectories.

32

Spatial Accuracy, Temporal Efficiency, and Repeatability of Self-Directed Breath Hold During MRI-Guided Gated Radiation Therapy

John Bayouth, Kathryn Mittauer, Patrick Hill, Eric Wallat, Andrew Baschnagel, Michael Bassetti, University of Wisconsin — Madison, Madison, WI

Purpose: Real-time magnetic resonance imaging guided radiation therapy (MRgRT) provides a new approach to monitoring and addressing tumor motion directly. Requesting patients to execute breath hold maneuvers during radiation oncology imaging and treatment procedures is common, and compliance with devices that control patient's respiration is poor. If left to self-directed breathing the tumor repositioning accuracy and the temporal period with which a patient can reproduce their breath hold is poorly understood. We hypothesized that patients treated under real-time MRgRT could accurately and repeatably re-position their tumor with spatial accuracy and temporal efficiency. **Materials and methods:** Over 5000 min of cine-acquisition MRI images captured during respiratory tracked MRgRT were analyzed, drawn from 52 patients exhibiting > 1 cm tumor motion during respiration. Acquired at 4 frames per second, this represents over 1.1 million images. Patients executed self-directed breath hold to position their tumor, with tidal volume adjustments instructed by the treating Radiation Therapy Technologist based on real-time cine imaging. Once the tumor centroid was <2 mm of the prescribed location treatment commenced. Raw image files were retrospectively transformed into 24-bit RGB images using the image processing toolbox in MATLAB and the centroid of the tumor contour in every frame was calculated. **Results:** The median breath hold executed once the tumor centroid came to rest within 2 mm boundary was 25 ± 13 s, 36% of the breath holds executed were beyond 30 s, 12% were beyond 45 s, and 5% were beyond 60 s. The median recovery time for patients before self-directing their subsequent breath hold was 9.5 ± 1.6 s. The breath hold duty cycle was 62 ± 12%, with 75 percent of treatments maintaining a duty cycle above 50%. One quarter of the patients maintained a duty cycle above 73%. The median length of treatment time was 14.9 ± 8.3 min. **Conclusions:** Patients are able to reproduce tumor centroid positioning to within 2 mm in repeatable self-directed breath hold maneuvers, with minimal audio feedback provided by the Radiation Therapy Technologists during treatment. Ample length of time to facilitate MRIgRT tumor tracking has been established with a reasonable duty cycle. Recovery from the breath hold maneuvers was ~3 normal breath cycles, producing an excellent duty cycle for gated RT and making this technique accurate and efficient for the majority of patients.

33

Proton Pencil Beam Scanning in An MRI Scanner: Modelling and Experimental Verification

Brad Oborn[1], Sebastian Gantz[2], Sonja Schellhammer[2], Armin Luehr[3], Julien Smeets[4], Aswin Hoffmann[2], (1) University of Wollongong, Wollongong, NSW, (2) OncoRay — National Center for Radiation Research in Oncology, Dresden, DE, (3) Helmholtz-Zentrum Dresden-Rossendorf, Dresden, DE, (4) Ion Beam Applications, Louvain la-Neuve, BE

Purpose: Serious efforts are currently underway to integrate real-time MRI guidance with proton therapy. At OncoRay in Dresden (Germany), a proton pencil beam scanning assembly has been integrated with a low-field (0.22 T) MRI scanner for pre-clinical studies. The purpose of this work is to present experimental verification of the modeling on how scanned proton pencil beams of clinical quality behave as they travel through the MRI scanner towards the imaging isocentre. **Materials and methods:** Finite element modeling (COMSOL) was performed to measure the magnetic field generated by the MRI scanner. The magnetic field model was input into Monte Carlo (Geant4) simulations of the proton beamline, emulating a scanning pattern consisting of 9 beam spots coinciding with a 40×20 cm^2 nominal field size outline. The identical setup was experimentally performed, and EBT3 film was used to determine the pencil beam deflections that occurred at the MRI isocentre for 70, 125, and 220 MeV pencil beams. Experimental measurements of the MRI fringe field values were taken for comparison with the modeling predictions. The path of the proton beams was simulated over the last ~2.6 m of mixed vacuum and air volumes to reach the MRI isocentre plane. **Results:** As predicted in previous studies, the MRI fringe and main field acted together to distort and deflect the 40×20 cm^2 scanning pattern points, by as much as 30 mm. The rectangular field outline becomes trapezoidal in shape, and furthermore there is no direct correlation between deflection amount and beam energy. On a point-by-point comparison between modeling and film experiments (3 energies $\times$ 9 beam spots = 27 points total), there was a mis-match that ranged from 0 to 7 mm at the isocentre plane. However, 60% of all points matched to within 3 mm of the modeling prediction. Generally, there was better agreement for the points scanned either purely vertically or horizontally (87% inside 3 mm difference). For the extreme corner points, the modeling generally consistently over predicted the vertical deflection (~3 mm) while under predicting the lateral deflection (~3 mm). This is indicative of inaccuracies in the magnetic field map away from the beam central axis. Experimental measurements of the MRI fringe field along the beam central axis were generally observed to be within 0-2% of the modeling prediction. **Conclusions:** For the first time, experiments have been performed confirming the complex distortion and deflection of proton pencil beam scanning in the magnetic field of an MRI scanner. An acceptable level of accuracy was observed with modeling predictions, in alignment with the known limitations of the current magnetic field modeling approach. Future work will include refinement of the integrated magnetic model with comparison to 3D measured data through high-precision 3D mapping out of near and far fringe field of the MRI scanner.

34

Automated MRI-Only Treatment Planning Using Data Augmentation and Deep Autoencoder Similarity Matching

Michael Lempart[1], Niklas Eliasson[1], Hunor Benedek[1,2], Christian Gustafsson[1,2], Lars E. Olsson[2], (1) Skåne University Hospital, Lund, SE, (2) Lund University, Lund, SE

Purpose: With the use of MRI-only workflows and MRI-linacs in external radiation therapy (ERT), treatment planning is performed on synthetic computed tomography (sCT) images. Generating patient treatment plans for ERT is often a trial and error process and even if all clinical constraints are fulfilled, it is not guaranteed to be optimal. New technologies like machine and deep learning can improve the field of ERT and might be beneficial for the development of decision supportive tools in an MRI-only workflow or even for rapid MRI-linac re-planning. A deep neural network-based autoencoder combined with a k-nearest neighbor patient similarity matching approach was used to generate pareto optimal treatment plans for prostate cancer patients based on sCT images. The performance of the used model was

evaluated by comparing the treatment plans to a known reference pareto front generated by an in house-developed autoplanning software in combination with a commercially available treatment planning system (TPS, RayStation). **Materials and methods:** For a training dataset consisting of 50 prostate cancer patients, the autoplanning software was used to create 800 augmented treatment plans for each of the patients by varying the objectives of the TPS optimizer in a pre-defined way. Only the clinically acceptable and pareto optimal treatment plans were selected for further investigation. The objectives leading to the selected plans were stored in a training database. Additionally, a deep autoencoder was trained with the sCT images of the patients, where 80% of the dataset was used for training and 20% for model validation. Training was performed for 200 epochs using the RMSprop gradient descend algorithm, a mean squared error (MSE) loss, a learning rate of 0.001 and a batch size of 110. The sCT images of the training dataset were then fed through the encoder part of the autoencoder and a feature vector was extracted for each image from the bottleneck layer of the network. These feature vectors were then compared to the features of four test patients using the k-nearest neighbor algorithm. The objectives of the nearest neighbors were then used to generate new treatment plans for the corresponding test patients. To evaluate the performance of the model, a clinically weighted Euclidean distance was used to measure the difference between the front of new created plans and a reference front generated by the autoplanning software. **Results:** Multiple near-pareto optimal treatment plans could be generated using the proposed deep similarity matching approach. Weighted Euclidean distances of 0.076, 0.209, 0.0260 and 0.066 were computed for the four test patients. **Conclusion:** The deep autoencoder in combination with a k-nearest neighbor matching could provide a powerful tool for MRI-only treatment planning or rapid MRI-linac re-planning. Furthermore, multiple pareto optimal or near-optimal treatment plans can be found for a single patient in a short time. Modifications in the deep learning models hyperparameters such as learning rate, batch size or model structure could further improve the results. Such parameter exploration has not been performed yet, but should be assessed to guarantee a robust patient matching model.

35

A Novel and Rapid Approach to Estimate Patient-Specific Distortions Based on MDIXON MRI

Steffen Weiss[1], Siamak Nejad-Davarani[2], Holger Eggers[1], Eliza Orasanu[1], Steffen Renisch[1], Carri Glide-Hurst[2], (1) Philips Research, Hamburg, GER, (2) Henry Ford Health Cancer Institute, Detroit, MI

Purpose: In MR-only-based radiation therapy planning (RTP) geometrically correct MR imaging is essential, because target tumor and organs-at-risk are delineated on the MR images and dose planning and patient positioning are performed based on these delineations. One source of geometric distortions in MR images are B0 field inhomogeneities caused by patient-specific variations in magnetic susceptibility. Conventional B0 mapping with a dual-acquisition gradient recalled echo (GRE) sequence is increasingly used to quantify and correct for such distortions, but this sequence requires additional scan time. Purpose of this work was to explore B0 mapping based on mDixon imaging as an alternative to separate conventional B0 mapping. This offers an advantage because mDixon imaging is commonly performed for synthetic CT generation in RTP and provides simultaneous acquisition of B0 field maps and RTP data, which minimizes the risk of misalignments due to patient motion. **Materials and methods:** The experimental B0 mapping approach using mDixon imaging was compared to conventional B0 mapping. For the experimental approach a T1-weighted gradient-recalled bipolar dual-echo mDixon sequence was used as used clinically for synthetic CT generation. Conventional B0 mapping was performed with a gradient-recalled dual-acquisition sequence with the same image resolution and field of view. Corresponding images were acquired in a phantom and in the head and neck regions, including brain, of 10 healthy volunteers both at 1.5 and 3.0 T. Distortion maps were derived from both field maps for a T2-weighted sequence with high bandwidth [820 Hz/mm (1.5 T), 713 Hz/mm (3 T)] and compared between approaches using difference maps and histogram analysis. **Results:** Overall, conventional B0 mapping was well approximated by mDixon imaging: The distortions of 95% of the voxels in the phantom estimated by mDixon and conventional B0 mapping differed by <0.02 mm (1.5 T) and <0.04 mm (3 T), while the 95-percentiles of the distortions estimated by conventional B0 mapping were <0.06 mm (1.5 T) and <0.12 mm (3 T). In head and neck the distortions of 99% of the voxels were within ±0.2 mm at 1.5 T for both approaches and within ±0.4 mm and ±0.5 mm at 3 T for mDixon imaging and conventional B0 mapping, respectively. The majority of differences *in-vivo* were confined to regions with high spatial variation of the B0 field, mostly around internal air cavities. For 1.5 T, the mDixon imaging-based correction alone reduced the 95-percentile of distortions 30 from 0.15 to 0.03 mm and within the brain from 0.06 to 0.02 mm. Slightly lower reductions were observed at 3 T. All calculated distortions were relatively small due to the very high bandwidth of the T2- weighted sequence. **Conclusions:** mDixon imaging closely approximated conventional B0 mapping for distortion assessment. Estimates in the brain were in good agreement, and slight differences were observed near air/tissue interfaces in head and neck. Overall, mDixon-based B0 mapping may be advantageous for rapid patient-specific distortion correction without additional imaging. This would also avoid inter-scan motion between B0 mapping and mDixon imaging and lower the probability of inter-scan motion between mDixon imaging and subsequent T2 scanning.

36

A Multi-Institutional Analysis of a General Pelvis Continuous Hounsfield Unit (HU) Synthetic CT Software

Neelam Tyagi[1], Jani Keyrilainen[2], Ilyes Benslimane3, Petra J. Van Houdt[4], Marloes N. J. Frantzen-Steneker[4], Mo Kadbi[5], Aleksi Halkoa[5], Gerald Schubert[5], Uulke A. Van der Heide[4], (1) Memorial Sloan Kettering Cancer Center, New York, NY, (2) Turku University Hospital, Turku, FI, (3) Columbia university, New York, NY, (4) Netherlands Cancer Institute, Amsterdam, NL, (5) Philips Healthcare, Gainesville, FL

Purpose: To assess the image quality, dosimetric and geometric accuracy of a synthetic CT (syn-CT) software with continuous HUs and large field-of-view (FOV) coverage for MR-only workflow of a general pelvis anatomy **Materials and methods:** A synthetic CT software for general pelvis anatomy (prostate, female pelvis and rectum) has been developed by Philips Healthcare and includes continuous HUs assignment along with large FOV coverage. The method is an extension of the existing MRCAT (**MR** for **C**alculating **AT**tenuation) software package that is currently implemented clinically at various institutions. General pelvis syn-CTs were generated using a two-stack T1-weighted mDixon FFE sequence (TR/TE1/TE2 = 4.7/1.4/2.8 ms, voxel size = 1.40 × 1.40 × 1.40 mm^3, bandwidth = 866.3 Hz) on 1.5 and 3 T Philips Ingenia MR-RT scanners with a superior-inferior coverage of 36 cm. Syn-CT includes both male and female bone model shape variations. Body outline and bones are segmented from mDixon in-phase and water images. The bones are identified using a model-based segmentation. A continuum of HUs is assigned separately in the bone and soft tissue compartments. Depending on the fat and water intensities of the voxels, these continua span the range from dense cortical bone to light spongy bone and fat to muscle tissue, respectively. 77 prostate, 43 rectum and 27 gynecological cases were scanned by three different institutions on a 1.5 or 3 T MRI scanner. Cases included both prone and supine setup as well as some male patients with unilateral hip implant. Dose prescription varied from standard fractionation for prostate, rectum and gynecological cases to hypofractionation for prostate alone. mDixon image quality and syn-CTs were evaluated for soft tissue contrast by using a confidence level scale from 1 to 5 for bladder, prostate/rectum interface, mesorectum and fiducial maker visibility. Dosimetric comparison was performed by recalculating the IMRT/VMAT plans on the syn-CT after rigid registration. Digitally reconstructed radiographs (DRRs) were generated and qualitatively compared with CT-based DRRs. **Results:** Two-stack mDixon scans with large FOV did not show any image inhomogeneity or fat-water swap artifact. Continuous HUs provided soft tissue and bone contrast on the syn-CT that is comparable to CT. Fiducials and Foley catheter were visible as dark signal on the syn-CT. Even rectal spacer showed a slightly darker contrast on syn-CT compared to nearby soft-tissue. Average visibility confidence level on the syn-CT was 5 ± 0, 4.6 ± 0.5, 3.8 ± 0.4 and 4 ± 1.1 for bladder, prostate/rectum interface, mesorectum and fiducial markers. Syn-CTs reconstructed fine in both prone and supine positions as well as slight frog legged position used for gynecological setups. Dosimetric accuracy showed on average <1% difference with the CT-based plans for target and normal structures. Continuous HUs resulted in realistic DRRs showing excellent qualitative agreement with CT-based DRRs. Unilateral hip implant cases with femur head replacement were also dosimetrically accurate. **Conclusions:** MRCAT with continuous HU generated realistic synthetic CTs and DRRs to enable MR-only planning for general pelvis anatomy. Two-stack acquisition enabled geometrically accurate MR as well as synthetic CT images and allowed anatomic coverage up to L1–L3 vertebrae to enable treatment of para-aortic nodes.

37

Rapid Brain and Pelvis Synthetic CT Using Generative Adversarial Networks

Carri Glide-Hurst[1], Ming Dong[2], Siamak Nejad-Davarani[1], Carri Glide-Hurst[1], (1) Henry Ford Health System, Detroit, MI, (2) Wayne State University, Detroit, MI

Purpose: While MR-only treatment planning using synthetic CTs (synCTs) offers potential for streamlining clinical workflow, a need exists for an efficient and automated synCT generation to facilitate near real-time MR-only planning. This work describes a novel method for generating brain and pelvis synCTs based on generative adversarial networks (GANs), a deep learning model that trains two competing networks simultaneously. **Materials and methods:** The proposed method is evaluated on two patient CT/MR cohorts: Post-Gadolinium T1-Weighted/CT-SIM images from fifteen brain cancer patients and T2-Weighted/CT-SIM images from fourteen prostate cancer patients. In the brain, the GAN model was developed to generate synCTs using a residual network (ResNet) as the generator. The discriminator is a CNN with five convolutional layers that classified the input image as real or synthetic. Five-fold cross validation was performed to validate our model.

For pelvis, which is more challenging due to the need to handle bladder/rectal status and soft tissue changes, a modified version of the generator architecture is used. The modified residual network has the same number of residual blocks and convolutional layers, but also includes several skip connection from the input MRI. The added skip connections from the input MRI to the encoder layers help to preserve the structure of organs in the input MRI image. A regular CNN with five convolutional layers is used as the discriminator similar to the brain experiments. To better preserve air in the input MRI image, a new weighted loss function was implemented. The weighted loss function gives different weights for different areas when calculating the differences between the real and generated synthetic CTs proposed by the GAN model. Replacing classical GAN loss with the weighted loss helps the generator to focus more on the air areas and generate more accurate synthetic CTs. Five-fold cross validation was performed to validate our generated synthetic CT results with the new generator architecture and weighted loss function. **Results:** GAN testing took ~11 h with synCT generation time of 5.7 ± 0.6 s for the both brain and the pelvis experiments. For the brain dataset, MAEs between synCT and CT-SIM were 89.3 ± 10.3 HU across the entire FOV. In the pelvis, MAEs between synCT and CT-SIM were 44.7 ± 5.14 HU across the entire FOV. Modified GAN synCTs with skip connections and weighted loss functions preserved details better than regular GAN, and air regions were well represented on GAN synCTs. Using the weighted loss function helped the network to depict internal air in regions consistent with the MR input image. **Conclusions:** We developed and validated GAN models using a single MRI input (T1 for brain, T2 for pelvis) that generate robust, high quality synCTs in seconds. Use of a modified generator architecture and weighted loss function in the pelvis experiments helped to obtain more accurate synthetic CTs with preserved organ structures and air regions consistent to the input MR image. Our method offers strong potential for supporting near real-time MR-only treatment planning in both brain and pelvis while preserving features necessary for high precision applications.

38

Dosimetric Modelling of the Couch and Coil Structures for Unity MRI Linac

Nina Tilly[1,3], Gerhard Feist[1], Klas Marcks von Würtemberg[1], Stefan Pencea[2], James Dolan[2], Nicholas Schupp[2], David Tilly[1,3,4], (1) Elekta Instruments AB, Stockholm, SE, (2) Elekta Inc. St. Louis, MO, (3) Uppsala University, Uppsala, SE, (4) Akademiska Hospital, Uppsala, SE

Purpose: The aim of this work was to dosimetrically characterize each part of the Patient Positioning Support (PPS) (the couch, bridge, table top and the comfort mattress) and MRI coils for treatment planning for treatments with Unity. **Materials and methods:** Starting from design drawings displaying the cross section of the PPS and coils, the different structures were divided in zones where each zone was assigned a single material and a mass density.

The materials were initially characterized by assigning effective mass densities. This was accomplished by fine-tuning the effective densities using Collapsed Cone calculations to match the results from experimental attenuation measurements with slabs of the different materials in an 6 MV beam (no magnetic field).

With the resulting model of the PPS introduced in the TPS, dose was calculated with GPUMCD and compared to full-circle verification measurements performed using a PTW Farmer ion chamber with a Perspex buildup cap at the isocenter of the Unity MRI Linac (in Crawley and Utrecht) for a 2-degree gantry angle increment. **Results:** The results show that TPS dose can be calculated within 1% compared to measurements (with 2 mm dose calculation grid resolution) through the entire PPS and both coils for all gantry angles.

The influence of the cryostat was deconvolved from measurements of the PPS and Coils for the purposes of comparison.

Irradiating through the PPS from below (gantry angle 180°) results in approximately 10% attenuation of the beam. Irradiation through the anterior coil results in approximately 1% attenuation of the beam. Sharp gradients in the attenuation per gantry angle can be seen when the beam goes through the edges of the PPS and are effectively calculated by the TPS. **Conclusions:** The entire PPS and both coils could be dosimetrically modelled within 1% compared to measurements for all gantry angles.

39

MR-only Radiotherapy with MR-CBCT Treatment Verification for Prostate Cancer: First UK Clinical Implementation

Jonathan Wyatt, Rachel Pearson, John Frew, Serena West, Michele Wilkinson, Karen Pilling, Rachel Brooks, Dean Ainslie, Andrew McNeil, Neil Richmond, Christopher Walker, Newcastle upon Tyne Hospitals NHS Foundation Trust, Newcastle upon Tyne, UK

Purpose: MR-only radiotherapy does not require a planning CT scan, eliminating the MR-CT registration uncertainty and improving the patient experience. MR-only radiotherapy using the MR directly as the reference data for MR-CBCT verification enables MR-only radiotherapy to be implemented without using fiducial markers. This is essential for extending MR-only treatments to other pelvic cancers but has not been reported in the literature to our knowledge. An end-to-end evaluation of an MR-only pathway compared to a conventional MR-CT fusion pathway for prostate cancer has also not been reported. This paper presents the results of the first UK clinical implementation of MR-only radiotherapy and an evaluation of the process compared to a MR-CT fusion pathway. **Materials and method:** Four patients received planning MR and CT scans on a radiotherapy couch top. Each patient was delineated, planned and treated on an MR-only pathway and independently delineated and planned on a MR-CT fusion pathway.

The MR-only pathway consisted of a small Field Of View (FOV) MR image for target delineation and a large FOV MR image for Organs At Risk (OAR) delineation, synthetic CT (sCT) generation and on-treatment verification. The sCT was produced using MriPlanner (Spectronic Medical, Sweden) and the VMAT plan created using RayStation (RaySearch Laboratories, Sweden). For on-treatment verification the CBCT was matched to the large FOV MR, which was relabelled as a "CT" in the DICOM header so it could be used on the TrueBeam linear accelerator (Varian, Palo Alto, USA).

The MR-CT fusion pathway used the small FOV MR and CT for target delineation and the CT for OAR delineation and dose calculation.

The MR-only pathway was evaluated on: target delineation, doses to the OARs, accuracy of dose calculation and on-treatment verification. Target delineation was evaluated by calculating the ratio of the MR-only delineated prostate and seminal vesicles volume to the MR-CT fusion delineation volume. OAR doses were compared by calculating the dose to 50% of the rectum volume for each plan. The sCT dose calculation accuracy was assessed by recalculating the MR-based plan on the CT and determining the dose differences. The on-treatment accuracy was determined by comparing MR-CBCT and CT-CBCT matches performed independently by two radiographers. **Results:** The prostate and seminal vesicle volumes were smaller on the MR-only plans than on the CT-MR fusion plans, with the volume ratio being $V = 0.83 \pm 0.06$ (mean $\pm$ standard error on the mean). This reduction in treated volume reduced the dose to 50% of the rectum volume by $13 \pm 5\%$ (mean $\pm$ SEM). The sCT dose calculation was accurate, with a mean dose difference in the PTV D50 of $\Delta D = -0.2 \pm 0.3\%$ and no point dose difference >1.3%. The MR-based treatment verification was accurate, with a mean difference between MR and CT treatment verification matches to the CBCT of $\Delta R = -0.5 \pm 0.5$ mm. **Conclusion:** MR-only planning with soft-tissue matching has been successfully clinically implemented. The evaluation against a MR-CT fusion pathway was promising, with prostate volumes and rectal doses being smaller on the MR-only pathway and with high dose calculation and on-treatment verification accuracy.

This suggests that there may be improved OAR sparing using an MR-only approach, compared to using MR-CT fusion. This study also implies that MR-only prostate radiotherapy can be safely delivered using MR-CBCT soft-tissue matching, enabling MR-only radiotherapy to extend to other pelvic cancers.

40

Uncertainty in MRI Simulation Scans for Radiotherapy Planning: CNS and Lung Cancer

Monique Heinke[1], Lois Holloway[2], Robba Rai[1], Shalini Vinod[2], (1) Sydney, AU, (2) South Western Clinical School, University of New South Wales, Liverpool, Australia, Sydney, AU

Purpose: CT-based imaging is the standard modality for radiotherapy planning. CT images allow visualisation of anatomical structures and provide the electron density information necessary for radiotherapy dose calculations. MRI has superior soft tissue resolution but are prone to distortion. Currently MR images can be registered to the simulation CT to aid in volume delineation. The objective of this study was to assess the reproducibility of MR images in the radiotherapy position. **Materials and methods:** Ten patients with brain tumours (CNS) and ten lung cancer patients who were planned to undergo definitive or adjuvant radiotherapy treatment were prospectively recruited. CT simulations were performed on a Phillips Brilliance Big Bore 16 slice CT scanner with an image matrix of 512 × 512 mm and a slice thickness of 2 mm with 2 mm slice increments. Anatomical T2-weighted MRI sequences were obtained on a MAGNETOM Skyra 3T wide bore scanner. A 20-channel receive-only head and neck coil was used for the CNS scans and a 32-channel spine coil combined with an 18-channel surface array coil for the Lung scans. A 2 mm (CNS) or 4 mm (Lung) slice thickness and 0 mm spacing were used. Following the first MRI (MRI1), patients got up off the couch and subsequently were repositioned for a second scan (MRI2). A series of normal anatomical landmarks were contoured on the CT and the two MRI datasets. Both MRI scans were rigidly registered with the simulation CT and to each other using MIM Software. Contour comparison metrics using Dice Similarity Coefficient (DSC) and Centre of Mass (COM) were determined for all structures considering 3 scenarios (a) MRI1-MRI2; (b) CT-MRI1, and (c) CT-MRI2. **Results:** For the CNS scans the median DSC for the Cerebellum, Left and Right Maxillary Sinus were ≥0.84 for the MRI1-MRI2 comparison and ≥0.75 for both CT-MRI1 and CT-MRI2 comparisons. The median COM for the MRI1-MRI2 comparison was ≤1.9 mm for these structures and was greater for the CT-MRI comparison (≤4.0 mm). A similar pattern was seen for the Lung structures. The median DSC value for the Aorta was 0.81 for the MRI1-MRI2 comparison compared to 0.70 and 0.73 for the CT-MRI1 and CT-MRI2 comparison. For the Carina and T9 Cord the DSC value was better for the MRI1-MRI2 comparison, ≥0.71 than for CT-MRI1 or MRI2, ≥0.57. The median COM values for the three lung structures were closer for MRI1-MRI2, 2.5–3.3 mm, than for CT-MRI, 2.6–6.2 mm. **Conclusion:** There was greater consistency seen in the contoured anatomical landmarks between the two MRI scans than the registration of the CT with either MRI. There was more variability in the Lung scans reflecting increased movement due to respiration. Overall, these results suggest there is good reproducibility of normal anatomical structures between sequential MRI scans, with the ultimate aim MRI-only radiotherapy planning.

41

Geometrical Analysis of Target Definition on Corrected MR Images and its Effect on Stereotactic Radiosurgery Treatment Planning

Ali Fatemi, Chunli (Claus) Yang, Madhava Kanakamedala, University of Mississippi Medical Center, Jackson, MS

Purpose: MRI images suffer geometric distortion originating from both patient- and MRI system-specific factors. We assessed the geometric distortion inherent in MR images used in stereotactic radiosurgery (SRS) treatment planning and attempted to evaluate changes in target volume contour and dose delivery based on the target location. **Materials and methods:** Geometric distortion of MR images was evaluated on a phantom and ten patients with targets from 0.13 to 0.01 cc. We evaluated the geometrical volume comparison between gross target volumes contoured on corrected and uncorrected MRI using simple volume assessment (%) and concordance index (CI%) with its location on a derived distortion map. To study dosimetry, their corresponding center of mass shift [both absolute and in all directions (X, Y, Z)] was evaluated for both contours. We evaluated differences in target dose coverage as a dose volume histogram after geometric distortion correction based on the target location with respect to the MRI distortion map, volume difference after correction, and center of the mass shift. **Results:** The target volume of corrected MRI images on average is 11.3% is smaller than non-corrected images, with a CI% of 0.41% and 0.45-mm distortion. The average change in the center of mass shift between contours was 0.04 mm, with the maximum shift in the Z direction. The average under-dose for corrected MRI images was 1.5%. As we expected, the maximum under-dose was in the highest distortion area, where the lesions located near periphery region and boundaries such as cerebrum and brainstem with 0.7–0.8 mm distortion as high as 8.98%. The average center of shift change on targets for corrected MR images was 0.2 mm. **Conclusions:** The changes in contours using the corrected MRI images is definitive. This technique will offer new opportunities to evaluate its effect on SRS tumor control probability and normal tissue complications.

42

***In Silico* Analysis of MR-only Planning for Simulation-Free MR-Guided Spine SBRT**

Olga Green, Soumon Rudra, Alex Price, Sasa Mutic, Clifford Robinson, Washington University School of Medicine, St. Louis, MO

Purpose: Spine SBRT is a proved treatment modality for patients with good performance status, potentially long projected life spans, and/or radioresistant tumors. The proximity of the spinal cord necessitates the acquisition of either MR or CT myelography imaging. The time between diagnostic imaging, simulation, and treatment can stretch to upward of 2 weeks, potentially reducing the probability of favorable outcome. However, the availability of hybrid MR-linac systems allows for a reduction of imaging to treatment time, as both the spinal cord and target area are well-visualized. In this study, we sought to apply our current online adaptive radiotherapy methods to a simulation-free workflow for spine SBRT patients, wherein the patient is imaged on the hybrid MR-linac unit, a pre-selected base plan adapted, and treatment commenced while patient is on-table. As there would be no CT image acquired, we investigated the potential for dosimetric error when using a bulk density override method only. **Materials and methods:** Five patient datasets were chosen to be representative of typical patient habitus observed in the clinic (1 obese, 2 over-weight, 2 non-obese; 2 male, 3 female). For each, the MR imaging datasets from previous MR-linac treatments as well as simulation CT datasets were collected. For each dataset, six CTVs were contoured on MR according to International Spine Radiosurgery Consortium (ISRC) consensus guidelines. The bulk density override function of the integrated MR-linac treatment planning system was used to assign a tissue-equivalent density (1.02 g/cc) to all non-boney anatomy except lung-equivalent (0.25 g/cc) as appropriate. The spinal column and adjacent rib bones were assigned a standard bone density override value of 1.12 g/cc. The patients' own CT datasets were fused as secondary images to the MR datasets. For each PTV, three plans were created and compared: using bulk density override only, recalculating the first plan using the patient's registered CT scan; reoptimizing using the patient's CT scan. **Results:** PTV coverage changed by an average of 2.5% for plans calculated with bulk density overrides as compared to using the real relative electron densities. The maximum dose to spinal cord changed by an average of 0.24 Gy (corresponding to 0.9% of the constraint maximum dose of 28 Gy), with a maximum observed deviation of 0.83 Gy (all plans achieved maximum cord doses well below 28 Gy, with a maximum of 21.44 Gy). Similar differences were observed for 3, 5, 7, and 10 mm expansions around the spinal cord and 100% and 50% conformality indices, indicating that the chosen bulk density overrides provided for robustness equivalent to CT-based plans. **Conclusions:** Using a bulk density override for spine SBRT based on MR-linac images was found to have acceptable accuracy for a simulation-free process.

43

Zero TE Based Pseudo CT Conversion: Toward A Silent Patient-Friendly Solution for Both Head and Pelvis Applications

Cristina Cozzini[1], Mikael Bylund[2], Sandeep Kaushik[1], Joakim H Jonsson[2], Josef A. Lundman[2], Mathias Engström[1], Tufve Nyholm[2], Florian Wiesinger[1], (1) GE Healthcare, Munich, GER, (2) Umeå University, Umeå, SE

Purpose: Patient specific and accurate pseudo CT are needed for the adoption of an MR-only Radiation Therapy (RT) workflow. Silent Zero Echo Time (ZTE) MR imaging was recently demonstrated suitable for Attenuation

Correction in PET/MR and for pseudo CT conversion for head and neck applications[1] and a feasibility study was performed also on 25 pelvis patients.[2] Here we investigate the impact on the dose accuracy of continuous vs single HU value assignment focusing specifically on bones. We evaluate both the ZTE correlation to CT bone values as well as Deep Learning (DL) methods for accurate pseudo CT conversion for Head and Pelvis applications. **Materials and methods:** Four patient data-sets from the Head study evaluated in Ref. [1] (data-set A) and four patient data set-sets from the pelvis study[2] (data-set B) were analyzed, where a 3.0 T GE SIGNA PET/MR scanner (GE Healthcare, Chicago, IL) was used for both studies. A CT scan was also provided for each patient. A bone mask was generated for values larger than 150 HU for both CT and pseudo CT data. The pseudo CT bone mask was rigidly registered to its corresponding reference CT bone mask.

Four different HU bone assignments were embedded in the original CT data to avoid misclassification or registration errors from soft tissue and air voxel values:

1. single bulk density assignment of an average bone density value of 700 HU;
2. single bulk density assignment of an average soft density value of 42 HU;
3. pseudo CT bone values from the inverse linear scaling correlation described in Ref. [1];
4. Deep Learning HU value assignment from the method described in Ref. [3];

Training was performed on Head and Neck ZTE data only and DL inference for bone was limited to data-set A only.

The datasets were imported into the following RT Planning softwares: RayStation, RaySearch, Stockholm, Sweden and Oncentra, Elekta, Stockholm, Sweden. Dose distributions for all evaluated plans were analyzed and exported from the treatment planning system into the image analysis software MICE (Medical Interactive Creative Environment).[4] The four bone value data-sets variations under study were analysed with respect to the reference CT data. **Results:** The Target Volume (TV) average dose difference for data sets A and B was evaluated. While in (1) and (2) the pure dose difference originating from different HU value assignment is measured for step (3) and (4) dice coefficient and registration errors also enter in the analysis.

An excellent correspondence between dose calculated on the CT with its original bone values and on the CT with DL pseudo CT bone values (for Head) and pseudo CT inverse scaling values (for both data-sets) can be observed with variations inferior to 0.3% for all cases. **Conclusions:** The strength and the reliability of ZTE based bone value conversion has been shown for both Head and Pelvis applications. This paves the way to a silent patient-friendly MR-only RT solution.

References

1. Wiesinger, Florian, et al., MRM (2018):1440–1451.
2. C.Cozzini, et al., ISMRM 2018.
3. S.Kaushik, et al., ISMRM 2018.
4. T. Nyholm, et al., 3rd ESTRO Forum, 2015.

44

The Impact of MRI Geometric Distortion in Stereotactic Radiosurgery

Ergys Subashi[1], Yang Sheng[2], Sharif Elguindi[1], John Kirkpatrick[2], Fang-Fang Yin[2], Yunfeng Cui[2], (1) Memorial Sloan Kettering Cancer Center, New York, NY, (2) Duke University, Durham, NC

Purpose: To evaluate geometric distortion in a 3 T MRI scanner and assess its impact in stereotactic radiosurgery (SRS). **Materials and methods:** Gradient-nonlinearity (GNL) distortion was measured using an anthropomorphic head phantom containing a 3D grid of 3.0 mm rods with a spacing of 15.0 mm. The coordinates of the intersection points were determined by a regional search and 3D normalized cross-correlation. Intersection points identified in a high-resolution CT (voxel size = 0.6 × 0.6 × 0.6 mm^3) were used as the ground truth for distortion estimation. The phantom was scanned over the course of five consecutive days using a T1-weighted 3D SPGR sequence with the following imaging parameters: 1 mm^3 isotropic voxel, TE/TR = 3/2110 ms, FA = 8°, BW = 240 Hz/px. GNL distortion was corrected using the vendor's approach based on 2D or 3D spherical harmonics deconvolution. Distortion magnitude was calculated as the distance between the coordinates of control points in MRI images and those in the CT image. Patient-specific distortion was estimated with a dual-echo GRE pulse sequence: 3.1 × 3.1 × 2.5 mm^3 voxels, TE1/TE2/TR = 10/14.9/84 ms, FA = 60°, BW = 240 Hz/px. A model for the GNL-distortion vector-field was generated by considering the magnitude of measured distortion as a function of distance-to-isocenter in left–right, anterior–posterior, and superior–inferior direction. The impact of distortion was studied in simulations as a function of target size, shape, and distance from MRI-isocenter. The effects were also studied in 15 patients treated with SRS. **Results:** Median GNL-distortion was unchanged over five days, was significantly lower when distortion correction was applied, and did not depend on correction method (Kruskal-Wallis test, $\alpha = 0.05$). In a 20 × 20 × 20 cm^3 imaging field-of-view (FOV), centered at MRI-isocenter, residual GNL (rGNL) distortion was less than 1.0 mm in a sphere of radius 87 mm; over the entire FOV, maximum rGNL-distortion was 2.2 mm. At the surface of a 5.0 mm spherical target centered at the MRI-isocenter or at the edge of the FOV, the maximum, mean, and range of rGNL-distortion was (0.0, 0.0, 0.0) mm and (2.3, 2.2, 0.1) mm, respectively. For a 50.0 mm spherical target, these values were (0.3, 0.3, 0.1) mm and (2.7, 2.3, 0.9) mm, respectively. Maximum rGNL-distortion was dependent on both target size and distance to MRI-isocenter, mean distortion was primarily dictated by distance to MRI-isocenter, while range was mainly dictated by target size. Volume changes for spherical targets varied from ~3% to ~5% with a negligible dependence on target size. The shift in target centroid as a function of distance from MRI-isocenter was approximately linear, ranging from ~0.0 to ~2.3 mm, with negligible dependence on target size. The Paddick-Conformity-Index, the over-treatment ratio, and the under-treatment ratio were primarily dependent on distance to MRI-isocenter, with small targets experiencing largest effect. Coverage of elongated targets was affected the most when oriented perpendicular to distortion field. Patient-specific distortion had a large effect next to high-susceptibility tissue-boundaries but decayed quickly with distance from the boundary. **Conclusions:** Residual geometric distortion at large distances from MRI-isocenter should be evaluated in MR-based planning for radiosurgery. In this context, correction methods must be routinely considered.

45

Quality Assurance of a Compressed Sensing T2 Mapping Sequence for Multiparametric MRI in Prostate Cancer

Yu-Feng Wang[1], Gary Liney[2], Robba Rai[2], Lois Holloway[2], Annette Haworth[1], (1) University of Sydney, Sydney, AU, (2) Ingham Institute for Applied Medical Research, Sydney, AU

Purpose: Quantitative mapping of T2 relaxation time has been shown to correlate with citrate concentration and proven useful in prostate cancer (PCa) discrimination. Low citrate concentration of PCa tissue is associated with low T2 values. However, T2 mapping is not currently a component of recommended multiparametric MRI due to the long acquisition time of using conventional multi-echo spin echo sequences. Compressed sensing (CS) is a model-based accelerated image reconstruction technique that has been adapted for T2 mapping to decrease image acquisition time. The goal of this study is to evaluate the accuracy and short-term repeatability of the CS T2 mapping sequence at various under sampling factors. **Materials and methods:** A phantom with T2 elements from the National Institute of Standards and Technology Systems (NIST) was used to determine the accuracy and repeatability of the CS T2 mapping technique. The phantom was placed in the bore 8 h prior to imaging to reach thermal equilibrium. Images were acquired on a 3 T MRI scanner (MAGNETOM Skyram, Siemens, Erlangen, Germany) with 16 echoes (12.5–200 ms, 12.5 ms echo spacing), under sampling factors of 5, 3, and 1, and voxel size of 1.6 × 1.6 × 3 mm^3. To evaluate short-term repeatability, T2 maps were acquired 5 times within the same session for each under sampling factor. T2 maps were calculated using the Syngo workstation (Siemens, Erlangen, Germany) and T2 values for each element were extracted from a region of interest. Accuracy of the T2 values were evaluated by calculating the percentage deviation of the mean T2 from the NIST reference value. Intra-session repeatability was evaluated by calculating the coefficient of variance (COV) in the repeat measurements. Accuracy and intra-session repeatability were calculated for the all T2 elements (5.6 to 581.3 ms), with focus on the range of prostate T2 values (64.1 to 190.94 ms). **Results:** T2 mapping acquisition time using under sampling factors of 1, 3, and 5 are approximately 10, 4, and 2 min respectively.

Accuracy and intra-session repeatability of T2 outside the range of 22.6–403.5 ms deteriorated significantly. The accuracy for CS T2 mapping with under sampling factors of 1, 3, and 5 were not significantly different (2.4%–14.5%, 4.8%–15% and 1.2%–11.3% respectively) for T2 in the range of 22.6–403.5 ms. CS T2 mapping showed high intra-session repeatability, with median CV of 0.4%–0.5% for T2 range of 22.6–403.5 ms at the various under sampling factors. For the T2 values relevant to prostate, the lower under sampling factor slightly increased accuracy, whilst repeatability was similar at all under sampling factors (CV $\leq$ 0.5%). **Conclusion:** T2 mapping using a novel CS reconstruction technique was evaluated for accuracy and short-term repeatability using a commercial phantom with known T2 values. CS T2 mapping with under sampling factor of 5 produced accurate, repeatable and high resolution T2 maps with clinically viable image acquisition time of 2 min for PCa imaging. Future work will focus on assessing the longitudinal repeatability of the CS T2 mapping sequence for use in a sequential imaging study to assess treatment response for PCa.

46

Initial Experience of the Performance Characteristics of the Elekta Unity MR-Linac

Ian Hanson, The Royal Marsden NHS Foundation Trust, London, UK

Purpose: The Elekta Unity MR-Linac (Elekta AB, Stockholm, Sweden) has been used to treat patients at the Royal Marsden Hospital/Institute of Cancer Research since September 2018. A quality assurance (QA) program has been developed to ensure the safety of patient delivery. Here we present results on the stability and performance characteristics of the Elekta Unity MR-Linac based on QA measurements acquired over several months. **Materials and methods:** Our QA system consists of daily, weekly and monthly tests of both the linac and MR components. These test-measurements include linac dosimetry, radiation field collimation, mechanical stability, alignment of the radiation and imaging systems, and MR image quality. Certain tests are conducted more frequently than recommended by current national guidance (AAPM TG-142, IPEM 81) whilst confidence is built in this new technology.

Many of the QA tests rely on the EPID panel that is rigidly fixed onto the rotating gantry of the Elekta Unity. For example, the EPID has been used to perform daily checks on radiation output and collimation consistency. Other tests have been created for use specifically on the MR Linac, either to test the systems unique capability, or to address the challenges of performing measurements within a high magnetic field. An example of the former is the Elekta MR to MV phantom, used to confirm the alignment of the MRI and linac. An example of the latter is a star-shot radiation isocentre phantom that sandwiches film between copper rings to mitigate against the Lorentz force acting upon electrons. **Results:** As an example of this stability of the Unity system, a sample of the average QA measurements is presented below.

The mean variation in daily output measured using the EPID panel is (-0.17 ± 0.60)%. The output is also measured weekly using the StarCheck Maxi array (PTW, Freiburg, Germany), where the variation has been (0.19 ± 0.31)%, and monthly using a Farmer chamber in a water tank, where the variation has been (0.62 ± 0.68)%.

The mean deviation in daily EPID measured field size along the *Y*-axis (jaw) is (0.13 ± 0.18) mm, and for the x-axis (MLC) is (-0.12 ± 0.05) mm.

The mean deviation in the daily measured MR-to-MV alignment along all 3 axes is (0.04 ± 0.04) mm.

The MRI slice thickness (with expected value of 5 mm) has been measured weekly using an ACR large MRI phantom, and has been found to be (4.99 ± 0.18) mm for a T1 sequence and (4.87 ± 0.35) mm for a T2 sequence.

The percentage integral uniformity is also measured weekly using the ACR large MRI phantom and has been found to have a mean value of 93.9% (range: 92.8%–94.8%) for a T1 sequence and 93.38% (range: 92.36%–94.39%).

In all measurements to date, none have exceeded our action tolerance levels. **Conclusions:** Our initial QA experience of the Elekta Unity MR-Linac indicates that the machine is very stable, and to date all clinical treatments have been completed on time. Most parameters have not changed significantly over nearly 6 months of use and remain well within tolerance.

47

Online and Offline Patient Specific Quality Assurance for an MR-Linac System

Alex Price, Washington University in St. Louis, St. Louis, MO

Purpose: In this study, we look to investigate various methods of patient-specific IMRT QA for the ViewRay MRIdian system. There is an increase in the use of MR-Linacs due to its ability to provide excellent soft tissue contrast and adaptive workflows. The constant magnetic field and inability to perform pre-treatment measurement-based IMRT QA for adaptive treatments requires special considerations. This research is novel in that the ArcCHECK-MR (AC-MR) is being used in absolute dose mode and provides guidance for different treatment sites when using the AC-MR and the online adaptive QA tool. **Materials and methods:** The absolute dose measured for a 9.98 cm $\times$ 9.98 cm open field by the AC-MR was compared against the TPS and verified with an ion chamber (IC). Once verified, output factors and dose linearity were measured on the AC-MR to verify the AC's response under a 0.35 T magnet under field size/MU conditions similar to the VR's treatment plans. 95 patient plans across multiple treatment sites were delivered to the AC-MR using gamma passing rates of 3%/3 mm, 3%/2 mm, and 2%/2 mm, 10% threshold with global dose max normalization without the inclinometer turned on. IC measurements were also included for all measurements. Looking specifically at off-axis treatments, 15 breast patients were isolated to look at the correlation between isocenter and target distance with gamma passing rates. Finally, 4 adaptive patient plans (2 with 15 fractions and 2 with 5 fractions) had both AC-MR and online adaptive QA measurements performed to track QA results over multiple adaptive fractions. **Results:** For the absolute dose measurements, the output corrected diode measurement was 0.04% higher than what was expected from the TPS's highest expected Monte Carlo accuracy. The ADCL calibrated IC was 0.02% higher than expected. The AC-MR dose linearity has a maximum percent difference from the mean at 2 MU which was -1.61%. The output factors measured on the AC-MR are within 2% when compared to the TPS down to a field size of 1.66 $\times$ 1.66 cm. For all treatment sites, the 3%/3 mm, 3%/2 mm, and 2%/2 mm is 97.53% $\pm$ 1.97%, 93.34% $\pm$ 3.86%, and 89.27% $\pm$ 5.41%, respectively. The average IC measurement is 0.993 $\pm$ 0.013 of what is expected. There is a r = 0.85 correlation between isocenter and target distance with gamma passing rate for 15 breast patients. When the inclinometer is turned off, the gamma passing rate absolute difference is 3.75% higher when compared to the measurements with the inclinometer turned on. For the adaptive patients, the standard deviation across all AC-MR 3%/3 mm measurements is 1.14% and online adaptive 2%/2 mm is 0.66%. The largest change in AC-MR 3%/3 mm from the mean per patient is 3% but still within the measured confidence limit at 3%/3 mm. **Conclusions:** This study provides guidance when measuring IMRT QA for the ViewRay MRIdian system using a suite of QA tools. One must be wary of off-axis delivery on an AC-MR, especially for small complex fields. Despite changes in segment shapes in adaptive treatments, IMRT measurements are within the confidence limit, and together with built in log file QA and online adaptive QA provide necessary precautions when performing adaptive radiotherapy.

48

Comprehensive Distortion Assessment in a 0.35 T MR-Linac

Siamak Nejad-Davarani, Dongsu Du, Joshua Kim, Carri Glide-Hurst, Henry Ford Cancer Institute, Detroit, MI

Purpose: Introduction of the MRI Linear Accelerator (MR-linac) has provided a unique tool for near real-time tumor tracking and monitoring during radiation therapy (RT) delivery. However, to facilitate high precision RT, it is of critical importance to perform a comprehensive assessment of the distortions intrinsic to the MR-linac. This work assesses gradient non-linearity (GNL), including temporal evaluation, and subject-induced magnetic susceptibility distortions in a 0.35 T MR-linac. **Materials and methods:** An in-house large field of view modular phantom was configured ($60 \times 42.5 \times 55$ cm^3, >6000 spherical landmarks spaced at 2.5 cm) to fit the bore of the ViewRay MRIdian MR-linac. GNL was isolated and measured by acquiring six image volumes with the reverse gradient technique at the left–right (LR), anterior–posterior (AP) and superior–inferior (SI) frequency encoding directions (3D Gradient Echo, TR/TE: 30/6 ms, FA: 28°, BW: 260 Hz/pixel, FOV: 540 $\times$ 540 $\times$ 528 mm, Voxel size: 1.54 $\times$ 1.54 $\times$ 1.5 mm, single channel transmit/receive body coil). Vendor supplied 2D/3D corrections were applied to acquired images. CT images were acquired (120kVp, Philips Brilliance Big Bore, FOV:

600 × 600 × 600 mm^3, Voxel size: 1.17 × 1.17 × 1 mm^3) to serve as the distortion-free reference for landmark positions, after co-registration with the MR image volumes. Data were acquired over >1 yr of operation. To measure susceptibility-induced distortions, a novel pelvic phantom was used to simulate rectal air volume changes (30, 90 and 150 cc). Dual-Echo Gradient-Recalled-Echo (GRE) (BW: 261 Hz, TR/TE1/TE2: 45/20.65/41.3 ms) images were acquired to map the B0 field within the bore and phantom. Clinical TrueFISP parameters (Pixel size in frequency encoding direction: 1.5 mm, BW: 537 Hz/pixel) were used to estimate susceptibility-induced distortions in mm. Gantry angle was fixed at 0 degrees throughout experiments. **Results:** Almost all landmarks within 10 cm distance from the isocenter had <1 mm distortion along all axes which can be considered negligible (<1 mm) for most MR-linac RT applications. Landmarks in the 20–25 cm range showed the highest magnitude of distortions with ~40% having distortions >1 mm in the AP-PA, LR-RL and SI-IS directions. Largest distortions were measured in the AP direction with values up to ~7 mm in the 20–25 cm range. Although SI-IS distortions were higher near the isocenter compared to the other two directions, it remained <4 mm within the entire FOV. Magnitude of distortions varied <2% across the two timepoints in the SI-IS and AP-PA directions; however LR-RL distortions were reduced by 16% and 20% in the 10–20 and 20–25 cm ranges, respectively. Susceptibility-induced distortions within a 2 cm ring around the 150 cc rectum were −0.02 ± 0.05 mm (range: −0.44 to 0.30 mm). Increased air volumes revealed higher distortion magnitudes at the edge of the rectal cavity and showed a larger radial impact (up to a few centimeters away from the cavity). **Conclusions:** Based on phantom data, susceptibility based distortions in the pelvic area can be considered negligible for RT applications such as treatment of prostate cancer. However, GNL can add non-negligible distortions to the image which for RT applications necessitates correction or further considerations such as positioning the RT target near the isocenter. As future work, we will investigate the effect of the gantry angle on perturbing the B0 field and the resulting geometric distortion.

49

Comparison of Image Distortion of 1.5 T and 3 T MR Scanners with An Elekta G-Frame and Pins using a Grid Phantom

Zhifei Wen, Tina Briere, Ping Hou, Dennis Mackin, R. Jason Stafford, MD Anderson Cancer Center, Houston, TX

Purpose: Geometric fidelity of MRI is critical in achieving sub-millimeter accuracy in intracranial stereotactic radiosurgery (SRS). When the patient is imaged with a metal frame and fixation pins in the MRI, the metal may have an impact on the geometric distortion, and the MR system with a higher magnetic field may suffer more. In this study, we evaluated the geometric distortion of two MR scanners (1.5 and 3 T) using a grid phantom with the presence of a G-frame. **Materials and methods:** An Elekta Leksell G-frame with two anterior fixation posts and two 45 mm titanium pins were attached to a QUASAR GRID 3D phantom (14 × 13 × 11 cm^3). The phantom was first scanned with a CT fiducial box (voxel size 0.49 × 0.49 × 1 mm^3) in a Philips Brilliance Big Bore CT scanner. The same phantom was then scanned with an MR fiducial box and a quadrature transmit-receive radiofrequency head coil on a 1.5 T MR scanner (GE Optima MR450w) and a 3 T MR scanner (GE Discovery MR750w). The intrinsic image distortion (without metal) for the two scanners had been evaluated with a MAGPHAN (ADNI) 051 phantom and was found to be similar (mean of top 10% distortion ~0.7 mm for both). The clinical 3D T1 weighted GRE sequence was used with FOV = 24 × 24 cm^2, slice thickness = 1 mm, acquisition matrix = 256 × 256. For 1.5 T, TR/TE/FA = 6.9 ms/2.5 ms/12° with a receiver bandwidth of ± 41.67 kHz; for 3 T, TR/TE/FA = 6.6 ms/2.0 ms/12° with receiver bandwidth = ±62.5 kHz.

The CT and MR images were analyzed using two methods. We first used the software provided by the phantom vendor to automatically identify the fiducial markers and localize the grid vertexes (total of 2002). Distortion was calculated as the differences between the calculated locations of the identified vertexes and their nominal locations. Next, we imported the images into the GammaPlan software (version 11.1, Elekta), in which the fiducial markers were automatically identified to establish the stereotactic coordinate system. We then sampled 28 vertexes in 4 axial planes. Distortion was calculated as the differences between the stereotactic coordinates of the corresponding vertexes localized in MRI vs CT. **Results:** With data analyzed in the phantom software, the mean absolute deviation (MAD) of the vertexes in CT was (0.23, 0.31, 0.21; 0.51) mm in x,y,z, and radially. For 1.5 T, MAD = (0.13, 0.76, 0.34; 0.87) mm; for 3 T, MAD = (0.09, 0.74, 0.29; 0.83) mm.

With data analyzed in GammaPlan, the CT images were used as the reference and MAD for the sampled 28 vertexes at 1.5 T was (0.20, 0.76, 0.33; 0.89) mm. At 3 T MAD = (0.28, 0.88, 0.23; 1.00) mm. **Conclusions:** The image distortion of a 3 T MR scanner evaluated using a 3D grid phantom with an Elekta G-frame was similar to that of a 1.5 T MR scanner. With higher SNR, the 3 T MR scanner seems a better choice for intracranial SRS, since the frame and pins do not show higher impact on the image distortion compared with 1.5 T.

50

A Repeatable Physiological 4D Deformable Motion Phantom Insert for Edge Detection and Tracking in MR-IGRT Workflows

Madeline Perrin[1], Nicholas Hartman[1], Kalin. I. Penev[2], Markus Glitzner[3], Cornel Zachiu[3], Enzo Barberi[1], (1) Modus Medical Devices Inc., London, ON, (2) Western University, London, ON, (3) University Medical Center Utrecht, Utrecht, NL

Purpose: MR-IGRT has the potential to provide real-time intrafraction imaging of tumor motion utilizing MRI's powerful soft tissue contrast for high precision radiation therapy. A major challenge for this technique, and EBRT as a whole, is the geometric uncertainties introduced by the motion of both tumors and nearby organs. This uncertainty is typically covered by treatment margins, inflicting damage to surrounding healthy tissue through overdose. If such uncertainties are not taken into account during planning, the likelihood of underdosing the tumor significantly increases along with the risk of cancer recurrence. MR-based target tracking has paved the way for increased confidence in tumor localization. This work evaluates a custom-designed modular MR-compatible 4D motion phantom insert, capable of repetitive physiological deformation, with the goal of benchmarking MR-IGRT QA. **Materials and methods:** The deformable insert simulates a compressible tumor made from a custom molded low density open-cell polyurethane foam with a central tumor shaped void and hollow axial fiducial markers. The open cellular structure, capable of absorbing large amounts of liquid contrast solution with MR-signal, has desirable tissue-like mechanical properties. It is both amenable to custom foam molding and provides accurate shape generation in a practical production environment. The cylindrically molded foam body was connected to a reciprocating deformation mechanism capable of pressure compensation through volume change, all housed within a sealed acrylic body. Motion was created using an MR-safe Modus QUASAR MRI4D Motion Phantom Drive Unit within a Motion Phantom Oval. The insert and foam were filled with 50 cSt polydimethylsiloxane/tert-butyl alcohol solution (90/10 vol.%) doped with 1000 ppm Gd(TMHD)3 to simulate liver tissue with T1 approximately 700 ms at 3 T. Scans were acquired using 3D T1 Vibe, and TrueFISP MRI in the coronal plane on a 3 T MAGNETOM Prisma scanner (Siemens). **Results:** Repeatable, sinusoidal and physiological, deformable motion was successfully achieved. The T1 contrast of the solution was slightly higher than expected (T1 ≈ 900 ms), and showed distinct separation between external foam and tumor. Reciprocating deformation mechanism and housing materials exhibited no MR signal, as expected. A deformation range of ±1 cm was achieved; comparable to the typical motion range of mobile abdominal organs during respiration. **Conclusions:** A novel deformable proof-of-concept insert accessory was developed that simulates tissue like deformation in physiological respiratory motion patterns. Future work includes modifications to foam density, investigations of alternative contrast media, and the creation of internal foam boundaries that presents with conservation of volume during deformation.

51

Harmonic Analysis Method Based Geometric Distortion QA Phantom Design for Sub-Millimeter Accuracy

Enzo Barberi[1], Mike Cole[1], Teo Stanescu[2], (1) Modus QA, London, ON, (2) Princess Margaret Cancer Centre, University of Toronto, Toronto, ON

Purpose: MRI for Simulation and RT Planning as well as new hybrid systems combining an MRI-scanner with a Linac for MRI-guided treatments are now of great interest to clinical sites. While MRI can provide superior soft-tissue contrast and biomarker information related to cancer, there are system limitations common to all MRI and MRI-Linac vendors based on human factor design compromises and interaction of magnetic fields with matter. MRI-guided RT methods require new QA tools to quantify these issues that contribute to image geometric distortions to ensure confidence in treatment. Overall accuracy and

precision of <2 mm is desired, with SRS applications requiring sub-millimeter specifications, therefore a high-quality QA program using phantom measurement techniques is required. An MRI geometric distortion QA phantom with submillimeter accuracy is presented. **Materials and methods:** A method of quantifying geometric distortion based on harmonic analysis (HA) applied to a boundary phantom (hollow cylinder) was compared with conventional grid phantoms. The method follows guidance pertaining to geometric distortion phantom design recommended in recently published standards. A pressure and temperature compensation system was implemented to ensure 3-dimensional stability of fluid filled phantom structures as uncompensated phantoms experience internal ΔP over 40 psi for a 10°C ΔT. Optimal liquid contrast media were investigated: (a) avoid absorption into phantom's plastic housing leading to structural changes and (b) provide good contrast relevant to physiological T1 and T2 values. Two strategies were applied to minimize the susceptibility-induced effects arising at material interfaces and affecting the true-location of measurement control points: (a) phantom wall thickness was modelled for sufficient separation between air-plastic interfaces and control points and (b) susceptibility values were closely matched between liquid contrast media and phantom plastic housing. FOV measurement accuracy was ensured by using a sufficiently dense map of sampling points. Phantom's manufacturing accuracy was measured and verified using traceable standards. Dedicated analysis software was developed to analyze phantom image data, namely to automatically and robustly detect >99% of all control points, compute 3D distortion vector fields using HA, separate B_0 from gradient non-linearity, and visualize data using multiple analytics. Validation of HA results was performed using a grid insert placed inside hollow phantom. Imaging protocols were investigated to generate good contrast and SNR (>50) while maintaining a 1–1.5 mm^3 voxel resolution. **Results:** Agreement within 1% between HA method using a boundary phantom and conventional grid phantoms was achieved. Phantom's manufacturing accuracy and precision was found to be ≤0.1 mm with an overall rigid and stable structure free of metal machining debris. The liquid-filled phantom has been shipped under a wide range of seasonal temperatures (−20°C to +50°C) without leaking, confirming efficacy of temperature and pressure compensation. Residual error in the boundary phantom measurement method is estimated by calculating B_0 distortion in the non-readout directions (theoretically zero) which typically averages 0.05 mm. Average manufacturing tolerance of 0.05 mm was verified by a calibrated Coordinate Measurement Machine. **Conclusions:** The HA method using a hollow boundary QA phantom designed according to recommendations in latest standards has been demonstrated to be dimensionally stable and submillimeter accurate.

52

Towards Real-Time High Resolution Dosimetry in An MRI-Linac: Proof of Concept

Trent Causer[1], Sarah J. Alnaghy, Natalia Roberts[1], Urszula Jelen[2], Bin Dong[2], Marco Petasecca[1], Anatoly B. Rosenfeld[1], Peter Metcalfe[1], Brad M. Oborn[1], (1) University of Wollongong, Wollongong, University of Wollongong, Wollongong, NSW, (2) Liverpool Hospital, Liverpool, UK

Purpose: High resolution monolithic silicon detectors have been shown to be suitable for dosimetry of advanced modern radiotherapy techniques such as Stereotactic Body Radiation Therapy (SBRT) and Stereotactic Radiosurgery (SRS).[1] The introduction of MRI-linac systems presents new challenges to these advanced techniques, such as quality assurance detector design, operation and performance. In this work we demonstrate the proof of concept use of two monolithic silicon strip detector systems to characterise a radiotherapy beam with high (0.2 mm) spatial resolution, in real-time, in the presence of the 1 T magnetic field on the Australian MRI-linac system. This included during MR-imaging. **Materials and methods:** Two high-resolution (0.2 mm sampling) silicon based detectors were used; the single-strip sDMG256A (256 channels covering 50 mm) and the dual-strip DUO (two orthogonal strips each with 256 channels forming a cross-hair of 50 mm width). A custom designed radiofrequency (RF) shielding constructed of aluminum was incorporated into the detector packaging to minimise cross-talk between the detector and MR-imaging. The detector arrays were positioned at a depth of 50 mm within a 30 × 30 × 20 cm^3 solid water phantom stack.

The x-ray beam in the Australian MRI-linac prototype is a 6 MV accelerator (Varian Linatron) with a 120 leaf MLC (Millenium 120). Small radiation beams (<5 × 5 cm^2) were investigated and their profiles measured. The influence of real-time MR-imaging sequences (2D cine, 2.5 Hz) on the dosimetry was studied and compared with equivalent measurements outside the MRI scanner, that is, at 0 T. The detector systems operate in real-time (dose per linac pulse mode) and so the impacts of MR-images was investigated for both real-time and integral dose mode. **Results:** High-resolution profiles of small 6MV beams were successfully observed in real-time with/without simultaneous radiation beam delivery and imaging inside the 1 T MRI-linac. A small change (reduction) in the penumbral width (<1 mm) was observed when inside the 1 T MRI field. This is attributed to the inline magnetic field acting to reduce lateral beam spread and is well understood in the literature. There was an increased background noise in the detectors during MR-imaging, attributed to non-perfect RF decoupling between the MRI (imaging RF) and the detector systems housed in the aluminum shielding. Overall, the quality of the beam profiles measured within the MRI field and during imaging is slightly degraded as compared to those without a magnetic field or MR-imaging occurring. This is presented as a random noise distributed throughout the profiles, in the order of ±10% of the maximum dose. **Conclusion:** For the first time, we have shown the feasibility of performing real-time high spatial resolution dosimetry with simultaneous imaging in an MRI-linac System. Future work will include further improving the detector system's shielding design to decrease the noise introduced to the dosimetry measurements. Inversely, the impact on the quality of the MR images will also be examined. **Acknowledgement:** The authors would like to acknowledge the Cancer Council NSW project grant (no. 1128336).

References

1. Petasecca M et al., Med Phy, 2015 vol: 42 (6Part1) pp: 2992-3004.

53

Construction and Performance of An MR-Compatible Water Calorimeter

Mark D'Souza[1], Humza Nusrat[1], James Renaud[2], Gerrard Peterson[3], Niloufar Entezari[1], Arman Sarfehnia[4], (1) Ryerson University, Toronto, ON, (2) National Research Council, Ottawa, ON, (3) Sunnybrook Health Sciences Centre, Toronto, ON, (4) University of Toronto, Toronto, ON

Purpose: It has been well documented that MR-integrated linear accelerators have a different dosimetric impact due to the electron return effect. Due to this, accurate dose-to-water measurements must be taken. Calorimeters have been a standard for these measurements. Calorimeters measure the radiation induced temperature change in a medium, from which dose can be calculated if the specific heat capacity of the medium is known. We aim to design and construct a MR-compatible water calorimeter that can perform these measurements accurately. **Materials and methods:** Finite Element Method (FEM) analysis (COMSOL Multiphysics 5.3a was used to design the calorimeter. To reduce effects of convection, the calorimeter was designed to run at a stagnant 4°C. To insulate from the exterior environment, a three-shell acrylic system was simulated with different insulators (Cryogel, air, and Styrofoam) between shells. The point of measurement is surrounded by a glass vessel to ensure water purity and minimize heat defect. To minimize heat conduction and beam perturbation at this point, glass vessel's dimensions (height, radius, and thickness) were numerically varied to determine the optimal values. Dose distributions for 6 MV, 6 FFF, 9 MeV, and 18 MeV beams were used and simulated using Monte Carlo simulation (GEANT4.10.3). The calorimeter was then constructed using only plastic and ceramic components allowing it to be imaged using KV or MR imaging. The lid was constructed with a beam window minimizing disturbance of the beam. The calorimeter was then placed in a 6 MV beam (Elekta Synergy, FS: 10 × 10 cm^2, SSD:100 cm) to perform preliminary measurements. Measurements in an Elekta MR-linac (7.2 MV) in the presence of a 1.5 T magnetic field are currently underway. **Results:** FEM analysis showed Cryogel to be the best insulator when using a three-shell acrylic system. This showed resistance against ambient temperature fluctuations of up to 2°C. The final calorimeter design had a cylindrical top and a hemispherical bottom. This allowed for irradiation with MRLinac/Conventional linacs from the top, as well as sideway setup to allow for volumetric and Gamma Knife measurements. Analysis of glass vessel parameters showed that heat transfer was most sensitive to changes in vessel height. The lid was designed to house a hydraulically controlled stirring mechanism as well as coolant flow to provide uniform tank cooling all around.

The beam window in the lid proved to be a significant loss of thermal stability, and efforts are underway to mitigate the heat loss. Temperature detectors were visible using MR and KV imaging showing feasibility of positioning the calorimeter using imaging alone. Initial measurements inside the MR-linac in absence of magnetic field showed that our calorimeter agreed

with the A1SL measurements to within 2%. **Conclusions:** A MR-compatible water calorimeter was constructed based on simulation results. The beam window was further insulated to help restore thermal stability. Dose-to-water measurements were successfully obtained inside an MR-linac in the absence of a magnetic field and measuring with the magnetic field are currently underway.

54

Skin Dose Measurements on An Inline 1T MR-Linac

Peter Metcalfe[1], Natalia Roberts[1], Elizabeth Patterson[1], Urszula Jelen[2], Gary Liney[2], Trent Causer[1], Lois Holloway[2], Michael Lerch[1], Anatoly Rosenfeld[1], Dean Cutajar[1], Brad Oborn[1], (1) University of Wollongong, Wollongong, NSW, (2) Ingham Institute for Applied Medical Research, Sydney, AU

Purpose: Lorentz force from the magnetic field of an MRI interacting with electrons generated by a linear accelerator has an impact on radiation dose distributions at the surface. The fringe field of the Australian MR-linac causes contaminant electrons to be focused along the central axis resulting in a high surface dose. It is necessary to accurately characterise this electron hot spot before testing methods to reduce the effect. Skin dose enhancement due to the electron focus effect (EFE) for the inline Australian MR-linac has been measured using a MOSkin™, microDiamond (PTW 60019) and Gafchromic EBT3 film. **Materials and methods:** The MOSkin® has been used to characterise a skin dose enhancement effect on the Australian inline MRI-linac. The device was placed in the MR-linac and doses at sub mm build up intervals at central axis and off axis positions were measured. The linac is mounted on rails hence build up measurements at 180 cm SSD in 0 and 1 T can be compared. **Results:** The MOSkin® has been used to measure a small electron focusing zone in the Australian inline MR-linac build up region. Skin dose in this MR-Linac was 48% at 0T and 186% at 1T for the 6 cm × 6 cm field size; it was 61% at 0T and 369% at 1 T for the 12 cm × 12 cm field size; and it was 79% at 0T and 711% at 1 T for the 23 cm × 23 cm field size. While measurements with the MOSkin™ agree at depth the microDiamond appeared to over-respond in the 1 mm to 3 mm depth. Note due to the encapsulation the microDiamond could only measure to within nominally 1 mm of the surface. The Gafchromic film was used to assess the width of the circular hot spot in the beams eye view orientation. The circular hot spot produced by the 12 cm × 12 cm field measured 2 cm diameter of the full width half maximum dose intensity. **Conclusions:** A MR compatible high resolution MOSkin® which can measure within 70 mm of the surface has been used to characterise the surface dosimetric characteristics of the Australian MR-linac. The magnitude of this surface dose for this particular in line MR-linac design is several orders of magnitude greater than current commercial transverse designs, however the dosimeter is sensitive enough to also be useful in measuring these smaller dose enhancements from electron return effects in these devices. We have started exploring methods to ameliorate the significant skin dose effect which seems to be significant to our particular in line design. **Acknowledgment:** The authors would like to acknowledge the Cancer Council NSW project grant (no. 1128336).

55

Dosimetry for the First Live Irradiation on the Australian MRI-Linac

Urszula Jelen[1], Bin Dong[1], Jarrad Begg[2], Natalia Roberts[3], Hilary Byrne[4], Tara Roberts[5], Paul Keall[4], Gary Liney[1], (1) Ingham Institute for Applied Medical Research, Liverpool, AU, (2) Liverpool and Macarthur Cancer Therapy Centre, Liverpool, AU, (3) University of Wollongong, Wollongong, NSW, (4) University of Sydney, Sydney, AU, (5) Western Sydney University, Sydney, AU

Purpose: Four MRI-Linac designs exist using a range of magnetic field strengths and either perpendicular or parallel (inline) beam-to-magnetic-field orientation. Two of these systems, both using perpendicular orientation, are now in clinical use, while the inline configuration, as used in the Australian MRI-Linac, has not been employed for live irradiations previously. The purpose of this work was to establish the dosimetric aspects of the first therapeutic animal imaging and irradiation on the Australian MRI-Linac within an on-going trial investigating theranostic nanoparticle contrast agent. **Materials and methods:** The Australian MRI-Linac features a variable source-to-isocentre distance (SID). In order to benefit from the highest field shaping resolution, the shortest SID of 1.8 m was used. Based on the MR imaging performed in the pilot phase of this study, a vertically off-axis field of 2.25 × 2.90 cm^2 was selected encompassing the whole brain of the animal. A 2 cm thick solid water slab was placed proximal to the beam serving two purposes: as a bolus to shift the target beyond the build-up region for more homogeneous dose distribution and to mitigate increased skin dose due to electron focusing.

The number of monitor units to deliver 10 Gy to the target (right brain hemisphere), as defined in the study protocol, was determined using a microdiamond detector (60019, PTW) cross-calibrated to a Farmer chamber (FC-65G, Scanditronix/Wellhofer), previously characterised in the magnetic field. The microdiamond was placed in a solid water block resembling the geometry and the scatter conditions of small animal irradiation: the block was 3 × 3 × 8 cm^3 oriented sidewise to the beam with the detector placed 1.5 cm from the tip. The result was verified through Gafchromic (EBT3, Ashland) film measurements in following experiments: films were irradiated (a) in the same block geometry at the beam entry surface, in the middle of the block and at beam exit surface, (b) on either side of a rat cadaver in treatment position and (c) in the same setup during the treatment of live animals. **Results:** The doses recorded in the block geometry were: 10.2–10.5 Gy at the entry surface, 8.7–9.0 Gy in the middle and 7.8–8.6 Gy at the exit surface on the central axis. The doses measured around the rat cadaver were 11.3 Gy in the upstream film and between 11.3 and 7.2 Gy in the downstream film depending on the thickness of the tissue traversed by the beam. Since these films were placed in air, rather than at tissue surfaces, they served primarily for the verification of the positioning. However, they were also used as benchmark for films irradiated in the same setup during the treatment of the live animals, which yielded 11–11.5 Gy in the proximal films and between 10–11 Gy and 7–7.6 Gy in the distal films. **Conclusions:** Pre-treatment and in-vivo dosimetric procedures for small animal irradiations have been developed and executed constituting, to the best of our knowledge, the first irradiation of this type on any MRI-Linac and a key step towards the clinical application of the Australian MRI-Linac.

56

Magnetic Field Correction Factor, KB, for A Roos Chamber in An Inline MRI-Linac

Jarrad Begg, Urszula Jelen, Gary Liney, Lois Holloway, Ingham Institute for Applied Medical Research, Sydney, AU

Purpose: Ion chamber response in magnetic fields has been shown to be dependent on radiation beam to magnetic field orientation (perpendicular vs inline) as well as orientation of the chamber relative to the magnetic field. For inline MRI-linacs with a radiation beam aligned parallel to the B_0 magnetic field, the magnetic field correction factor, k_B, for Farmer type chambers is in the order of 1%. Magnetic field correction factors have been predominately investigated for cylindrical chambers. Different chamber designs could potentially have smaller correction factors. The purpose of this investigation was to establish a methodology and measure the magnetic field correction factor, k_B, for a Roos parallel plate chamber. **Materials and methods:** The Australian MRI-linac features a linac system on rails, allowing movement along the fringe field of a 1.0 Tesla magnet, including into a zero field region close to the bore. Measurements can be acquired with and without the magnetic field without the need to ramp-up or down the MRI. Previous measurements have established an absorbed dose to water calibration factor, N_{Dw}, at B = 1 T for an IBA Farmer chamber (s/n: 819) via alanine dosimetry. The same chamber was calibrated at the National Physics Laboratory (NPL) for B = 0 T conditions. Cross calibration between the IBA Farmer chamber and a secondary chamber at both 1 and 0 T can establish the N_{Dw} for the secondary chamber at both magnetic field strengths. The magnetic field correction factor, k_B, is then calculated via the ratio of the calibration factors at B = 1 T relative to B = 0 T. Cross calibration between the IBA Farmer chamber and a PTW30013 (s/n: 10066) chamber was used to calculate k_B on a secondary chamber and verify the methodology. Once verified, the methodology was used to calculate the k_B for a Roos chamber. Relevant polarity and recombination factors were measured for all chambers and applied to the measurements. **Results:** Recombination and polarity measured for all chambers at 0 and 1 T was within 0.25% of unity. The calculated k_B for the PTW30013 was 0.992 ± 0.015. Monte Carlo simulations of the PTW30013 chamber showed a 0.9937 for an inline MRI-linac at a magnetic field strength of 1.5 T.[1] Magnetic field corrections for cylindrical type chambers in an inline MRI-linac have previously been shown to be consistent with only a small difference between 1 and 1.5 T.[2] The agreement between measured correction factors and simulated correction factors validates this methodology. The calculated k_B for the Roos chamber was 1.004 ± 0.013. **Conclusions:** This work has demonstrated a cross-calibration procedure for chamber specific magnetic field correction factors in an inline MRI-Linac.

Results for a Roos chamber have shown the need for a much smaller correction factor with a parallel plate chamber than has previously been established with a cylindrical type chamber.

References:
1. Malkov, V. N. and D. Rogers (2018). *Medical Physics* **45**(2): 908-925.
2. Reynolds, M., et al. (2013). *Medical Physics* **40**(4).

57

Improving Megavoltage X-Rays Radiotherapy Efficacy: Using Theranostic Gadoliniuom-Bismut Nanoparticles

Nader Riyahi Alam[1], Somayyeh Farahani[1], Soheila Haghgoo[2], Ziynab Derakhshan[1], (1) Tehran University of Medical Sciences, Tehran, IR, (2) Food and Drug Control Research Center, Tehran, IR

Purpose: Maximizing on-target radiosensitivity and minimizing off-target toxicity is the ultimate goal of radiation therapy. The magnetic resonance (MR) /computed tomography (CT) image-guided radiation therapy (IGRT) shows significant potential to increase the targeted dose escalation. Great advances in nanotechnology have led to administer metal-based nanostructures as radio-enhancers to selective killing of cancer cells. Combining these two novel approaches can effectively enhance the quality and therapeutic ratio of radiotherapy. Consequently, the purpose of this study was to investigate new theranostic bismuth-gadolinium (Bi/Gd) nanocomposites as the radiation dose enhancer at clinically relevant MV x-ray energy. **Materials and methods:** Bi/Gd nanoparticles (NPs) consisting of Bi2O3 as the contrast enhancer of CT imaging and Gd2O3 as the contrast enhancer of MR imaging were synthesized in three separate ratios ([Bi]:[Gd] ions molar ratio of 1:1, 2:1, and 1:2, which were named Bi-Gd, 2Bi-Gd, and Bi-2Gd, respectively). To investigate quantitatively the dose enhancement of nanoparticles, the MAGICA polymer gel loaded with Bi/Gd nanoparticles (0.01% (w/v) NPs) was synthesized. All phantoms containing gel (with and without nanoparticles) were irradiated by 18 MV x-ray beams at doses of 0–600 cGy. Finally, the radiation-induced polymerization amounts of the synthesized samples were read using a 3 Tesla MRI scanner. **Results:** Using an R2 map computing program coded in MATLAB, the mean dose enhancement factor (DEF) from Bi-Gd, 2Bi-Gd, and Bi-2Gd nanoparticles were measured as equal to 12.40%, 19.82%, and 36.52%, respectively. **Conclusion:** This dosimetric research has evaluated the dose amplifying effect of Bi/Gd nanocomposites by applying the MAGICA polymer gel as a tissue equivalent dosimeter. Our results confirm the use of Bi/Gd nanocomposites, particularly Bi-2Gd nanoparticles as a new class of theranostic radiation sensitizer in the high-energy MV radiation therapy.

58

Online Geometric Fidelity Inspection for MR-Guided Treatments on 1.5 T MRI-Linac: Visualizing the Cumulative Effect of Gradient Errors and Patient Specific Susceptibilities

Rob Tijssen[1], Robin Vos[2], Marielle Philippens[1], Astrid van Lier[1], Bas Raaymakers[1], Cornelis van den Berg[1], Bjorn Stemkens[1], (1) University Medical Center Utrecht, Utrecht, NL, (2) B.V., Zaltbommel, NL

Purpose: MRgRT holds great promise for high precision stereotactic radiation therapy. The geometric fidelity of MR images, however, is patient specific and spatially dependent. This makes online inspection of the total geometric error vital, to assure that MRI scans can be used for accurate localization. For this purpose we have developed an online visualization tool that quantifies the total geometric distortion from the combined effect of gradient inaccuracies and B_0-field inhomogeneities (caused by system imperfections and patient-induced susceptibility variations).[1] The results are presented as an overlay on top of the (daily) anatomical MRI. **Materials and methods:** The online tool runs on the scanner host computer of the MR-linac (1.5 T Unity, Elekta AB, Sweden) where it converts the acquired B_0-field map into a patient-specific map, which shows the local displacements based on the scan parameters of the acquired scan using PRIDE inline scripting. The necessary acquisition parameters of the anatomical MRI (i.e., readout bandwidth and readout direction) are extracted directly from the scanner exam database as the DICOM headers do not contain the necessary information. The displacements by gradient imperfections, which were obtained during commissioning,[2] are automatically added to the patient-specific displacement map. The visualization is performed with a semi-transparent overlay with optional isocontours. Basic functioning of the tool was assessed by retrospectively running the analysis tool on five patients (3 pelvis, 1 abdomen, 1 thorax) that had undergone imaging on the MR-linac and had B_0-field maps acquired. **Results:** The software tool did not require installation and ran properly as a portable application on the MR host computer. Gradient system-related displacement maps acquired with two different geometric fidelity phantoms (Modus MRID3D and Philips 7-slab phantom) loaded successfully and were displayed in the correct orientation. Differences between the system-related displacement maps derived from the two different phantoms were small (<0.5 mm in the PTV region). The automatically extracted scan parameters, required for the conversion of the B_0-map into the patient-specific displacement map, agreed with the parameters observed in the actual scan protocols. Visual inspection showed that the patient-specific displacement maps agreed with the underlying anatomy. Overall, the geometric displacements were <1 mm for pelvis region, <1.5 mm in the abdomen, and up to 2 mm in the thoracic area for the clinical sequences that were tested. **Conclusions:** Our geometric fidelity visualization tool correctly adds the system-related distortions to patient-induced displacement maps. The implementation appears fast enough to allow online geometric fidelity inspection. The analysis, however, still needs to be validated quantitatively on phantoms prior to clinical use. Future work will involve commissioning of the software and embedding the geometric inspection tool into our online MR-linac workflow.

References
1. Goodburn et al. *ESTRO 37.* 2018.
2. Tijssen et al. *RadOnc.* 2019.

59

Multi-Institutional MRI Benchmarking of 0.35 T MR-Linacs

Sebastian Klüter[1], Amish Shah[2], Kristian Boye[3], Keith DeWyngaert[4], Anthony Doemer[5], Pierre Fau[6], Olga Green[7], Görkem Güngör[8], Alonso Gutierrez[9], Daan Hoffmans[10], Hugues Mailleux[6], Kathryn Mittauer[11], Eenas Omari[12], Miguel A. Palacios[10], Ryan Pennell[4], Tino Romaguera[9], Anil Sethi[12], Poonam Yadav[11], Maria Bellon[13], Rajiv Lotey[13], Carri Glide-Hurst[5], (1) Heidelberg University Hospital, Heidelberg, GER, (2) UF Health Cancer Center at Orlando Health, Orlando, FL, (3) Rigshospitalet Copenhagen, Copenhagen, DK, (4) New York Presbyterian Hospital, New York, NY, (5) Henry Ford Health System, Detroit, MI, (6) Institut Paoli-Calmettes, Marseille, FR, (7) Washington University in St. Louis, St. Louis, MO, (8) Acibadem Mehmet Ali Aydinlar University, Istanbul, TR, (9) Miami Cancer Institute, Miami, FL, (10) Amsterdam University Medical Center, Amsterdam, NL, (11) University of Wisconsin, Madison, WI, (12) Loyola University Chicago, Maywood, IL, (13) Viewray Inc., Mountain View, CA

Purpose: The introduction of hybrid MR-linac systems into the clinic presents unique quality assurance challenges due to the presence of a rotating linac gantry and shielding components. To date, limited commissioning data are available to evaluate the overall imaging performance of low-field MR-linacs nor are comparison data currently available. This work summarizes the imaging acceptance and commissioning results from a multi-institutional cohort of twelve 0.35 T MR-linacs. **Material and methods:** The ViewRay MRIdian Linac houses a 0.35 T split superconducting magnet with split gradient coils and a gap of 28 cm between both magnet halves. Aside from the body coil, receive coils consist of radiolucent phased arrays with 10 channels (5 anterior/5 posterior) for head and neck and 12 channels (6 anterior/6 posterior) for the torso. Coincidence of MRI, radiation, and lasers isocenters was quantified using pre-established laser/radiation relation, a cylindrical, water-filled phantom with its MR-scan registered to a CT reference dataset, and radiochromic films. Spatial integrity was assessed in 3 cardinal planes at isocenter as well as off-axis ($\pm$7 cm and $\pm$12 cm lateral displacements) for the clinically used 3D gradient-echo, balanced steady state sequence with a ~30 $\times$ 30 cm^2 phantom containing ~400 landmarks. Positional deviations between phantom landmarks and a binary template were evaluated via vendor-supplied, MATLAB®-based software and the differences were quantified. Image uniformity and signal to noise ratio (SNR) were evaluated for the body, torso, and head and neck coils following NEMA standards. An ACR phantom was scanned using axial T1 and T2 weighted spin echo sequences and slice position accuracy, slice thickness accuracy, high contrast spatial resolution, low contrast detectability, image intensity uniformity and percentage ghosting tests were conducted. Magnet field homogeneity (MFH) was measured via the spectral peak method at 5–12 gantry angles using a 24 cm homogeneous sphere phantom aligned to magnet isocenter. **Results:**

Coincidence between MRI, lasers, and radiation isocenters was ≤0.8 mm for all 12 MR-linacs. Averaged over all institutions, MRI spatial integrity yielded 100% of landmarks with spatial agreement <2 mm within 35 cm DSV and <1 mm within 20 cm DSV at all orientations and off-axis locations. Average SNR for combined-channel torso and head and neck coils were 39.6 ± 4.9 and 42.0 ± 6.3, respectively, while single channel SNR exhibited higher variability: 100.8 ± 11.2 and 104.5 ± 15.3, respectively. Image uniformity for the body, torso and head and neck coils were 71.2% ± 1.6%, 83.9% ± 7.1%, and 83.9% ± 6.9% respectively. All ACR tests evaluated were within ACR specifications for all institutions. Averaged over all gantry angles, MFH results were 2.93 ± 1.82 ppm. For 3 out of 12 institutions, some gantry angles exceeded the vendor-defined specification of 5 ppm. To address this, a dynamic gantry angle-dependent shim technique using a gradient offset look-up table was implemented by the vendor. **Conclusions:** Overall, excellent agreement of imaging performance was observed across 12 different 0.35 T MR-linacs. Spatial integrity and ACR tests were within specification. These multi-institutional data can be used for benchmarking new MR-linac installations and help establish action limits for the MRgRT community.

60

Usability of Radiolucent MRI-Guided Radiotherapy Receive Arrays in Hybrid PET/MRI Systems

Stefan Zijlema, Woutjan Branderhorst, Luca van Dijk, Rob Tijssen, Jan Lagendijk, Dennis Klomp, Hugo de Jong, Nico van den Berg, University Medical Center Utrecht, Utrecht, NL

Background: Simultaneous PET/MRI acquisitions require placement of receive arrays within the PET detector ring to achieve an optimal signal-to-noise ratio (SNR). Conventional, diagnostic arrays contain electronics and other dense materials that can significantly attenuate the 511 keV photons. To maintain PET sensitivity and quantitative accuracy, scan times or activity must be increased and attenuation correction must be performed. Similarly, MRI-guided (external beam) radiotherapy (MRIgRT) requires receive arrays that do not attenuate the high-energy (MV) photon beam that passes through, that is, radiolucent arrays. Simultaneous PET/MRI may also benefit from such radiolucent receive arrays. **Objectives:** Here, we investigate two radiolucent receive arrays, which were developed for MRIgRT, on their usability for simultaneous PET/MRI. We compare the impact on PET sensitivity of three arrays: (a) the anterior element of a conventional, diagnostic receive array (16 channels), (b) the anterior element of a preclinical receive array for the 1.5 T MR-linac (4 channels), and (c) a self-developed prototype receive array consisting of an anterior (16 channels) and posterior element (15 channels), as proposed by Ref. [1]. Additionally, we assess the MR imaging performance of array (a) and (c). **Materials and methods:** PET sensitivity loss was investigated by scanning a cylindrical Ge-68 source (scan time: 3 min, total activity: 89.17 MBq) in a PET/CT system (Siemens Biograph mCT 40), and calculating the percentage reduction of true coincidences with respect to a scan of the source without a receive array present. The source was fixed in a wooden frame to avoid variations due to position changes.

MRI performance was assessed on a pelvis-sized phantom in a 1.5 T MRI system (Ingenia, Philips) for the anterior elements of arrays (a) and (c). Gradient echo acquisitions (TR/TE = 30/4 ms, FA = 20°) were converted to 2D SNR maps.[2] The mean SNR was assessed in the anterior half of the phantom. **Results:** The PET sensitivity losses were as follows:

Conventional array (anterior only): 8.36%

Preclinical MR-linac array (anterior only): 1.05%

Preclinical MR-linac array (anterior + posterior): 6.49%

Prototype array (anterior only): 1.00%

Prototype array (anterior + posterior): 2.16%

The anterior elements of the MRIgRT receive arrays lead to a significantly lower PET sensitivity loss than the conventional array. However, the posterior element of the preclinical MR-linac array increases sensitivity losses by >5%, affecting the quantitative accuracy of the PET reconstruction if no attenuation correction is performed. Our full 31-channel prototype array does not require attenuation correction, as it only attenuates 2.16% of the coincidences.

The MRI data produced similar SNR maps for the conventional and prototype array, with mean SNR values in the anterior half of the phantom of 95.9 ± 54.4 and 101.2 ± 58.0, respectively. **Conclusion:** The receive arrays, originally developed for MRIgRT, are suitable for use in PET/MRI applications, as they significantly reduce PET photon attenuation with respect to conventional diagnostic arrays. Compared to the diagnostic array, our 31-channel prototype achieves a similar MRI performance, while it can be positioned arbitrarily, as PET attenuation correction is not required.

References

1. Zijlema (2019). Procs. ISMRM Benelux Chapter.
2. Kellman (2005). Magn. Reson. Med. 54, 1439–1447.

61

Evaluating the Accuracy of MR Images Geometrical Distortion Correction for Intracranial Brain Tumors Radiotherapy

Ali Fatemi, Chunli (Claus) Yang, Madhava Kanakamedala, University of Mississippi Medical Center, Jackson, MS

Background: Magnetic resonance imaging (MRI) data must be corrected for geometric distortion and non-uniform intensity before use as a primary dataset for radiation treatment planning. Corrected anatomical and functional MR images can be used for better delineation and assessment of tumor and normal tissue. **Objective:** We sought to determine: (a) the effectiveness and robustness of correction for gradient-non-linearity and susceptibility effects on MR images of both QUASAR GRID^{3D} and CIRS phantoms; (b) the magnitude and regions of residual distortion before and after gradient non-linearity and field map-based corrections for susceptibility on head MR images. **Materials and methods: Phantom study:** MR, CT, and CBCT images were acquired using a QUASAR GRID^{3D} image distortion analysis head phantom (Modus Medical Devices Inc., Canada) and MRI distortion head phantom (CIRS, USA). MR images were acquired using MAGNETOM Siemens Aera 1.5 T RT edition, Axial T1W-MPRAGE, 1 × 1 × 1 mm^3, TR/TE=2200/2.91 ms, FA = 150, 300 Hz/pixel. We used both vendors' commercially available software to analyze geometric distortion before and after correction. **Patient study:** Under an IRB-approved protocol, MRI and CT images for stereotactic radiosurgery treatment were acquired for ten patients. A 3D post-contrast axial MPRAGE MRI pulse sequence was used for stereotactic coordinate definition, 3D gradient echo collecting (magnitude and phase), TE in phase and matched spatial resolution and bandwidth, with T1 MPRAGE, used to reconstruct a high-resolution gradient field map for patient-specific distortion correction. All scans included 3D distortion correction and pre-scan normalization to correct for gradient non-linearity and intensity non-uniformity. **Correction algorithm:** Field map images were acquired (TE1 = 9.52 ms/TE2 = 4.76 ms): two magnitude- and one phase-difference image. Then, the field map was created in FSL software. A MATLAB program was used to calculate the geometric distortion in the frequency encoding direction from the field map, and 3D interpolation applied to resize it to match MPRAGE images. MPRAGE images were warped according to the interpolated field map in the frequency encoding direction. **Analysis:** We used MIM software to (a) fuse corrected and uncorrected MR images, (b) deformable registered, and (c) generate difference distortion maps correlated with corresponding regions in MR brain images. **Results:** Modus medical GRID^{3D} image analysis software shows improvement in maximum deviation, with deviations of 0.23, 0.07, and 0.27 mm (x, y, z); the corresponding maximum distortion deviations on uncorrected MRI images are 0.32, 0.68, and 0.91 mm. CIRS software shows maximum geometric error correction of 0.34, 0.1 and 0.09 mm at an outer radius of 20, 40 and 60 mm (spherical diameter from isocenter). Patient data shows a correction range of 0.2–1.2 mm depending on the location of distortion; most was found around air cavities: sinuses and eye globes. **Conclusions:** The phantom data validates our fast distortion correction algorithm. These patient-specific data can be acquired in <2 min and analyzed and available for planning in less than a minute. The data show non-uniformity of distortion locations between patients, and there is no magic formula for prediction. It is more pronounced around the air cavities, but the order changes based on location and procedure.

62

First Proof-of-Concept Delivery of Intensity Modulated Arc Therapy on the Elekta Unity MR-Linac

Charis Kontaxis, Peter Woodhead, Gijsbert Bol, Jan Lagendijk, Bas Raaymakers, University Medical Center Utrecht, Utrecht, NL

Purpose: The Elekta Unity MR-linac (Elekta AB, Stockholm, Sweden) featuring a 1.5 T MRI and a gantry mounted 7 MV linear accelerator enables online treatment monitoring and adaptation during fixed-beam IMRT

delivery. In this work we enable arc therapy on the MR-linac taking advantage of the high-speed gantry capable of continuous rotation at 6 revolutions per minute (rpm). Moreover, we demonstrate that the gantry is able to accurately follow a prescribed trajectory with simultaneous MLC and jaw motion during beam-on. The dosimetric accuracy of this proof-of-concept arc delivery is assessed relative to the current clinical standard. **Materials and methods:** Multiple plans were generated using our MRL Treatment Planning system (MRLTP) modified to generate arc therapy plans, targeting a cylinder in cranial caudal direction (CYL) and featuring low amplitude MLC motion as well as a fully modulated prostate plan. In order to explore the machine performance during irradiation in multiple dynamic scenarios, the optimization parameters during the MRLTP arc planning of the CYL plans were constrained to near constant gantry speeds by setting equal MU and gantry increments per control point. The control points containing the leaf/jaw positions, dose and MLC/gantry angles were then sent to the modified treatment control system of the MR-linac using an in-house developed client. Several control system modules were modified to allow for dynamic arc delivery, ranging from pre-processing of the incoming dynamic control points to the real-time layers interacting with the gantry, MLC and beam modules. The dose was chosen as the delivery reference and gantry was set to track the dose progression during delivery. The above experimental plans were delivered while the status of MU, dose rate, prescribed and actual gantry position were logged. Two plans were delivered on Gafchromic™ EBT3 film and undergone standard clinical QA procedures. **Results:** All plans contained one clockwise arc spanning from 21 to 360° in 3° increments; 0–20 was excluded to avoid irradiating the MRI cryostat pipe. The three CYL plans were calculated to yield near constant gantry speed with delivery times of 56.5 (1 rpm), 42.4 (1.33 rpm) and 28.3 (2 rpm) s. The difference in prescribed and actual gantry position during treatment was on average 0.2 ± 0.5° and 0.6 ± 1.2° for the CYL and prostate plans respectively. For the CYL_1 rpm and prostate plans film dosimetry was performed for a coronal slice, both achieving 100% pass rate at a 3%/3 mm gamma analysis including all values greater than or equal to 10% of Dmax. **Conclusions:** We demonstrated the first arc delivery on the 1.5 T MR-linac. In this proof-of-concept work we have successfully delivered a fully modulated prostate plan conforming to the current VMAT standards. Moreover, we explored gantry speeds higher than the maximum constraint of 1 rpm used by most typical VMAT-enabled linacs. We are now further evaluating the performance of the machine on fast deliveries and exploring new types of arc treatments beyond VMAT in the context of MRI-guided therapy by combining high-modulated arcs with this high-speed 6 rpm gantry.

63

A Mask-Compatible, Radiolucent Head and Neck Receive Array for MRI-Guided Radiotherapy Treatments and Pre-Treatment Simulation

Stefan Zijlema[1], Luca van Dijk[1], Lovisa Westlund Gotby[2], Michel Italiaander[2], Rob Tijssen[1], Jan Lagendijk[1], Nico van den Berg[1], (1) University Medical Center Utrecht, Utrecht, NL, (2) MR Coils, Zaltbommel, NL

Background: Head and neck (H&N) radiotherapy uses masks for reproducible patient positioning to reduce treatment uncertainties. The shape and size of these masks hinder the use of regular, close-fitting H&N MRI receive arrays. Alternative setups that are now used during the pre-treatment simulation phase of MRI-guided radiotherapy (MRIgRT) often have suboptimal geometries or coil placement, that is, have a low filling factor. This results in a reduced signal-to-noise ratio (SNR). Moreover, a radiation transparent, or radiolucent, H&N array for the treatment phase on the 1.5 T MR-linac (Unity, Elekta AB) does not exist. **Objectives:** In this work, an 8-channel dedicated H&N array (MR Coils B.V., the Netherlands) was developed that is compatible with a radiotherapy mask and can be used in both treatment and simulation phases of MRIgRT. The array consists of (a) a single-channel baseplate on which the mask is secured and (b) a flexible 7-channel element following the shape of the radiotherapy mask for an optimal filing factor.

Here, we characterize the array's radiolucency and quantify the gain in SNR with respect to a current clinical setup. Our design aims to create an anterior element that has a negligible impact on the dose to allow exclusion from treatment planning, as its exact position is unknown. **Materials and methods:** Radiolucency: the response of EPID panels has been shown to be linear with dose with a high spatial resolution.[1] A 10 cm thick phantom was placed against the panel. 10 × 10 cm^2 beams (250 MU/min) were delivered and 50-frame average EPID responses were recorded for three setups: (a) phantom only (reference), (b) phantom + anterior element, and (c) phantom + posterior element. The attenuation was calculated as the signal change relative to the reference measurement.

Imaging: MRI performance was determined on an anthropomorphic saline water phantom (3.4 g/l NaCl) in a 1.5 T MRI system (Ingenia, Philips). Two setups were investigated: (a) the 8-channel prototype and (b) our clinic's setup for the simulation phase: two flex coils combined with a 16-channel anterior body array. Gradient echo acquisitions (TR/TE = 30/4 ms, FA = 20°) were converted to 2D SNR maps.[2] The SNR was assessed in a large region of interest (ROI) around the pharyngeal and laryngeal cavities. **Results:** Dosimetry revealed the following attenuation values:

Anterior element (support): 1.1 ± 0.7% (max: 3.4%);

Anterior element (support + conductor): 1.9 ± 0.3%;

Posterior baseplate (support): 10.8 ± 0.4%.

The MRI data showed that the SNR in the ROI increased by 35% from 781 ± 370 with the clinical setup to 1053 ± 416 with the dedicated prototype. **Conclusions:** Our 8-channel prototype is the first dedicated radiolucent H&N array for MRI-guided radiotherapy on the 1.5 T MR-linac. The anterior element's attenuation is low and support materials will be further optimized to be able to disregard it during treatment planning. The baseplate must be included. Additionally, our mask-compatible array can be used in the pre-treatment simulation phase, where SNR increased by 35%.

References

1. Zijlema (2019). Procs. ISMRM Benelux Chapter.
2. McDermott (2004). Med Phys 31(2):285–295.

64

MR-Only Radiation Therapy: A Novel Light-Weight, Flexible Coil for Head and Neck

Cristina Cozzini[1], Chad Bobb[2], Mathias Engström[3], Sandeep Kaushik[4], Molthen Robert[2], Dan Rettmann[5], Venkat Goruganti[6], Wen-Yang Chiang[6], Florian Wiesinger[1], (1) GE Healthcare, Munich, GER, (2) GE Healthcare, Waukesha, WI, (3) GE Healthcare, Stockholm, SE, (4) GE Healthcare, Bangalore, IN, (5) GE Healthcare, Rochester, MN, (6) MR Coils, Pewaukee, WI

Purpose: MR-only Radiation Therapy (RT) planning is very appealing for its potential of improving tumor targeting, while simplifying the workflow, by using a single imaging system. To achieve an optimized workflow however, dedicated RT coils are needed to allow patient positioning in the MRI with the RT fixation devices. Current clinical practice often results in uncomfortable set-up typically in form of a composition of different coils to ensure the desired coverage and image quality. Here a highly flexible, novel RT coil based on GE lightweight Air technology[1] is presented, demonstrating that a patient friendly MR-only simulation is feasible in a clinical setting and compatible with RT fixation devices. **Materials and methods:** A 3-tesla GE SIGNA MR and a PET/MR scanner (GE Healthcare, Chicago, IL) were used for silent Zero Echo Time (ZTE) MR imaging on ten volunteers with a prototype coil. The coil consists of 22 channels of which 15 located in the face, allowing for 3 different coil modes: head only, head and neck and chest only. For signal to noise ratio (SNR) and coil coverage assessment, phantom scans were also performed using a reference GEM RT open Head and Neck suite coil. ZTE data were processed with a Deep Learning (DL) method, which was previously trained on N = 50 patients using matched pairs of ZTE and CT patient data sets using standard product surface coils.[2] Standard gradient echo (LAVA-Flex) and fast spin echo (FS) MR pulse sequences including Dixon type fat-water separation were added for some volunteers to check overall coverage and image quality. **Results:** The head and neck coverage, including the shoulders, as required for RT planning, as well as SNR ratio of the prototype coil over the RT suite were analysed. An improvement of ≥20% in SNR is measured over the whole head phantom. The DL inference results show that the coil has appropriate coverage and image quality for pseudo CT conversion and training on data acquired with the prototype coil is expected to improve results. **Conclusions:** A new AIR coil prototype has been successfully included in the RT workflow, which is compatible with typical fixation devices and is suitable for standard MR imaging as well as for ZTE based pseudo CT image conversion. By being lighter and more flexible than traditional coil technology, the prototype adapts well to patient anatomy and improves the overall perceived scan experience.

References
1. S.S. Vasanawala et al., 2017. Development and Clinical Implementation of Next Generation Very Light Weight and Extremely Flexible Receiver Arrays for Pediatric MRI. arXiv preprint arXiv:1705.00224.
2. Kaushik et al., Deep Learning based pseudo-CT computation and its application for PET/MR attenuation correction and MR-guided radiation therapy planning, ISMRM 2018.

65

Investigating the Effects of A Magnetic Field on the Arccheck-MR Array Calibration

Alex Price, Washington University in St. Louis, St. Louis, MO

Purpose: In this study, the influences of the magnetic field on the inclinometer and the array calibration for patient-specific IMRT QA for an ArcCHECK-MR (AC-MR) is investigated. MR-Linacs are being implemented at a rapid pace in the radiation oncology field due to adaptive workflows provided by some vendors and the soft-tissue contrast for image guidance. The AC-MR is a heavily utilized tool for patient-specific IMRT QA and there are investigations needed for the effect of the MR-field on the array calibrations. **Materials and methods:** An array calibration was performed for a 6 FFF (Conv6FFF) and 6X (Conv6X) field on a conventional linac with no MR-field and then performed on the ViewRay MRIdean which has also a 6 FFF beam (MR6FFF). To look more closely at the array calibrations, 2D correlations and differences were taken of the array calibration matrices for each setup. Utilizing these array calibrations, a set of 95 patient plans were measured using the array calibrations for both 6FFF beams. The measurements were compared to the TPS using the gamma analysis test at 3%/3 mm, 3%/2 mm, and 2%/2 mm with a 10% threshold and global max dose normalization, inclinometer turned off. A subset of 15 breast patient plans were evaluated to look at the MR-field effects on off-axis treatments since there is a measured off-axis dependency on the AC-MR. **Results:** Due to limitations in VR MRIdian field sizes only diodes irradiated in the vendor specified array calibration were included in this analysis. Looking specifically at the array calibration correction factor matrix for each diode, the 2D correlation between the Conv6FFF-MR6FFF, Conv6X-MR6FFF, and Conv6FFF-Conv6X is r = 0.9974, r = 0.9765, and r = 0.9842, respectively. The mean difference in the array correction factor matrices for Conv6FFF-MR6FFF, Conv6X-MR6FFF, and Conv6FFF-Conv6X is 0.0022, 0.0024, and 0.0002, respectively. This represents 0.22%, 0.24%, and 0.02% of the average correction factor within the array calibration matrix, respectively. Moving towards patient data, we see that the average gamma analysis for the MR-array calibration patient data set for 3%/3 mm, 3%/2 mm, and 2%/2 mm is 96.83% $\pm$ 2.28%, 92.36% $\pm$ 4.37%, and 88.02% $\pm$ 6.00%, respectively. For the Conv6FFF array calibration, the 3%/3 mm, 3%/2 mm, and 2%/2 mm is 97.53% $\pm$ 1.97%, 93.34% $\pm$ 3.86%, and 89.27% $\pm$ 5.41%, respectively. For a subset of breast patients with the inclinometer turned on, the 3%/2 mm for the MR6FFF, Conv6FFF, and Conv6x is 89.47%$\pm$6.34%, 90.40%$\pm$6.12%, and 90.93%$\pm$5.34%, respectively. Both sets of measurements are well within the standard deviations of each other. The MRArray calibration provides the lowest passing rate. Due to off-axis dependencies of breast patients, the breast results are lower than all other patient plans with the inclinometer turned on. **Conclusions:** This study investigates the effects of the MR-field on the array calibration and measurement of the AC-MR. Looking at the comparison of the array calibration matrices, there are minimal differences of an array calibration with and without the presence of an MR-field. This is also seen across measured patient plans. Due to limitations of VR field size and SAD, array calibration should still be done on a conventional linac and causes uncertainties in the patient results when using the MR6FFF array calibration.

66

Evaluating Conditional Generative Adversarial Network Models for Head and Neck MR-Only Radiotherapy Treatment Planning

Peter Klages, Ilyes Benslimane, Sadegh Riyahi, Jue Jiang, Margie Hunt, Joseph O. Deasy, Harini Veeraraghavan, Neelam Tyagi, Memorial Sloan Kettering Cancer Center, New York, NY

Purpose: To implement and evaluate two conditional generative adversarial networks (GAN) models for MR-only treatment planning. **Materials and methods:** Twenty paired CT and mDixon FFE MR datasets from head and neck (HN) cancer patients treated at our institution were retrospectively analyzed to evaluate the accuracy and robustness of two conditional GANs, the Pix2Pix and Cycle GAN models, for MR-only treatment planning. Pix2Pix and Cycle GAN are conditional GANs that share similar network components (U-Net generator networks, and multi-layer discriminator networks), but differ in a few significant ways. Pix2Pix requires paired images since in addition to the standard GAN loss it uses the absolute difference (L1 difference) between the sCT and CT in training, while Cycle GAN does not expect paired images and instead relies on cycle consistency, that is, L1 difference between the starting and ending images, for two network loops (MR->sCT->sMR and CT->sMR->sCT) for training.

The original CT images were deformably registered to the MR images. The two networks were trained for 200 epochs. Random linear deformation (mirroring, rotation in range [$-$3.5,3.5°], shearing [0.97, 1.03], and scaling [0.9, 1.1]) and then random cropping is performed to augment the datasets for training. Ten patient cases were used for training and ten were used for evaluation. The training cases had high quality MR images (no motion blurring, good contrast) and included cases with dental artifacts. The evaluation set included a larger range of features commonly found in clinical HN cases, including: strong dental artifacts, a case with fused vertebra, and case with abnormal anatomy.

The sCT generation accuracy and robustness were evaluated using Mean Absolute Error (MAE) and Mean Error (ME) based on the Hounsfield Units (HU) for three regions (whole-body, bone, and air regions within the body). Dosimetric evaluation for all clinically relevant structures was also performed. **Results:** The MAEs for the Pix2Pix and Cycle GAN models were 92.4 $\pm$ 13.5 HU and 100.7 $\pm$ 14.6 HU, respectively, for the whole-body region, 166.3 $\pm$ 31.8 HU, and 184 $\pm$ 31.9 HU, respectively, for the bone region, and 183.7 $\pm$ 41.3 HU and 185.4 $\pm$ 37.9 HU for internal air regions. The ME (CT $-$ sCT) was 21.0 $\pm$ 11.8 HU and 37.5 $\pm$ 14.9 HU for Pix2Pix and Cycle GAN, respectively, showing that there are systematic offsets for both models, influenced in part by maximum bone HU values and metal implants.

Absolute percent mean/max dose errors were 2% or less for the PTV and all clinically relevant structures, including structures that had image artifacts present. DRRs generated from the models were qualitatively similar to CT-based DRRs. **Conclusions:** The dosimetric and MAE based accuracy, along with the qualitative similarity between DRRs from sCTs based on MR images with commonly observed artifacts shows that Pix2Pix and Cycle GAN are promising methods to use in MR-only treatment planning, with Pix2Pix outperforming Cycle GAN for our datasets. However, the systematic offsets in ME, and imperfect translations of metal artifacts shows that deep learning based sCT generation should be studied further before full implementation.

67

Geometrical Analysis of Interfractional Changes of Internal Target Volumes Using Real-Time 4D-MRI of Moving Lung Tumors

Moritz Rabe[1], Mathias Düsberg[2], Christian Thieke[1], Sebastian Neppl[1], Sabine Gerum[1], Michael Reiner[1], Nils Henrik Nicolay[3], Heinz-Peter Schlemmer[4], Jürgen Debus[5], Julien Dinkel[1], Guillaume Landry[1], Katia Parodi[1], Claus Belka[1], Christopher Kurz[1], Florian Kamp[1], (1) University Hospital, LMU Munich, Munich, GER, (2) Klinikum rechts der Isar, Technical University, Munich, GER, (3) University Hospital of Freiburg, Freiburg, GER, (4) German Cancer Research Center, Heidelberg, GER, (5) University Hospital of Heidelberg, Heidelberg, GER

Purpose: Respiratory-induced target motion in photon therapy is today accounted for by 4D-CT-based internal target volume (ITV) concepts. However, when using 4D-CTs, target motion is averaged over only a few breathing cycles. Methods to investigate interfractional changes of ITVs based on 2D cine-MRI exist but have limited capabilities in capturing 3D out-of-plane motion. Earlier studies on interfractional changes of moving targets have quantified changes in terms of motion amplitudes, baseline shifts and Sørensen–Dice similarity coefficients. We propose an alternative geometrical analysis method based on real-time 4D-MRI for improved patient-specific ITV definition. The approach is also compared to the current clinical practice of ITV definition based on 4D-CT scans to assess its potential. **Materials and methods:** Three lung cancer patients underwent weekly 4D-MR scans (TWIST4D; 50 $\times$ 50 $\times$ 36 cm³ field-of-view; 3.9 $\times$ 3.9 $\times$ 10 mm³ spatial resolution; 500 ms temporal resolution; 80 s acquisition time). The GTV was contoured on breath-hold 3D-MR images and propagated to all 4D-MR images by 3D b-spline deformable image registration to appropriately capture GTV translations, rotations and deformations. 4D-MR-based ITVs were defined on basis of the probability of presence of the GTV. The first 4D-MR

images served as reference for all consecutive MR datasets, which were rigidly registered to the reference by focusing on patients' spines or motion-averaged tumor volumes. Volume overlap of reference (ITVr) and consecutive ITVs (ITVn) was quantified in terms of sensitivity [SE: (ITVr ∩ ITVn)/ITVn] and precision [PRE: (ITVr ∩ ITVn)/ITVr]. Additional margins around ITVr needed to reach different SE thresholds were determined. The results were compared to a 4D-CT-based ITV. **Results:** A total of 21 4D-MR datasets were analyzed. The median GTV centroid motion amplitude was 8.6 mm with a median ITV to GTV volume ratio of 1.37. The median SE and PRE were 76% and 80% for spine-focused registrations and 80% and 82% for soft-tissue-focused registrations, respectively. To reach a SE higher than 90% (95%), a mean additional isotropic margin of 4.3 mm (6.2 mm) was needed at the cost of PRE which dropped from 82% to 64% (60%). A 4D-CT-based ITV was used as ITVr for one patient and yielded similar median SE (78%) but lower PRE (71%) with respect to the 4D-MR-based ITVr (79% and 81%). **Conclusions:** The proposed method inherently captures interfractional changes in motion and anatomy such as different breathing patterns, baseline shifts, tumor shrinkage and normal tissue alterations. It enables defining patient-specific 4D-MR-based ITV margins by trading off SE and PRE. The description of interfractional ITV changes in terms of SE and PRE as differentiated measures of volume overlap was found to be more informative than a description in terms of only Sørensen–Dice similarity coefficients and motion amplitudes. SE and PRE are assumed to be more appropriate surrogates for tumor coverage and normal tissue sparing. Latest technological developments in the field of real-time 4D-MR imaging are expected to further extend the scope and capabilities of the proposed method.

68

Streamlining MR Simulation Using Sense Parallel Imaging Acceleration Combined with Compressed Sensing

Neelam Tyagi, Memorial Sloan Kettering Cancer Center, New York, NY

Aim: High spatial resolution, large volumetric coverage and short acquisitions are essential for successful clinical implementation of MR simulation. In recent years, the development of techniques which accelerate MR imaging by k-space under sampling and reconstruct images by solving an optimization function has been intensive and widespread. Compressed sensing uses incoherent under-sampling of k-space and an iterative reconstruction algorithm that exploits sparsity in an appropriate transform domain. The Compressed SENSE (CS) product (Philips, Best, The Netherlands) combines SENSE parallel imaging acceleration with compressed sensing to further increase the acceleration rate. The iterative reconstruction algorithm balances a data consistency term and a sparsity constraint, derived from the wavelet transform, to remove aliasing artifacts. By reducing the amount of k-space data needed to reconstruct images, CS can be exploited to reduce scan time or improve spatial-resolution and volumetric coverage while sustaining a clinically acceptable scan time. The goal of this study was to assess the impact of using CS to improve MR-based radiation therapy simulation. **Materials and methods:** All exams were performed on a Philips 3 T Ingenia MR-RT system using the recently introduced CS product. We evaluated CS for (a) shortening scan time, (b) increasing spatial-resolution or volumetric coverage, and (c) improving other aspects of image quality while limiting scan times. Particular image sites/series included: fat/water imaging of the head and neck (HN) using a Dixon technique, high spatial-resolution 3D T2-weighted imaging of the prostatic urethra ($0.5 \times 0.5 \times 0.5$ mm^3, FOV = $330 \times 330 \times 165$ mm^3), T2-weighted imaging of brachytherapy applicators, metal artifact reduction (MAR) sequences. **Results:** In general, CS enabled ~20% reduction in acquisition time for 2D sequences and up to 30% reduction in 3D sequences with respect to standard protocol based on SENSE alone. For example, the scan time for extremity protocol was reduced from 14 to 10 min using CS factor from 1.6 to 2.3 for 2D T2, fat-saturated T2 and T1-post gadolinium sequences. In gynecologic brachytherapy patients, image quality was improved while the scan time was reduced by 20% using a CS factor of 2.6. A high resolution ($1.2 \times 1.2 \times 2$ mm^3, FOV = $270 \times 450 \times 280$ mm^3) T1-FFE Dixon sequence for HN simulation was achieved in <4 min using a CS factor of 3.5. In 3D isotropic T2-weighted imaging of the prostatic urethra, respiratory motion artifacts can be exacerbated by standard partial Fourier sampling techniques. CS acceleration (factor 7.3) instead of partial Fourier sampling along with foot-head phase direction resulted in greatly reduced motion artifacts with the same time as our original 3D sequence. Philips MAR sequence which includes View-angle-tilting and SEMAC techniques to reduce in-plane and through-plane distortion respectively was combined with CS using a research patch and tested on a gel-embedded titanium screw phantom. Addition of CS permitted scan time to be reduced by ~30% while maintaining the level of MAR. **Conclusion:** Image acceleration with CS enabled improvement of image quality and streamlining of MR simulation by a variety of means. The greatest impact at our site was seen in 3D T2-weighted sequences where acquisitions were shortened but high spatial resolution was maintained.

69

Real-Time Sliding Window Reconstruction of Golden Angle Stack-of-Stars Acquisition for Continuous 3D Tumor Trailing

Tom Bruijnen, Pim T. S. Borman, Jan J. W. Lagendijk, Bas W. Raaymakers, Cornelis A. T. van den Berg, Markus Glitzner, Rob H. N. Tijssen, University Medical Center Utrecht, Utrecht, NL

Purpose: Real-time tumor tracking reduces the required treatment margins by tracking respiration as well as drifts during the therapy. However, respiratory motion imposes high imaging constraints with respect to the spatio-temporal resolution which restricts the application to 2D imaging. In many cases, however, robust detection of these drifts (neglecting respiration) might be an effective motion compensation strategy, because it enables applications such as tumor trailing.[1,2,3] These applications have relaxed imaging constraints and therefore allow 3D imaging, which could enable intrafraction dose accumulation and ultimately intrafraction replanning.[4] The prerequisites of the imaging are that each volumetric acquisition represents the time-averaged position, that image reconstruction is robust to motion artefacts and that image reconstruction can be performed with low latency. In this work we propose to use a sliding window 3D golden angle stack-of-stars acquisition to capture the dynamic time-averaged position with high frame rate (1.2 Hz and latency of half acquisition time).[5] We implemented the method in an online in-house developed reconstruction pipeline (ReconSocket)[6] and we investigate the real-time performance. We show in 4D phantom experiments that the acquisition is able to accurately and robustly track the time-averaged position while being relatively unaffected by respiration. **Materials and methods:** Golden angle stack-of-stars data were acquired using a MR-compatible 4D motion platform (Modus QA, CA) on a 1.5 T MRI-Linac. Sequence parameters: spoiled gradient echo, eld-of-view = $300 \times 300 \times 300$ mm^3, resolution = $3 \times 3 \times 3$ mm^3, repetition time = 4 ms, 50 blades per volume ($T_{acq} \times 18$ s). We imposed a physiological motion trace that included drift (5 mm/min) and respiration (2.0 ± 0.2 cm amplitude and 4 ± 1 s period). Imaging data were streamed and processed in real-time using the ReconSocket in combination with the gpuNUFFT library.[7] Reconstructed images were rigidly registered to track the displacement of the phantom and compared with the dynamic time-averaged position of the ModusQA position feedback. This time-averaged position was de ned using a moving average lter (width = T_{acq}). The experiment was repeated with a 3D Cartesian near identical T_{acq} and resolution. In addition, the stack-of-stars data were acquired in a volunteer to qualitatively assess image quality. **Results:** Golden angle stack-of-stars data were successfully reconstructed using the ReconSocket with a reconstruction latency of 612 ± 12 ms. Note that the total latency includes the acquisition latency,[5] which adds 9 s ($T_{acq} = 2$). The measured phantom displacements were in very good agreement with the time-averaged-position of the imposed motion trace with a root-mean-squared-error of 0.4 ± 0.1 mm. The images reconstructed from the Cartesian acquisition showed considerable deviations from the time-averaged-position of the motion trace with a root-mean-squared-error of 2.4 ± 5.9 mm. **Conclusion:** We showed that golden angle stack-of-stars acquisition provides robust means to track organ drifts in 3D without being affected by respiration (1.2 Hz and latency $T_{acq} = 2$). The proposed method has the advantage over conventional Cartesian scans that it is not susceptible to coherent motion artefacts. We believe that the proposed method provides a robust strategy for tumor trailing and therefore can be used to facilitate intrafraction replanning.

References

1. Prins et al. (2018).
2. Tromov et al. (2008).
3. Fast et al. (2019).
4. Kontaxis et al. (2017).
5. Borman et al. (2018).
6. Borman et al. (2019).
7. Knoll et al. (2014).

70

Reconsocket: A Low-Latency Data Streaming Solution for Real-Time MRI-Guided Radiotherapy

Pim Borman, Bas Raaymakers, Markus Glitzner, UMC Utrecht, Utrecht, NL

Purpose: Hybrid MRI-Linac systems are able to monitor the anatomy and adapt the radiation treatment in real-time, by tracking tissue on continuously acquired 2D MR images. For MR-guided tracking it is vital to maximize the MR imaging frame rate and minimize the latency.[1] In this work we present a low-latency real-time reconstruction pipeline, termed ReconSocket, where k-space profiles are streamed directly from the MRI-Linac to an external reconstruction server. It provides a low-latency image stream, that may serve as input for MR-guided MLC tracking. **Materials and methods:** All experiments were performed on a 1.5 T MRI-Linac system (Elekta, SE). 1D sinusoidal motion (3 s period, 15 mm amplitude) was generated using a 4D motion phantom (Modus QA, CA) whose positions were reported with near-zero latency and served as the geometric reference. The ReconSocket consists of a software add-on to the MRI-Linac, which streams profiles over a TCP socket to an external receiver. There, it forwards the profiles to a custom reconstruction server equipped with a TITAN V GPU (Nvidia, US). Two experiments were performed to measure the streaming performance and imaging latency, respectively.

The **streaming performance** was measured by solely frequency-encoding the object in the direction of motion, resulting in a 1D projection image after every repetition time. For this a spoiled gradient-echo (SPGR) sequence with T_R/T_E = 100 ms/1.9 ms was used. The profiles were timestamped and saved on the external receiver. Retrospectively, the object's motion trace was determined from the profiles' centers-of-mass. The streaming latency was estimated from the phase difference between this trace and the phantom's reference trace. The streaming jitter was estimated from the time differences between successive profiles minus T_R, that is, $j_i = (t_i - t_{i-1}) - T_R$.

The **imaging latency** was measured for a 2D golden-angle-radial SPGR cine-sequence with T_R/T_E = 3.7 ms/1.8 ms, field-of-view = 350 × 350 mm^2, and varying number of profiles-per-frame: 50–300. The reconstruction of this non-cartesian dataset was performed using the gpuNUFFT[2] library after which the images were timestamped and saved. The latency was estimated by correlating the apparent motion trace of the object's center-of-mass to the reference motion trace. The image quality was quantified by calculating the artifact power caused by streaking[3]. **Results:** The streaming performance experiments showed a streaming latency of 3.5 ± 1.5 ms, and jitter characteristics of p_{50} = 1 us, p_{90} = 141 us, p_{99}= = 824 us. The total imaging latency for 50, 150, and 300 profiles-per-frame consisted of the following components, respectively:

- acquisition: 93, 277, 555 ms
- reconstruction: 21, 29, 39 ms
- data processing:28, 40, 65 ms

The corresponding artifact power decreased exponentially: 43,17,9 (a.u.). This shows that the acquisition latency increases linearly with the number of profiles per frame and is the dominant factor of the total imaging latency. **Conclusions:** We have demonstrated that raw data streaming using the ReconSocket is feasible with minimal latency and jitter. This enabled a fast online reconstruction pipeline for a golden-angle tracking sequence, where the total imaging latency was dominated by the acquisition latency. For 50 profiles-per-frame the acquisition, reconstruction, and data processing latencies contributed 65%, 15%, and 20% respectively to the total imaging latency.

References

1. Borman, PMB 2018:63(15).
2. Knoll, Proc. ISMRM 2014.
3. Xiao, MRM 2008:60(3).

71

Deep Learning Based Auto-Segmentation of Targets and Oars for MR-Only Planning of Prostate Radiotherapy

Sharif Elguindi, Michael Zelefsky, Jue Jiang, Harini Veeraraghavan, Joseph Deasy, Margie Hunt, Neelam Tyagi, Memorial Sloan-Kettering Cancer Center, New York, NY

Purpose: To develop a deep learning model to auto-segment targets and organs-at-risk for MR-only prostate treatment planning. **Materials and methods:** Fifty intact prostate cancer patients treated using an MR-only workflow were selected for this study. MR scanning protocol included a commercially available mDIXON based method for generating synthetic CT and a small FOV axial T2w MRI for contouring primary target and organ-at-risk. Six structures (bladder, rectum, urethra, penile bulb, rectal spacer, prostate and seminal vesicles) that were contoured and reviewed by a radiation oncologist, constituted expert delineations. Data was split into a 40/5/5 training, validation and test set respectively. Transfer learning was applied to retrain an open-source 2D fully convolutional neural network, DeepLab-v3+, which currently has the highest mean segmentation accuracy on real-world images (PASCAL Visual Object Classes 2012 segmentation challenge) to date. The network architectures defining feature makes use of dilated convolutions applied at varying rates to encode relevant contextual information at different spatial resolutions without reducing the dimensions of the image, which can degrade the quality of the segmentation mask. Because of the limited dataset available and large number of parameters in the model chosen, a transfer-learning technique was applied by using a pre-trained model made publicly available which served as an initialization point for both the encoder and decoder portions of the network. The T2w scans were necessarily pre-processed into separate axial false color image channels to mimic the pretrained dataset. The full network was then re-trained after initialization with a poly learning rate set initially at 0.007. A class weighted cross-entropy loss was implemented to reduce the influence of data imbalance. Early stopping was implemented according to the accuracy of volumetric Dice similarity coefficient (VDSC) on the selected five validation patients with the maximum training epoch of approximately 20. Algorithm performance was then evaluated with respect to expert delineations using VDSC and surface Dice similarity coefficient (SDSC). SDSC was chosen as it compares the Dice similarity coefficient between two surfaces adding a parameter, τ, with units of distance which reflects inter-observer uncertainty. Any difference of the surface boundary below τ would be considered clinically acceptable and would correlate with a segmentation needing no adjustment from experts. **Results:** Analysis of testing and validation sets are presented together. VDSC for bladder, prostate, penile bulb, rectum, urethra, and rectal spacer was 0.95 ± 0.02, 0.84 ± 0.04, 0.81 ± 0.06, 0.83 ± 0.04, 0.77 ± 0.07, and 0.83 ± 0.04 respectively. SDSC of greater than 0.90 was achieved with τ = 2 mm for bladder, prostate, urethra, penile bulb and rectal spacer. All six structures achieved an SDSC > 0.90 with τ = 3 mm. **Conclusion:** A deep learning based approach was applied to auto-segment the primary target and organs-at-risk in the MR-only based prostate radiotherapy setting by leveraging a pretrained fully convolutional neural network and retraining it for use on a small curated medical dataset. This method was able to produce contours that show promise in the ability to streamline an MR-only radiation therapy workflow in treating prostate cancer.

72

Application of A Convolution Model to Correct for the Influence of Magnetic Fields on Measured Transverse Signal Profiles

Ann-Britt Ulrichs, Björn Delfs, Louisa Brettschneider, Björn Poppe, Hui Khee Looe, Carl-von-Ossietzky University of Oldenburg, Oldenburg, GER

Purpose: The lateral dose response functions K(x) of photon-dosimetry detectors are distorted in magnetic fields due to the Lorentz force influencing the secondary electron transport within the detector. This detector and magnetic field dependent distortion has been characterized previously by Monte-Carlo (Looe et al. 2017, 2018) and experimental (Delfs et al. 2018) studies. Based on the knowledge of K(x), transverse signal profiles that have been distorted by magnetic fields can be deconvolved using an analytical and a numerical method. **Materials and methods:** The dose profile D(x) of a photon beam in the presence of a magnetic field is described by the convolution of the response function $K_H(x)$, which describes the secondary electron transport in water and the penumbra of the photon fluence profile, and a rectangular function R(x), which reflects the nominal collimator position of the linear accelerator.

$$D(X) = K_H(x) * R(x)$$

The function $K_H(x)$ is described using a linear combination of area-normalized Gaussian functions so that the above convolution can be fitted using a linear combination of error functions. Consequently, the measured dose profile M(x) can also be described by a convolution:

$$M(x) = K(x) * D(x)$$

where the convolution kernel K(x) incorporates the influence of the detector's volume effect and the additional influence of the magnetic field. In this work, the response functions that have been determined at a conventional linac equipped with an electromagnet by Delfs et al. 2018 were used. Again, the measured profile M(x) is fitted by a linear combination of error functions. The true dose profile D(x) can be derived analytically by utilizing the convolution properties of Gaussian functions.

As a second approach, the numerical iterative deconvolution according to van Cittert was applied to derive D(x).

Transverse dose profiles (1×1, 2×2, 4×4 cm²) of a 6 MV photon beam at a conventional linac were measured with two ionization chambers (types 31021, 31022, PTW Freiburg) as well as a silicon diode (type 60017, PTW Freiburg) and the microDiamond detector (type 60019, PTW Freiburg). Magnetic fields generated using an electromagnet of (0, 0.35, 1.42) T were used. The measured profiles of the diamond detector are used as an approximation of the dose profile. **Results:** The comparison of the deconvolved signal profiles with the measured profiles of the diamond detector shows that both methods can be used to determine dose profiles. The perturbation effects caused by the detector's volume effect and the influence of the magnetic field have been removed after the deconvolution. Only in the outer field region does the deconvolved profile show small deviations from the reference profile of the microDiamond detector. This remaining difference is partly caused by the distortions of the microdiamond profiles by the magnetic fields. **Conclusions:** Signal profiles obtained using ionization chambers and diodes are subjected to the influence of magnetic fields. This work presents correction strategies based on a convolution model previously established for the field-free case to obtain the dose profiles. The knowledge of the dose profiles is essential for the correct representation of dose distributions computed by treatment planning systems in MR guided radiation therapy.

73

A Convolutional Neural Network with ACGAN Augmented Data for Treatment Response Prediction Using Longitudinal Diffusion MRI

Yu Gao, Vahid Ghodrati, Anusha Kalbasi, Jie Fu, Dan Ruan, Minsong Cao, Chenyang Wang, Fritz Eilber, Nicholas Bernthal, Susan Bukata, Sarah Dry, Scott Nelson, Mitchell Kamrava, John Lewis, Daniel Low, Michael Steinberg, Peng Hu, Yingli Yang, University of California, Los Angeles, Los Angeles, CA

Purpose: A convolutional neural network was constructed to predict radiotherapy treatment effect score for localized soft tissue sarcoma patient using longitudinal diffusion MRI. ACGAN was implemented to synthesize images for improved prediction. **Materials and methods:** Patients enrolled in this study were diagnosed with soft tissue sarcoma and treated with five-fraction hypofractionated radiation therapy (RT) with no concurrent chemotherapy. Diffusion-weighted MRI (DWI) were acquired three times throughout the RT course using a 0.35 T MR-guided radiotherapy machine (ViewRay, MRIdian, Mountain View, CA). Pathological treatment effect score (TE) ranging from 0-100% was obtained after post-RT surgery as a surrogate of patient treatment response. Based on the treatment effect, patients were divided into three groups: G1: TE $\leq$ 20%, G2: 20% $<$ TE $<$ 90%, G3: TE $\geq$ 90%. A total of 30 patients were consented for the imaging study and had complete imaging and pathology dataset. DWIs were registered, and gross tumor region was manually contoured on DWI and transformed to the corresponding ADC map.

The prediction model was built on top of a pre-trained convolutional neural network VGG-19 by adding two dense layers with 10 neurons and 3 neurons. ADC maps from the three time points were feed into the network as three channels. Categorical cross-entropy is used as an objective function. To cope with the small datasets and limited amount of annotated samples, Auxiliary Classifier Generative Adversarial Networks (ACGAN) was used to augment the data. More specifically, four patients, one from G1, two from G2 and one from G3, were randomly selected as the independent test set, and data augmentation was performed on the remaining 26 patients. 15 000 synthetic slices were generated for each group using the ACGAN model. The prediction model was trained using the 45 000 synthetic slices and validated on the original data from the 26 patients (296–313 slices). A close training and validation accuracy would imply that the synthesized data are generated from the underlying density of the real data. This trained model was then tested on the four patients that were unseen from aforementioned steps. To demonstrate the reliability of the model, the entire process was repeated five times, each time with four different patients removed as test set. **Results:** The average training accuracy and validation accuracy were around 94.3% and 90.1%, indicating the generated samples are good representation of the original patient data. Among the five round of testing, the slice by slice prediction accuracy was 92.3%, 79.6%, 88.2%, 92.9%, and 85.71% respectively. The overall accuracy was 87.3%. If the majority score of all slices was assigned for the patient, the model accurately predicted the treatment effect for all patients except for one that had 2 out of 4 slices classified incorrectly. **Conclusions:** In this work, the ACGAN was implemented and it generated augmented data with high quality and diversity. A VGG-19 network was built to predict post-RT treatment effect using the synthetic slices as training set and patient data as validation set. High accuracy of 87.3% was achieved on independent test sets for slice-based prediction. Patient-based accuracy was 95%.

74

Estimating 2D Deformation Vector Fields From Golden Angle Radial Undersampled K-Space Using Stacked Convolutional Neural Networks

Maarten Terpstra, Federico D'Agata, Bjorn Stemkens, Jan Lagendijk, Nico van den Berg, Rob Tijssen, University Medical Center Utrecht, Utrecht, NL

Purpose: It is imperative for accurate MRI-guided tumor tracking that the total latency is as short as possible. MRI, however, is a slow imaging modality and image reconstruction and motion estimation cause a significant latency.[1,2] In this work we aim to replace these steps by Deep Learning (DL) to determine deformation vector fields (DVFs) from highly under sampled k-space data in order to minimize latency. For this purpose, we employed a multi-step approach where first motion estimation was replaced by stacked convolutional neural networks (CNNs) and subsequently this model was extended to also include DL-based image reconstruction. **Materials and methods:** First Optical Flow (OF) was calculated on fully-sampled images using RealTITracker[4] to provide ground-truth data. Next, we trained stacked CNNs, similar to SPy-NET,[3] to replace OF. Subsequently, we retrained the model on NUFFT-reconstructed retrospectively under sampled radial k-space. Finally, we replaced the NUFFT by AUTOMAP, a DL-based reconstruction method.[6]

Data acquisition: Retrospectively collected abdominal sagittal 2D cine MR data (Cartesian, balanced gradient echo, FOV 320–450 mm^2, bandwidth 1252–2034 Hz/pix, 1.42-1.75 mm/pix, 106 patients, 26095 images).

Deep Learning models: A sequence of four multi-resolution CNNs (24×24, 48×48, 96×96, 192×192 pix) was used to learn the ground-truth DVFs. The end-point-error loss between the learned- and ground-truth DVFs was minimized during training. We used a 75/25% train-test split, and excluded two patients for validation. After training the CNNs on fully-sampled images, we retrained them on retrospectively tenfold under sampled golden-angle radial data. Finally, the AUTOMAP model was trained by maximizing the SSIM of the reconstructed images.

Evaluation: We compared the SSIM metric and the temporal intensity variance per pixel of the registered images, and the determinant of the Jacobian of the DVFs to assess tissue compression[5]. **Results:** Training a single CNN level took 12–24 h. DL and OF on fully-sampled images produced similar results, while DL motion was inferred in 9 ms. The SSIM of registered images using the DVFs were 0.85 and 0.90, respectively. When comparing motion estimation on under sampled data, DL significantly outperforms OF by at least 15% with an SSIM of 0.80 vs 0.67. The temporal pixel variance was also more than halved for DL compared to OF. Further, the mean Jacobian determinant of the DVFs is significantly closer to 1, with <1% divergence for DL vs 2%–6% and up to 50% on under sampled images for OF. Using AUTOMAP for under sampled image reconstruction instead of a NUFFT produces similar results in only 4 ms. **Conclusions:** Our DL model computes DVFs on fully-sampled data with comparable tracking quality, in <10 ms. For tenfold under sampled images the DL model outperforms OF. Our method thus provides an attractive real-time tracking approach on highly under sampled MR-data. Future work includes further optimizing AUTOMAP performance, extending our model to 3D MRI and exploring the maximum achievable under sampling factor.

References

1. Borman et al. *PMB* 2018.
2. Glitzner et al. *PMB* 2017.
3. Ranjan et al. *Procs. IEEE* 2017.
4. Zachiu et al. *PMB* 2015.
5. Zachiu et al. *PMB* 2018.
6. Zhu et al. *Nature* 2018.

75

Dosimetric Evaluation of Pseudocts, Generated Using 2D and 3D Unets, for MR-Guided Photon and Proton Therapy of Brain Lesions

Sebastian Neppl[1], Guillaume Landry[1], David Hansen[2], Ben Hoyle[1], Jochen Weller[1], Claus Belka[1], Katia Parodi[1], Florian Kamp[1], Christopher Kurz[1], (1) Ludwig-Maximilians-Universität München, Munich, GER, (2) Software, Aarhus, DK

Purpose: The recent developments of magnetic resonance (MR) based adaptive strategies for photon and, potentially for proton therapy, require a fast and reliable conversion of MR images to x-ray computed tomography (CT) values. Among deep-learning-based methods, 2D U-shaped convolutional neural networks (Unets) are the state-of-the-art approach to generate these pseudoCTs. However, 2D Unets may exhibit slice discontinuities, which potentially can be reduced by an extension to 3D.

The goal of this project was the generation and evaluation of pseudoCTs generated with a 3D Unet for photon and proton dose calculation. The results were compared to those of a state-of-the-art 2D Unet. **Materials and methods:** The dataset consisted of 90 T1 weighted MR head scans with rigidly registered CTs. The total number of slices was approximately 10 000. 58 patient cases were used for training, 28 for validation and 4 for testing. The data was fed into a Unet with 6 layers at different resolutions having 8 to 256 channels. The convolution kernel size was set to $3 \times 3 \times 3$ and 3×3 for 3D and 2D, respectively. A stack size of 32 slices was chosen for 3D training. Apart from the first and the last slices of the MRI volume, only the central slice of those stacks was used at the application stage for the pseudoCT generation in order to improve continuity.

Single-field uniform dose pencil-beam scanning proton plans from four different angles as well as single-arc VMAT plans were optimized on the CT for each test patient using a generic target. The plans were recalculated on the generated pseudoCTs.

Mean (absolute) error (MAE/ME) in CT intensity was calculated within the patient. Image sharpness was estimated in terms of a square root of summed squared gradients in x, y and z direction, normalized to the corresponding value of the original CT. Dose distributions were compared by means of a 1% dose difference criterion with a 20% threshold for the photon plans. Proton plans were evaluated using a 3D gamma (2%, 2 mm, 50% threshold) and range (80% fall off) difference (RD) analysis for beam's eye view profiles. For all results mean and standard deviation are given over all test patients and gantry angles. **Results:** Training 36 h over 1000 epochs in 3D (6 h over 200 epochs in 2D) yielded an average (over all test cases) MAE of 125 ± 29 HU (117 ± 24 HU). The mean ME value was 11 ± 52 HU (9 ± 35 HU). Slice discontinuities were not observed for 3D training but image sharpness was reduced ($85 \pm 3\%$) compared to 2D ($96 \pm 2\%$). For photons a mean dose difference pass rate of $98 \pm 3\%$ ($98 \pm 2\%$) and for protons a mean gamma pass rate of $97 \pm 3\%$ ($98 \pm 2\%$) was calculated. RDs were <2 mm for $90 \pm 13\%$ ($93 \pm 4\%$) and <3 mm for $96 \pm 7\%$ ($98 \pm 2\%$) of the proton beam profiles. **Conclusions:** 3D Unets perform well for pseudo CT generation and yielded similar proton and photon dose calculation performance compared to 2D Unets. Slice discontinuities disappeared using the 3D training at the cost of a slight blurring of the images.

76

High-Resolution Synthetic-CT Generation with Conditional Generative Adversarial Networks

Kevin N.D. Brou Boni[1], Ludovic Vanquin[2], Antoine Wagner[3], John Klein[2], David Pasquier[1], Nick Reynaert[3], (1) Université Lille, CNRS, Centrale Lille, Centre de Recherche en Informatique Signal et Automatique de Lille, Lille, FR, (2) Lille, FR, (3)Université Libre de Bruxelles, Lille, FR

Purpose: The establishment of a MRI-only workflow in radiotherapy depends on the ability to generate an accurate synthetic-CT (sCT) for dose calculation. Several methods have been proposed using a Generative Adversarial Network (GAN) for fast generation of sCT in order to simplify the clinical workflow and avoid the uncertainties of current workflow. We used a conditional Generative Adversarial Network (cGAN) framework called pix2pixHD[1] which addresses the two main issues of a cGAN: the difficulty of generating high-resolution images and the lack of details in the previous high-resolution results. In this work, we trained a cGAN with paired MR-CT images in the pelvic area in order to have a fast, simple and accurate sCT generation. **Data and methods:** This study included T2-weighted MR and CT images of 8 patients in treatment position coming from a public dataset.[2] MR images were normalized between 5% and 95% to their intensity interval over the whole patient. All voxels outside the body were set arbitrarily at the same value, for both CT and MR images.

GANs are constituted by an image generator followed by a discriminator whom it tries to fool. The cGAN proposed by Wang et al.[1] used in this work contains a coarse-to-fine generator and a multi-scale discriminator. The PyTorch implementation provided by the authors was fitted to use 16-bits greyscale images allowing the use of the whole CT an MR range of values. A leave-one-patient-out cross-validation was used, that is, the network was trained alternatively using training examples coming from 7 patients and tested on the 8th one. The Mean Absolute Errors (MAE) for each patient were evaluated between real and synthetic CT images. **Results:** It takes in average 9.4 s to generate a complete sCT (80 slices) for a patient. The MAE in Hounsfield units (HU) between the sCT and actual patient CT (within the body contour) is 62 ± 10 HU. A dosimetric evaluation is in progress. **Conclusions:** We found out with our dataset that the pix2pixHD model outperformed our implementation of a vanilla cGAN. This study demonstrated that a sCT can be generated with a unique MR sequence, reducing the pre-processing step while being fast and accurate. Future works imply a training with a larger dataset and combine a cGAN with a Recurrent Neural Net to mitigate the discontinuities across slices.

References

1. T.-C. Wang, M.-Y. Liu, J.-Y. Zhu, A. Tao, J. Kautz, and B. Catanzaro, "High-resolution image synthesis and semantic manipulation with conditional gans," in *Proceedings of the IEEE Conference on Computer Vision and Pattern Recognition*, 2018, pp. 8798–8807.
2. T. Nyholm *et al.*, "MR and CT data with multiobserver delineations of organs in the pelvic area-Part of the Gold Atlas project," *Med. Phys.*, vol. 45, no. 3, pp. 1295–1300, Mar. 2018.

77

Utilizing A Conditional Generative Adversarial Network for Synthetic CT Generation in MRI-Guided Proton Therapy for Prostate Cancer

Christopher Kurz[1], Cornelis A. T. van den Berg[2], Mark H. F. Savenije[2], Guillaume Landry[1], Claus Belka[1], Katia Parodi[1], Matteo Maspero[2], (1) Ludwig-Maximilians-Universität München, Garching, GER, (2) University Medical Center Utrecht, Utrecht, NL

Purpose: MRI-guided proton therapy promises to combine highly conformal dose delivery and high soft-tissue contrast imaging, allowing for treatment adaptation before or even during patient irradiation. While the MR images allow for accurate target and organ-at-risk (OAR) localization and delineation, they are not directly suitable for dose calculation. Thus, generation of synthetic CT images (sCTs) with accurate HU values is required for dose calculation and adaptation. The purpose of this work was to characterize for the first time the feasibility and accuracy of utilizing a conditional generative adversarial network (cGAN) for synthetic CT generation and dose calculation in the scope of MRI-guided proton therapy of the prostate. **Materials and methods:** For 42 prostate cancer patients planning CT (pCT) and MR images (dual echo 3D cartesian spoiled gradient echo sequence and Dixon reconstruction) were acquired within 2.5 h in radiotherapy treatment position. pCT and MR were rigidly registered and air cavities on both data-sets were matched by filling and emptying operations to diminish inter-scan differences for training. The cGAN (called pix2pix) was trained to translate slice-by-slice the MR into an sCT. Water, fat and in-phase images from the Dixon reconstruction were used as input. 32 patients were randomly selected for training over 200 epochs. The remaining 10 patients were used for feed-forward evaluation of the trained model. sCT and pCT were compared in terms of mean (absolute) HU error (MAE/ME) within the intersection of the two respective body outlines. Pencil-bean scanning opposing single-field uniform dose (OSFUD) proton plans, with beams entering horizontally from the left and the right of the patient, were optimized on pCT and recalculated on sCT to evaluate its dosimetric accuracy. To minimize inter-scan differences in the dosimetric analysis, a joint body contour, obtained from the intersection of pCT and sCT outline, was used. Single-sided SFUD plans at the same gantry angles were utilized to infer the proton range, defined as the 80% distal dose fall-off, in beam's eye view (BEV). **Results:** The trained cGAN model could generate 3D sCTs in an average time of about 6s. Comparing pCT and sCT, an average (over all test patients) MAE of 53 ± 7 HU (one standard deviation) and an ME of

4 ± 4 HU was determined. Comparing the dose distributions of the OSFUD plans on both images, an average 3D global gamma pass-rate of 96% was found for a (2%, 2 mm) criterion and a 50% dose cut-off. Average deviations in clinically relevant target and OAR dose-volume histogram parameters were below 1 Gy/1%, considering the total dose of the fractionated treatment. In terms of the proton range, a median difference of 0.6 mm was found between pCT and sCT and 96% of all BEV dose profiles had a range agreement better than 3 mm. **Conclusions:** The cGAN allows for the fast generation of sCTs suitable for accurate proton dose calculation. Thus, it represents an interesting option in the scope of future MRI-guided proton radiotherapy.

78

Rate of MRI Utilisation in the Setting of Patients Being Treated with Radiotherapy in the Curative Setting

Simon Tang1, Viet Do[1], Doaa Elwadia[2], (1) University of New South Wales, Kensington, AU, (2) Liverpool, AU

Purpose: Several studies have demonstrated the contour delineation benefits of MRI in the setting of head and neck, prostate, cervical and various other cancer subsites. This study aims to document the real world utilization of an MRI simulator used in the clinical and research setting in a tertiary hospital. **Materials and methods:** A retrospective analysis of all new patients (excluding breast cancer patients) treated with curative intent were audited between March 2018 and January 2019. Lists of patients for the months of July 2018 and November 2018 were incomplete and excluded for this preliminary analysis. Patients were grouped based on tumour site (i.e. central nervous system (CNS), head and neck (H+N), thorax, haematological, genitourinary (GU), lower gastrointestinal tract (LGI), upper gastro intestinal tract (UGI), and other/benign), and the use of the MRI simulator was recorded. All patients had a standard planning CT. Patients who did not undergo a planning MRI scan were subcategorised into those that did not have a MRI that was within or not within guidelines, based on departmental policy. Patients who underwent MRI simulation as part of a clinical trial were recorded. The true rate of utilization was calculated by dividing the number of patients who underwent an MRI simulation by the total number of patients treated with curative intent. The optimal rate of utilization was calculated by dividing the sum of the number of patients undergoing an MRI sim and those who were not MRI simulated not within guidelines, by the total number of patients treated with curative intent. **Results:** A total of 421 patients with treated with curative intent were identified during the measured 9 months, with the GU (n = 136) and H+N (n = 87) subsites having the largest volume of patients. Research MRI scan was performed only in 3.8% (n = 16) of total patients. The overall rate of MRI simulation utilization was 63% (optimal utilization rate 68%). The 3 subsites with the heaviest MRI use was the GU (n = 82), H+N (n = 43) and LGI (n = 49) subgroups. MRI utilization in prostate cancer was 66% (approaching the level of optimal utilization), 94% in cervix cancer (optimal rate 100%) and rectal cancer 90% (optimal utilization 92%). All other tumour sites except hypopharynx (60% utilization vs 100% optimal) and high grade gliomas (62% vs 78%) had a utilization rate within 10% of the calculated optimal rate. **Conclusions:** In our tertiary cancer care facility the MRI utilization for patients treated with curative intent for all subsites (except breast cancer) was 63%. Heaviest use of MRI simulator was seen predominantly in the pelvic subsites and head and neck subsite. Rates of utilization could be improved in head and neck and CNS subsites. Future studies will detail the barriers to MRI simulation, a necessary first step in ensuring true utilization rates approaches that of optimal utilization. This small study provides insight into the expected utilization of a MRI simulator in a tertiary radiation oncology centre and may assist other departments in their development and capacitance planning if an MRI simulator is being considered.

79

Liver SBRT on the MR-Linac: Quantifying the Dosimetric Impact of the ARMS-Down Treatment Setup

Wouter van den Wollenberg, Peter de Ruiter, Edwin Jansen, Marlies Nowee, Jan-Jakob Sonke, Martin Fast, The Netherlands Cancer Institute, Amsterdam, NL

Purpose: Patients with liver oligometastases treated with ablative SBRT show promising local control. To accurately deliver high biologically effective doses requires precision image guidance. We aim to increase treatment precision by exploiting direct tumour visualisation on the MR-linac without needing marker implantation. To facilitate MRI-guided liver SBRT, we developed a planning strategy for the MR-linac that satisfies clinical target objectives and organ-at-risk constraints. In imaging studies we observed that arms-down immobilisation improves patient comfort in the confined MR-linac bore. We therefore assessed the dose to the arms with arms-down immobilization while either avoiding or ignoring (except for dose calculation) the arms during MR-linac treatment planning. **Materials and methods:** 16 consecutive liver SBRT treatments were selected from the clinical database based on the following inclusion criteria: diagnosis in 2017–2018; 3 × 20 Gy; 10 MV FFF dual-arc VMAT; diagnostic MRI: both arms visible. New step-and-shoot IMRT treatment plans were created in Monaco 5.4 for the Unity MR-linac (Elekta AB, Stockholm, Sweden) by experienced dosimetrists. Planning CTs were acquired in arms-up position corresponding to the patient setup on the conventional linac. To model the arms, they were delineated on associated diagnostic MRIs, and transferred to the CTs following rigid registration on the body contour. The electron density in the arm delineations was set to water-equivalent. Two treatment setups were investigated. Avoid-arms: beam angles were avoided in case the beam's-eye-view projection of the PTV and the arms (on the beam entrance side) overlapped. Here, the PTV and the arms were isotropically expanded by 1 cm to account for daily setup variability. Ignore-arms: arms were neither avoided nor specifically constrained in the plan optimisation. In both setups, beam angles that intersected highly attenuating parts of the treatment couch or the cryostat-pipe were avoided following standard procedures. 15 beams were equidistantly distributed over the remaining beam angles. Patient-specific margins as appropriate for the mid-position treatment planning concept were identical between MR-linac and conventional linac plans. The number of segments was limited to 100. All plans were scaled such that PTV D95% equals 60 Gy. **Results:** The average beam-on delivery time was 17.8 ± 2.0 (17.0 ± 2.0) min in the avoid-arms (ignore-arms) setup. The average values for GTV D2%, D50% and D98% agreed within <1 Gy between the MR-linac plans and the conventional linac plans. The average volume of spared liver-GTV (<15 Gy) was 1238 ± 220 (1275 ± 214) cc for the avoid-arms (ignore-arms) setup, and 1291 ± 218 cc for the conventional linac plans. In the left arm an average D1% dose of 1.8 ± 1.5 (3.7 ± 3.2) was deposited in the avoid-arms (ignore-arms) setup and in the right arm 5.9 ± 3.1 (21.2 ± 7.3) Gy. In the left arm, the range of V5 Gy was 0–1.6 (0–80.0) cc. In the right arm, the range of V20 Gy was 0 (0–220) cc. **Conclusions:** Beams intersecting with the arms on the exit side lead to a moderate dose deposition in the avoid-arms setup. Ignoring arms for beam placement and not adding specific dose constraints during plan optimization leads to a substantial dose deposition in the right arm, without improving target coverage or liver sparing.

80

MRI-Based Evaluation of Normal Tissue Deformation and Breathing Motion Under Abdominal Compression

Maureen Lee, Anna Simeonov, Laura Dawson, Michael Velec, University of Toronto, Toronto, ON

Purpose: Abdominal compression can effectively minimize respiratory motion, however, it may also introduce further anatomic variations due to inconsistencies in plate placement and the degree of compression applied. Magnetic Resonance (MR)-guided treatment systems are being developed to improve treatment accuracy. Therefore, MR-based evaluations of anatomic variability is warranted. The objective of this study is to investigate the reproducibility of normal abdominal tissues with the use of abdominal compression and visualized with MR. **Materials and methods:** This is a retrospective secondary analysis of data acquired from 20 healthy volunteers who underwent 3 MR sessions over 3 days under an abdominal compression plate device placed inferior to the xiphisternum. Volunteers were positioned head first supine, and abdominal T2-weighted axial MR was acquired followed by 2 min of 2D cine imaging in the sagittal and coronal planes mid-liver. Axial images were rigidly registered about the vertebra in the treatment planning system and the following structures were contoured: liver, stomach, kidneys, spleen, spinal canal and compression plate. Organ motion was quantified as the centre-of-mass difference on the 2nd and 3rd images relative to the initial image. For cine-MR datasets, respiratory motion was quantified using research software which tracks frame to frame motion of liver vessels using grey-value based 2D image registration. Daily variations in these metrics greater than 5 mm (the typical planning margin applied) were assumed to be potentially clinically relevant. **Results:** The mean displacement of the liver, kidneys, canal, spleen, stomach and compression plate contours was found to be 0.36, 0.30, 0.08, 0.35, 0.81 and 0.79 cm, respectively. On an individual basis it was found that mean liver displacement exceeded 0.5 cm

in 42.9% of the images. The 3D-vector directions for the centre-of-mass points in the above stated regions were 0.57, 0.60, 0.34, 0.72, 1.29, and 2.25 cm, respectively. The cine-MRI data indicates the largest magnitude of motion in the superior–inferior (SI) direction, followed by the anterior–posterior (AP) and lastly left–right (LR) with mean values of 0.59, 0.56, and 0.11 cm, respectively. Variations in the compression plate position of more than 2 cm resulted in liver motion of >0.5 cm in 46% of cases. These variations occurred most frequently in the SI direction with a rate of 42.9%, followed by a LR displacement of 39.3% and an AP displacement of 17.8%. Stomach variations of more than 1 cm resulted in liver displacements of >0.5 cm in 53% of cases. **Conclusions:** Compression plate and stomach positioning/size variations have significant impact on daily liver displacement. More reproducible guidelines for compression plate placement and degree of compression, in conjunction with rigid dietary preparation may contribute to a reduction in these daily variations. With individual cases exceeding the liver motion tolerance of 5 mm in 42.9% of the cases, more individualized and adaptive-radiotherapy techniques are warranted.

81

Positional Consistency Using ZIFIX™; Immobilization of the Liver and Lungs

Alexandra Smythe, Kenne Zony, Daniel Coppens, Jeremy Carlson, Andrew Johnson, Qfix, Avondale, PA

Purpose: Unique challenges exist in immobilizing structures of the thorax and abdomen for imaging and treatment, especially those close to the diaphragm such as the liver and lower lobes of the lungs. This motivated the development of the ZiFix™ Abdominal/Thoracic Motion Control System, a novel system for treatment planning and follow-up examinations for immobilization of internal organs. **Materials and methods:** The ZiFix™ Abdominal/Thoracic Motion Control System has been designed to provide positional consistency between imaging, simulation, and treatment and may be suitable for patients who are either too large or too small for body bridges and compression paddle. It can be used as a standalone device for CT and MR applications which would benefit from suppression of internal organ motion. ZiFix™ creates no image artifacts on MR or CT and is considered MR Safe upon disconnect of the manometer pump and gauge before scanning is initiated. The novel paddle geometry is designed to conform to patient anatomy and contributes to additional ability to localize patient anatomy.

Tidal volume and inspiratory capacity in healthy volunteers were compared with and without ZiFix™. Each volunteer was differentiated into one of three size groups based on waist circumference and the presence of excess fatty tissue or loose skin in the upper abdomen, and further segmented into three groups:

1. Patient lying down without application of ZiFix™ (control).
2. Patient lying down with application of ZiFix™, without inflation.
3. Patient lying down with application of ZiFix™, inflated to 100 mmHg, quick-disconnect pump disconnected and shut-off valve engaged.

Inspiratory capacity and tidal volume results were analyzed with a Student's two-tail t-test between the control condition (no belt) and each of the two experimental conditions. The threshold for significance was set at $P \leq 0.05$.

The device was also examined for patient comfort and the ability to maintain compression when used on a human subject over a time period representative of a typical procedure. **Results and conclusions:** ZiFix™ is MR Conditional for field strengths up to and including 3 T and resulted in no artifacts or displacement force when imaged in a 3 T MRI scanner per ASTM standards.

Healthy volunteers exhibited a 41.77% ($P = 8.23 \times 10^{-8}$) reduction in inspiratory capacity and a 34.22% ($P = 2.42 \times 10^{-5}$) reduction in tidal volume while wearing the pressurized ZiFix™, which correlates to a decrease in motion of the diaphragm, therefore inducing shallow breathing.

In response to the overall comfort of the device 91.7% of participants rated ZiFix™ "Tolerable" or better, and 50% of participants rated the ZiFix™ Comfortable" or "Very Comfortable."

ZiFix™ provides abdominal compression to induce shallow breathing to manage internal motion due to respiration, especially of structures surrounding the diaphragm (i.e., structures in lower thoracic cavity and upper abdominal cavity). Further clinical studies have shown that ZiFix™ suppresses motion of lower lobes of the lung and liver for imaging and radiation therapy leading to crisp images without the need for additional software motion correction.

ZiFix™ is intended to be used independently or in conjunction with other devices, allowing for setup flexibility for a variety of clinical applications and needs, including SBRT.

82

Evaluating Geometric and Dosimetric Accuracy of Synthetic CT Images for MRI-Only Stereotactic Radiosurgery

Ali Fatemi, Chunli (Claus) Yang, Madhava Kanakamedala, University of Mississippi Medical Center, Jackson, MS

Purpose: We sought to determine and validate the clinical significance and accuracy of synthetic CT images for inhomogeneity correction in MRI-only stereotactic radiosurgery plans for treatment of brain tumors. **Materials and methods:** In this retrospective study, we analyzed data from four patients who received frameless SRS treatment. Synthetic CT images were generated from MR images using syngo.via RT Image Suite (Siemens Healthineers) using a fuzzy c-means method. Experienced physicians rigidly registered the CT and MRI image datasets and defined the target volume on MR images, and a physicist created SRS treatment plans using MR images and the TMR10 algorithm. SRS doses were prescribed in the range of 13–20 Gy to 50% to 75% isodose lines according to lesion sizes. The volumes were transferred to synthetic CT and CT images; this information was used for planning on both synthetic CT and CT datasets using the convolution algorithm, with the same dose prescription as on primary MRI images. Dose maps were calculated on the synthetic CT and on the original CT data using the same plan parameters. **Results:** Dose distributions appeared similar for both CT and synthetic CT plans, and both were more conformal than TMR10-derived plans. Overall, 1.84% decrease was observed for maximum point dose inside the targets for synthetic CT, and a 1.77% decrease for CT plans compared with TMR10. The average D100 and D95 for synthetic CT showed a 0.11% increase and 0.19% decrease compared with a 0.67% increase and 0.71% increase in CT-based compared to MRI plans. Overall, synthetic CT plans provided better coverage and a lower maximum dose. **Conclusions:** The results of this study show the similarity between CT and synthetic CT-based SRS plans. In addition, synthetic CT offered a noticeable improvement in target dose coverage and a more gradual dose fall off.

83

Evaluation of Synthetic CT of the Pelvis: Dosimetric Comparison with Conventional CT

Jonathan Goodwin[1], Matthew Richardson[1], Kate Skehan[1], Peter Greer[1], John Simpson[1], Victoria Sherwood[2], (1) Calvary Mater Newcastle, Newcastle, NSW, (2) Siemens Healthcare Pty. Ltd, Adelaide, AU

Purpose: Implementation of Synthetic CT (SyCT) is becoming recognised as a non-ionising alternative for radiotherapy (RT) planning. However, "real-world" validation is needed prior to wide spread adoption of MR only workflows. In this study we investigate the clinical viability of SyCT (WIP) generated with Syngo.via Synthetic CT for a cohort of pelvis patients, by retrospectively calculating the CT plan on the SyCT and comparing dosimetric differences. **Materials and methods:** T1 Dixon VIBE MR Images acquired from 6 patients (1f (endometrium), 5 m (rectum)) with a Siemens Skyra 3 T MRSim, were used for SyCT generation (SyCT images courtesy of Siemens). MRI was acquired to include skin edge laterally and at least top of L4 to below perineum Superior–Inferior CT and MRI sequences were imported into Eclipse (TPS) and fused using rigid registration. Bony pelvis was used for anatomical matching, along with standard planning procedures. SyCT images were imported into Eclipse and registered with CT. Visual inspection ensured no gross mismatch. Couch structure and CT structure set were duplicated onto the SyCT. The RT plan was copied onto the SyCT and calculated at pre-set MU values matching the original CT plan.

DVH analysis was performed on both plans and clinically relevant dose points chosen to assess isodose coverage for Gross Tumour Volume (GTV), primary Planning Target Volume (PTVp) and the nodal Planning Target Volume (PTVn). Organ at Risk (OAR) Max, Min and Mean values were recorded for comparison. Further comparative gamma analysis was calculated using in-house gamma code with 3D Gamma, 10% low dose threshold, 15 mm erosion of the skin, search area was 1.5× the DTA search area, with

CT calculation for reference. **Results:** SyCT dosimetric values showed good plan conformity with ICRU guidelines. For primary PTVp a mean percentage dose of 97.42% (±1.78) at 98% target volume was observed, compared to 96.21% (±1.58) for the CT plan. Max 2 cc dose was below 107% in 5 patients, with an elevated Max 2 cc of 110% observed in the sixth patient. Gamma analysis of all data showed mean pass and distance to agreement (DTA) of: 99.4 ± 1.39%, 0.17 ± 0.08 @ 3%, 3 mm; 97.9 ± 3.96%, 0.26 ± 0.12 @ 2%, 2 mm; 86.1 ± 13.34%, 0.53 ± 0.24 @ 1%, 1 mm. **Conclusions:** Our current results suggest generally good agreement between SyCT derived treatment plans of the pelvis vs their CT equivalent. On average all SyCT plans showed higher dose with a notably higher dosimetry observed in one patient. It was found the SyCT in this case had considerably less bone structure in the sacrum, which may have been a contributing factor. We also observed left right truncation of MRI data in patients with large lateral separation, which didn't appear to affect dosimetric outcome. Of note, there is a 25 cm Superior–Inferior limitation on SyCT generation for inclusion of bone anatomy. It should also be noted that OAR contours were not altered to match the SyCT, therefore some minor visual/HU discrepancies are likely to occur across the different acquisitions due to bladder/bowel filling. Despite these limitations, all plans were considered clinically acceptable.

84

Investigating the Accuracy of MR-CBCT Soft-Tissue Matching with MR as the Reference Image in An MR-Only Radiotherapy Workflow

Jonathan Wyatt, Newcastle upon Tyne Hospitals NHS Foundation Trust, Newcastle upon Tyne, UK

Purpose: MR-only radiotherapy enables the superior soft-tissue contrast of MR to be used for delineation without the additional CT scan. This removes the MR-CT registration uncertainty and the need for an additional patient visit. CBCT image guidance for an MR-only pathway using implanted fiducial markers and using a synthetic CT generated from the MR have been reported in the literature. However the superior image quality of MR should also facilitate online image guidance using the MR as the reference image for CBCT matching. To the author's knowledge this has not been previously reported. This study aimed to investigate the accuracy of CBCT-MR soft-tissue matching on a Varian linear accelerator for prostate MR-Only radiotherapy. **Materials and methods:** Three patient cohorts were used. All patients received planning MR and CT scans in the treatment position using a flat couch top and immobilisation. The first (10 patients) and second (5 patients) cohorts were treated using a CT-based plan and CBCT-CT online matching. The third cohort (4 patients) was treated using an MR-based plan and CBCT-MR matching.

For the first cohort the first fraction CBCT was automatically rigidly registered to the CT and MR scans in RayStation (RaySearch Laboratories, Stockholm, Sweden). These registrations were used to predict the CT-MR registration (CBCT-MR minus CBCT-CT) which was then compared to the actual automatic CT-MR rigid registration.

For the second cohort the MR was rigidly registered to the CT, focused on the PTV, and the CT structure set transferred to the MR. Two radiographers independently matched the first fraction CBCT to the CT and to the MR using Aria (Varian, Palo Alto, USA). Two matches were carried out: an automatic match followed by manual adjustment based on soft tissue information. Both radiographers had extensive experience matching CBCT images to CT and received training in matching CBCT images to MR.

This process was reversed for the third cohort, with the CT rigidly registered to the MR and the MR structure set transferred to the CT. In order to use the MR for online image guidance the MR was relabelled as a "CT" in the DICOM header. The same radiographers independently matched the first fraction CBCT to the MR and CT. **Results:** The mean difference between predicted and actual CT-MR registrations for the first patient cohort was $\Delta R = -0.1 \pm 0.2$ mm (standard error on the mean).

For the second cohort, the mean difference between MR and CT automatic matches (MR–CT) was $\Delta R_{Auto} = -0.3 \pm 0.1$ mm and between MR and CT soft tissue matches was $\Delta R_{STM} = -0.3 \pm 0.2$ mm.

In the MR-only patient cohort (third) the mean difference between MR and CT automatic matches (MR–CT) in all three directions was $\Delta R_{Auto} = 0.0 \pm 0.3$ mm and between MR and CT soft tissue matches was $\Delta R_{STM} = -0.5 \pm 0.5$ mm. **Conclusions:** CBCT soft-tissue matching using an MR as the reference data is not clinically significantly different to using CT. Relabelling the MR as a "CT" in the DICOM header does not appear to change the performance of the automatic registration algorithm within Aria. This suggests using a MR for soft-tissue matching within a MR-only workflow is accurate.

85

Stetagically Acquired Gradient Echo (STAGE) Imaging for MRI Only Stereotactic Radiosurgery Planning

Ali Fatemi[1], Edward Florez[1], Mark Haacke[2], (1) University of Mississippi Medical Center, Jackson, MS, (2) Wayne State University, Detroit, MI

Purpose: Accurate target volume definition is essential for precision stereotactic radiosurgery (SRS). MRI is widely used in conjunction with CT to provide necessary soft-tissue information. In the era of MRI-guided radiotherapy, the use of multiparametric quantitative MRI imaging allows modification of radiation therapy, customizing treatment based on an individual patient's prognosis or early response to treatment. The only drawbacks of this procedure are longer scanning times and poor image quality due to patient movement during simulation or online treatment at an MR-Linac machine. In this work, strategically acquired gradient echo (STAGE) imaging was optimized for use in MRI-only SRS planning. **Materials and methods:** We finalized MRI-only SRS planning for frameless patients using MRI-compatible Type S overlay (CIVCO) on an Aera 1.5 T Siemens RT edition. **Protocol:** (a) field map (1 min)—geometric correction; (b) T1 MPRAGE (5 min)—Anatomical and planning; (c) Synthetic CT sequences (6 min)—planning; (d) STAGE pre-contrast—generate T1-weighted, T1 map, T2-weighted, PD map, PD weighted, susceptibility weighted imaging (SWI), quantitative susceptibility mapping (QSM), T2*, R2*, FLAIR (10 min); (e) STAGE post-contrast Gd (4 min) — vascular imaging, simultaneous magnetic resonance angiography and venography (MRAV) — (total scanning time 26 min). **Results:** STAGE pre- and post-processing to generate quantitative and vascular MRI images provide substantial information about the location of the tumor, its surroundings, and extent, which improves the delineation process and renders it more precise. **Conclusions:** We initially optimized the protocol on one healthy volunteer and five patients. Our neuroradiologic and radiation oncology team will help us further study these cases retrospectively and correlate the new tumor regions with SRS patient outcomes.

86

MR.OCKS: Consensus Building for MR Guided Radiation Therapy: Opportunities, Challenges, Knowledge and Skills

Mikki Campbell[1], Darby Erler[2], Alejandro Berlin[2], Maria Boyd[3], Carrie Bru[4], Cathy Carpino Rocca[5], Sue Crisp[1], Andrei Damyanovich[2], Colleen Dickie[2], Shannon Eberle[6], Susan Fawcett[7], Mark Given[4], Nicole Harnett[2], Andra Morrison[8], Deborah Pascale[9], Marc Potvin[2], Christine Power[10], Laura D'Alimonte[2], (1) Sunnybrook Odette Cancer Centre, Toronto, ON, (2) University of Toronto, Toronto, ON, (3)Michener Institute of Education at UHN, Toronto, ON, (4) Canadian Association of Medical Radiation Technologists, Ottawa, ON, (5) University Health Network, Toronto, ON, (6) Cross Cancer Institute, Edmonton, AB, (7) University of Alberta, Edmonton, AB, (8) Canadian Agency for Drugs and Technologies in Health, Toronto, ON, (9) Centre Hospitalier de Université de Montreal, Montreal, QC, (10) Alliance of Regulators, Dieppe, NB

Background: There have been major technical innovations with imaging and radiation therapy (RT) practice over the last two decades. Magnetic Resonance Image Guided Radiation Therapy (MRGRT) represents the next evolution of highly precise and accurate delivery methods, by allowing superior soft tissue visualization and the potential for even more conformal high dose volumes. MRGRT holds a promise for both dose escalation and further margin reduction, leading to higher cure rates and/or decreased toxicities. The introduction of MRGRT has created new practice challenges, which includes the associated gap in knowledge and skills that currently exists for the utilization of MR in the RT environment. **Objective:** To identify the opportunities, challenges, knowledge and skills, required for the safe and effective implementation of MRGRT into routine clinical practice. **Materials and methods:** A national MR in RT taskforce with 16 participants from across Canada participated in a consensus-building workshop. The taskforce was comprised of radiation therapists (RTT), MR technologists (RTMR), dual trained RTT/RTMR, educators and cancer centre managers/operational directors, with representation from COMP, CARO, CAMRT, CADTH, the Alliance of Regulators and education institutions. The workshop began with an idea generation session aimed at identifying the **opportunities** MR introduces into RT practices and the potential **challenges** related to training and education for MR in RT. All suggestions were recorded, and each participant then selected what they perceived to be the top two opportunities and challenges. The final idea generation session required participants to identify

"what **knowledge and skills** are required to safely and effectively integrate MR into the RT environment?" which were then harmonized, grouped thematically and coded for discipline specific knowledge (RT, MR or New/Integrated). **Results:** The top two opportunities identified were maximization of RTTs' scope of practice to realize the full potential of MRGRT, and for RTTs to lead the integration of MRGRT into practice. The viability and sustainability of education/training programs; the process to develop standards and evaluate competencies in practice; and the clear and consistent communication of the competencies and educational initiatives were identified as the top three challenges related to training and education for MR in RT. The requisite knowledge and skills identified were organized into six domains: (a) MR Physics; (b) MR Safety; (c) Application of MRGRT; (d) MR Image Interpretation for RT; (e) Patient Care; and (f) Emerging Paradigms. 57% of the knowledge and skills within each domain were documented as new; that is, not currently recognized in either the RTT or RTMR competency profiles. **Conclusions:** Successful implementation of MRGRT into RT practice offers the potential for a new paradigm in radiation therapy that could significantly improve outcomes for patients while presenting other opportunities and challenges. Safely and effectively integrating MR into RT practice will require new competencies for RTTs. These differ to a significant degree from those required for MR practice in the diagnostic imaging space. As a next step, an international perspective will be obtained through a Delphi process to further develop and validate the requisite knowledge and skills for the healthcare professionals working in the MRGRT era.

87

Efficient Prediction of Dose Changes Due to Unplanned Gas Cavities in Magnetic Resonance Guided Radiotherapy

Jane Shortall[1], Eliana Vasquez Osorio[1], Andrew Green[1], Robert Chuter[2], Alan McWilliam[1], Karen Kirkby[1], Ranald MacKay[2], Marcel van Herk[1], (1) The University of Manchester, Manchester, UK, (2) The Christie NHS Foundation Trust, Manchester, UK

Purpose: Due to the Electron Return Effect (ERE), unplanned gas in or close to Organs At risk (OAR) could increase risk of toxicity during Magnetic Resonance guided Radiotherapy (MRgRT). We propose an analytic method for predicting dose perturbations caused by unplanned air cavities rather than re-calculating the dose in the Treatment Planning System (TPS) for every possible cavity location.

Here we characterise dose changes due to ERE around unplanned spherical air cavities during MRgRT in a single beam. This work forms part of a simulation platform for dosimetric accuracy of MRgRT, which will eventually input towards adaptive MRgRT treatments. **Materials and methods:** Water phantoms containing spherical air cavities (0.5, 3.5, 7.5 cm diameter) and a reference phantom without an air cavity were created. Monte Carlo dose calculations of a single 7 MV photon beam under the influence of a 1.5 T transverse magnetic field were produced using research Monaco5.19.02 TPS (Elekta AB, Stockholm, Sweden).

Dose distributions of phantoms with and without air cavities were compared. To separate ERE from attenuation effects, we repeated the simulations with B=0T, defining dose changes due to ERE as:

$$\Delta \mathrm{D}\%_{\mathrm{ERE}} = 100 * ((\mathrm{D}_{\mathrm{airB=1.5\,T}} - \mathrm{D}_{\mathrm{refB=1.5\,T}}) - (\mathrm{D}_{\mathrm{airB=0\,T}} - \mathrm{D}_{\mathrm{refB=0\,T}}))/\mathrm{D}_{\mathrm{refB=1.5\,T}}$$

where D_{air} and D_{ref} are dose in the phantom containing air/no air under the influence of B = 1.5 T/B = 0 T.

We used a spherical coordinate system originating in the centre of the cavity to assess dose changes around the cavities, $\Delta \mathrm{D}\%(\theta,\Phi)_{\mathrm{monte\ carlo}}$. These changes from the cavity surface up-to 1 cm distance (in 0.25 cm increments) were fit to modulated sinusoidal functions of the form:

$$\Delta \mathrm{D}\%(\theta,\Phi)_{\mathrm{fit}} = \mathrm{A} * sin(\mathrm{k}_1 * \theta + \psi_1)\sin(\mathrm{k}_2 * \Phi + \psi_2) + \mathrm{E}.$$

Absolute residual errors (ARE) were defined as:

$$\mathrm{ARE} = \Delta \mathrm{D}\%(\theta,\Phi)_{\mathrm{montecarlo}} - \Delta \mathrm{D}\%(\theta,\Phi)_{\mathrm{fit}}.$$

Results: For all fits, the mean ARE was <0.00002%, with a range of (−13.7%, 17.9%). The fit improved for larger cavities. The fit on the surface of the largest cavity has ARE standard deviation (SD) <3%, compared with 6.7% for the smallest cavity. The fit also improves with distance from the cavity; ARE SD of all fits at 1 cm from the surface is <1.3%.

Fit parameters for the medium and large cavities are similar and change linearly or exponentially with distance from cavity surface. For the smallest cavity, they behave sporadically with distance, particularly for the phase coefficients (psi_1, psi_2). However, because the ERE for this cavity is small, this may be due to noise in the Monte Carlo dose calculation. **Conclusion:** We show effects due to ERE around spherical air cavities up to a distance of 1 cm from the surface can be well characterised analytically. The fit is better for larger air cavities, and also improves as distance from the cavity surface increases. Because the equation is analytical, it is feasible to calculate dose perturbations for every possible location of a spherical cavity in any plan, when using planned dose distributions per beam.

We are currently working to form a generic equation taking into account the gas cavity size and distance from the cavity. This work will feed into a platform to efficiently evaluate the robustness of MRgRT for unplanned gas without requiring dose re-calculation in the TPS.

88

Quality Assurance for MRI in RT: Experiences with the ACR QA Phantom

Mary Adjeiwaah, Patrik Brynolfsson, Anders Garpebring, Tufve Nyholm, Umea University, Umea, SE

Purpose: Images for radiotherapy purposes are required to have high resolution and geometric accuracy. However, numerous factors based on the principles of magnetic resonance imaging (MRI), affect the quality of MR images. Routine image quality assessment and monitoring of MR system performance are therefore, crucial components of standard MRI quality assurance (QA) processes. We report on our 4-yr experience using the American College of Radiology (ACR) MRI QA phantom for image quality assessment of a 3 T PET/MRI scanner.

The ACR MRI QA phantom (JM Specialty Parts INC, San Diego, CA, USA) was scanned weekly in the head coil on a 3T GE Signa PET/MRI scanner (GE Healthcare, Milwaukee, WI USA). After careful positioning and alignment, a single sagittal localizer (TR/TE = 200/20 ms, slice thickness = 20 mm), 11-axial T1-weighted images (TR/TE = 500/20 ms, slice thickness/slice gap = 5/5 mm) and 11-axial images from a double-echo T2-weighted series (TR/TE1/TE2 = 500/20/80 ms, slice thickness/slice gap = 5/5) were obtained.

An automatic ACR analysis program designed in Matlab (The MathWorks Inc., Natick MA, USA) was used to evaluate image quality and system performance as described in the ACR MRI QA manual.[1] The analysis was made insensitive to rotational and positional variations by using the Hough Transform to find the radius and centre position of the phantom. For the geometric accuracy tests, the phantom edges were detected by taking discrete derivatives of the intensity profile and thresholding at 12.5% of the maximum intensity. The test results including trend plots of historical data are documented on a web-based portal. This program has been successfully implemented for a 1.5 T and two 3 T MRI clinical scanners. For this retrospective study, the tools of Shewharts statistical process control was used to determine the stability of the measurements. The measured and accepted ACR values for each image quality parameter were compared.[1] **Results:** Overall, the 3 T PET/MRI scanner was found to be stable. The system generally passed the geometric accuracy test while measuring the phantom's known length of 19 cm. The mean measured length was accurate within 0.3%. The ACR acceptable value is 19 ± 0.2 cm. The results of percent image uniformity (≥82% for a 3 T), high contrast spatial resolution (1.0 mm or better) and ghosting (<0.025) were within the acceptable ACR limits. Mean image uniformity was above 90.3%. Ghosting ratio was below 0.006. There were a few outliers with the measured slice position and slice thickness. The low contrast object detectability could not be integrated in the automatic ACR analysis. **Conclusion:** The ACR QA method has allowed the continuous monitoring of image quality and system performance of our clinical MR scanners. An update of the protocol to include immediate action triggers and the low contrast object detectability tests will further improve the sensitivity of the QA program in identifying hardware failures before any clinical impact.

Reference

1. American College of Radiology (ACR), "Phantom Test Guidance for the ACR MRI Accreditation Program, Reston, VA : ACR, 2005," 2005.

89

Prostate Tumor Characteristics in MR and Acetate-PET Images — Impact of Androgen Depravation Therapy

Ulrika Björeland, Joakim Jonsson, Sara Strandberg, Lars Beckman, Tufve Nyholm, Camilla Thellenberg Karlsson, Umea University, Umea, SE

Purpose: Tumor identification in prostate cancer for patients treated with ADT (androgen depravation therapy) before radiotherapy is a challenge. The tumor changes its appearance in diagnostic images after ADT and can be misinterpreted as normal prostate tissue. The aim of this study was to investigate the potential benefit of PET/MRI imaging in this patient group. Acetate-PET, DCE-MRI, T2-MRI and diffusion-MRI was performed for tumor identification before and after ADT. A classic first order statistics approach, as well as textural features were considered. **Materials and methods:** This present investigation is a part of a larger study that will follow prostate cancer patients during several years. The current sub study focuses on the two first PET/MRI scans in this study. The first PET/MRI (baseline) is performed just before the patient receives ADT and the second is acquired three months later when the patient starts radiotherapy.

At present, the study includes 49 patients — all of them have several types MRI scans including diffusion (ADC) and 35 have acetate-PET (SUV) both at baseline and after ADT.

The tumor, within the prostate, was identified in the calculated ADC, and outlined by a MRI radiologist. A reference ROI was also defined, located and at the opposite side from the tumor in the prostate. In the reference ROI, ADC showed normal prostate tissue. The tumor and reference ROIs were then transferred with deformable image registration from baseline ADC to subsequent studies in order to compensate for organ motion and deformation, but also for image distortions. With this approach the same tumor (and reference) volumes were investigated at baseline and after ADT.

The tumor and the reference volumes were analyzed with first order statistics and with invariant Haralick textural features analysis. Statistical analysis (Wilcoxon Signed Ranks Test) was performed, in this stage for PET and diffusion images only. Later more image information will be added to the analysis (work in progress) as well as the textural change in tumor and reference structures between imaging occasions will be investigated. **Results: ADC at baseline:** All first order measures (Mean, standard deviation, Skewness, Kurtosis, distribution of 5% Percentile, distribution of 95% Percentile) showed a significant difference ($P < 0.05$) between tumor and reference and 10 of 20 textural features showed a significant difference. **ADC after ADT:** In total 3 of 6 first order measures showed a significant difference ($P < 0.05$) between tumor and reference and 8 of 20 textural features showed a significant difference. **SUV at baseline:** In total 4 of 6 first order measures showed a significant difference ($P < 0.05$) between tumor and reference and 16 of 20 textural features showed a significant difference. **SUV after ADT:** Only 2 of the first order showed significant ($P < 0.05$) between tumor and reference and 10 of 20 textural features showed a significant difference. **Conclusions:** First order statistics seems to work well in differentiating tumor from normal prostate tissue, but if the imaging is performed after ADT texture features seems to be better suited to separate tumor from surrounding tissue compared to first order statistics.

90

Anatomical Deformation Due to Horizontal Rotation: Towards Gantry-Free MRI-Linac Therapy

Jarryd Buckley[1], Robba Rai[2], Gary Liney[3], Jason Dowling[4], Lois Holloway[2], Peter Metcalfe[1], Paul Keall[5], (1) University of Wollongong, Wollongong, AU, (2) Liverpool Hospital, Sydney, AU, (3)Ingham Institute for Applied Medical Research, Sydney, AU, (4) CSIRO, Brisbane, AU, (5) University of Sydney, Sydney, AU

Purpose: Gantry-free radiation therapy systems may be simpler and more cost effective, particularly for MRI-guided photon or hadron therapy systems. A challenge for gantry-free systems is patient rotation where introduction of anatomical deformations due to gravity needs to be accounted for during a treatment. The objective of this work was to understand and quantify anatomical deformations caused by horizontal rotation with scan sequences sufficiently short to facilitate their integration into an MRI-guided workflow. **Materials and methods:** Rigid and non-rigid pelvic deformations due to horizontal rotation were quantified for a cohort of 8 healthy volunteers using a bespoke patient rotation system and a clinical MRI scanner. For each volunteer an isotropic 3D (T2-weighted TSE voxel size: $1.7 \times 1.7 \times 1.7$ mm^3, scan time: 6 min) reference scan was acquired at the 0° position followed by sequential faster scans (T2-weighted TSE voxel size: $2.0 \times 2.0 \times 4$ mm^3, scan time: 55 s) in 45° increments through a full 360°. All fast scans were registered to the 0° image via a 3-step process: First, images were aligned using MR visible couch markers to place all the scans in the same coordinate space. Second, the scans were pre-processed with a bias field correction and histogram normalisation before being rigidly registered to the 0° image. Third, the rigidly registered scans were non-rigidly registered to the 0° image to assess soft tissue deformation. The residual differences after rigid registration were determined from the transformation matrix. The residual differences after non-rigid registration were determined from the deformation vector field. **Results:** The rigid registration yielded mean rotations of ≤2.5° in all cases. Average 3D translational magnitudes ranged from 5.8 ± 2.9 mm (volunteer 6) and 30.0 ± 11.0 mm (volunteer 3). Translations were most significant in the left–right direction varying sinusoidally with couch angle between 4.9 ± 6.1 mm (volunteer 6) and 29.0 ± 32.0 mm (volunteer 3). Smaller translations were observed in the anterior-posterior and superior-inferior directions with means of 2.2 ± 1.4 mm (volunteer 6) to 8.6 ± 5.0 mm (volunteer 8) and 0.91 ± 1.2 mm (volunteer 6) to 5.7 ± 3.6 mm (volunteer 4), respectively. Rigid translations were attributed to shifts within the airbag supports of the patient rotation system during rotation. Non-rigid deformation was most significant on the external surface of the volunteers and depended greatly on the volunteer. The average maximum deformations varied between 10.0 ± 0.9 mm (volunteer 4) and 28.0 ± 2.8 mm (volunteer 8). The average mean deformations varied between 2.30 ± 0.60 mm (volunteer 4) and 7.5 ± 1.0 mm (volunteer 8). Deformations were generally smallest at 180° and 360°. Average non-rigid deformation magnitude was correlated with BMI (correlation coefficient 0.84, $P = 0.01$). **Conclusions:** Rigid pelvic deformations were most significant in the left–right direction due to shifts within the airbag supports but could be accounted for with on-line adjustments to the treatment couch and/or MLC's. Non-rigid deformations of the external surface can be significant and will need to be accounted via an on-line imaging, non-rigid registration and/or re-plan in order to facilitate the delivery of gantry-free MRI-Linac therapy with an automated patient rotation system.

91

Applying A Commercial Atlas-Based Synthetic Computed Tomography Algorithm to Patients with HIP Prostheses for Prostate MR-Only Radiotherapy

Jonathan Wyatt, Hazel McCallum, Newcastle upon Tyne Hospitals NHS Foundation Trust, Newcastle upon Tyne, UK

Purpose: Magnetic Resonance (MR)-only prostate radiotherapy has recently been clinically implemented using commercial synthetic Computed Tomography (sCT) algorithms. However patients with hip prostheses have been excluded from all MR-only research to date and assumed to require dedicated sCT algorithms. The number of hip replacement operations carried out in the UK has increased by 50% in the last 10 yr, therefore there would be expected to be corresponding increase in radiotherapy patients with hip prostheses. Artefacts caused by the hip prosthesis are more localised on MR compared to CT, suggesting these patients would benefit from an MR-only planning approach. This study aimed to investigate the dosimetric accuracy of applying a commercial sCT algorithm, based on an atlas of patients without hip prostheses, to patients with unilateral prostheses. **Materials and methods:** 18 patients with unilateral hip prostheses received MR and CT scans in the radiotherapy position. sCTs were generated from the MR using a commercial algorithm. The clinical Volumetric Modulated Arc Therapy (VMAT) plan, consisting of partial arcs which avoided the prosthesis, was recalculated using the sCT and the dose distribution compared. **Results:** The mean isocentre dose difference was $\Delta D = (-0.4 \pm 0.2)\%$ (mean ± standard error of the mean (SEM), range – 1.9%, 1.1%) and the mean differences in Planning Target Volume, bladder and rectum mean doses were ≤0.3%. The 3D global gamma pass rate with dose difference 1% and distance to agreement 1 mm within the body was $\Gamma_{Body}^{1/1} = (95.0 \pm 0.5)\%$ (SEM) and within the 50% isodose volume, which excluded the prosthesis, was $\Gamma_{50\%}^{1/1} = (98.5 \pm 0.4)\%$ (SEM). The pass rate within the PTV was $\Gamma_{PTV}^{2/2} \geq 99.7\%$ for all patients, although for PTVs close (≤3.5 cm) to the prosthesis $\Gamma_{PTV}^{1/1} < 85\%$ for three patients. The sCT did not accurately represent the prosthesis with a mean difference in radiological isocentre depth near the prosthesis of $\Delta d_{Outside} = (15.8 \pm 2.6)$ mm (sem). However inside the treatment plan arc the difference was $\Delta d_{Inside} = (-1.8 \pm 0.5)$ mm (SEM). **Conclusions:** Using a commercial prostate sCT algorithm for patients with unilateral hip prostheses is dosimetrically accurate (<0.5%) providing the

routine prosthesis-avoidance treatment planning approach is used and the PTV is >3.5 cm from the prosthesis. This suggests MR-only prostate radiotherapy can be extended to patients with hip prostheses without requiring a specific sCT algorithm, avoiding the significant additional resources developing such an algorithm would require.

92

Five Years' Experience of An MR-Guided Tracking and Online Adaptive Radiotherapy Program: Process IMPROVEMENTS Measured by A Radiation Oncology Incident Learning System

Kathryn Mittauer[1], Dustin Jacqmin[1], Michael Bassetti[1], Poonam Yadav[1], Patrick Hill[1], Mark Geurts[2], Daniel Steinhoff[1], Bhudatt Paliwal[1], (1) University of Wisconsin-Madison, Madison, WI, (2) Aspirus Wausau Hospital, Wausau, WI

Purpose: To evaluate the impact of implementation and thereafter continued process improvement of a new technology of MR-guided radiotherapy (MRgRT) on safety and quality of patient care through quantifying reported event forms from a departmental Radiation Oncology Incident Learning System (RO-ILS) and comparing to conventional non-MRgRT treatments over the last 5 yr among a single institution. **Materials and methods:** Twenty-seven event forms from September 2014 to March 2019 for a clinical MR-guided tracking and online adaptive radiotherapy program were analyzed. In total 319 patients underwent MR-guided radiotherapy (MRIdian, ViewRay Inc., Cleveland, OH) with treatment performed on a clinical MR-guided cobalt (236 patients) or MR-guided linac (83 patients). CT-IGRT (i.e., TomoTherapy HDA, Accuray Inc., Sunnyvale, CA, and TrueBeam, Varian Medical Systems, Palo Alto, CA) event forms (n = 107) from January 2019 to March 2019 were also evaluated to compare to MRgRT reported trends. Event classification was performed in accordance to RO-ILS criteria of five categories: therapeutic radiation incident, other safety incident, near-miss, unsafe condition, and operational/process improvements. Timing of event discovery and occurrence was also logged following RO-ILS criteria. Process improvements were implemented following evaluation of each ILS submission by a departmental MRgRT service improvement committee. **Results:** Of the 27 MRgRT event forms, 13 were from the MR-cobalt system and 14 were from the MR-linac system. The majority of events were categorized as near misses (40.7% MRgRT vs 36.5% CT-IGRT, $P = 0.6879$) and operational issues (51.9% MRgRT vs 47.7% CT-IGRT, $P = 0.6975$). For occurrence in workflow process, events frequently arose at Pre-planning Imaging and Simulation (40.7% MRgRT vs 25.4% CT-IGRT, $P = 0.1168$) and Treatment Planning (18.5% MRgRT vs 30.0% CT-IGRT, $P = 0.2345$). Among MRgRT event forms, a trend was observed when the workflow process required interface of MRIdian-software based tasks with the rest of the clinic, including the following: hand-off after MR simulation, data export/import to contouring software (i.e., selection of incorrect images for planning/registrations), and delays in the completion of electronic tasks within an external Oncology information system, resulting in delayed downstream tasks (i.e., planning, coordination of MR and CT simulation). For MRgRT, common causes of event forms included delay in communication/completing electronic tasks (51.8% MRgRT vs 11.8% CT-IGRT, $P < 0.0001$) and machine/software issue (18.5% MRgRT vs 2.7% CT-IGRT, $P = 0.0019$), including one therapeutic radiation incident. Events were more likely to propagate to treatment delivery on MRgRT compared to CT-IGRT systems (22.2% vs 6.4%, respectively, $P = 0.013$), potentially due to online adaptive processes. **Conclusions:** The implementation of a non-integrated Oncology information system combined with complexity of multimodality simulation resulted in greater number of event forms, regarding workflow communication and simulation, compared to conventional CT-IGRT technologies at the same institution. A solution for a vendor-supplied interface between the MRIdian software and an Oncology information system is recommended. No significant dose deviation across the first 319 patients treated were observed despite the complexity and risk of implementation of a new modality of MRgRT, owing to the benefit of quality assurance and safety precautions implemented. As such, MRgRT programs shall continue to utilize robust processes to mitigate risk.

93

A Survey of MRI in Radiotherapy — Opinions on Organization and Education

Lars E. Olsson[1], Teo Stanescu[2], (1) Lund University, Malmö, SE, (2) Princess Margaret Cancer Centre, University of Toronto, Toronto, ON

Purpose: Traditionally, MRI-scanners and MRI-physics expertise are in the diagnostic radiology department, to which also the specialist in reading the MR-images, the radiologists, belongs. Due to the increased and more advanced use of MRI in radiotherapy (RT), there is a trend that dedicated MRI-scanners are installed in radiation oncology departments. The most sophisticated equipment in this development is the integrated MR-Linac. Thereby, the need for MRI-physics expertise and MRI radiology support arise in the radiotherapy department.

The objective was to investigate: how the preferred organization of MRI-physics and diagnostic radiology support should be provided to radiotherapy, the need of cross-disciplinary education of MRI and radiotherapy physicists, and to what extent MRI-only radiotherapy and MR-Linac RT will be applied in the future. **Materials and methods:** An anonymous survey was performed during February 2019. A questionnaire was sent by email using Google Forms. The email addresses were extracted from the abstracts of the MRinRT meeting 2018. From the abstract book the first and the last author of each presentation was identified. In addition, key stakeholders for MRI in RT in the main research institutions and industry were identified. The email addresses were obtained from an internet search. In total 255 email addresses were extracted for the survey. **Results:** The number of participants was 75 (29%) from 14 countries. The majority of responses came from the Netherlands (27%) UK (17%) and US (16%). Answers from Radiation Oncology (56%) and Medical Physics (40%) were the dominating cohorts of respondents. 63% of participants' institutions had more than 8 linacs. There was an overrepresentation of responses by different types of physicists (66%). 60% of the responders had an MRI-scanner in Radiation Oncology in their hospital.

63% of respondents were of the opinion that the MRI-physics support should be provided to the RT-department by in-house MRI-physicist(s) employed by the RT-department. In contrast, 41% believed that the radiology support could be provided from the diagnostic department on a need basis. More than 50% of the respondents said that an MRI-physicist should have knowledge in radiotherapy corresponding to at least 30% of a radiotherapy physicist. Similarly, 50% of the responders thought that a radiotherapy physicist should have a knowledge in MRI-physics corresponding to at least 30% of a MRI-physicist.

From the survey, it is estimated that, MRI-only radiotherapy will be practiced in clinical routine for most cancer diagnosis in 5 yr. For the patients with brain cancer and cancer prostate it is expected that more than 50% will receive MRI-only radiotherapy. In 10 yr, the ratio of MR-Linacs to conventional linacs is expected to be 1/10 by 17%, 1/5 by 37% and more than 1/3 by 33% of the responders. **Conclusions:** There is strong drive for in-house MRI-physicists embedded in radiotherapy departments, while the radiology support can be supplied from diagnostic radiology. The MRI-physicists are required to have a substantial knowledge in radiotherapy and vice-versa. With the increasing use of MRI in radiotherapy, there will be an increasing need for cross-disciplinary education and training.

94

MRI-Guided Focal HDR Brachytherapy as Monotherapy for Prostate Cancer: Early Feasibility and Quality of Life Results

Rachel Glicksman, Noelia Sanmamed, Joelle Helou, Peter Chung, Alejandro Berlin, University of Toronto, Toronto, ON

Purpose: Gastrointestinal (GI) toxicity remains a dose-limiting factor for curative-intent prostate cancer (PCa) radiotherapy (RT). Polyethylene glycol (PEG) hydrogel has been approved for increasing the distance between the prostate and rectum, consequently sparing the latter from the high-dose RT regions. However, certain material properties limit PEG hydrogel broader applicability, particularly in the brachytherapy (BT) setting. Herein, we report our clinical experience in unique clinical scenarios in which MR-guidance allows maximizing PEG hydrogel's benefits compared to conventional workflows where risk of treatment morbidity may exceed acceptable thresholds. **Materials and methods:** PEG hydrogel was employed in localized PCa scenarios treated at our institution where risk of RT-associated rectal toxicity may be increased. Prior to treatment, PEG hydrogel spacer was inserted transperinealy by transrectal ultrasound-guidance under local anesthesia. All patients underwent multiparametric MR (mpMR; T2w, DWI and 3D-CISS sequences) for hydrogel visualization, prostate and tumour delineation, and BT implant guidance and planning where applicable. **Results:** Three case scenarios were identified: RT in the setting of inflammatory bowel disease (IBD), salvage BT after previous external beam RT (EBRT), and tailored dose-escalation with focal BT to the gross tumor volume followed by stereotactic body RT (SBRT). In all cases, the PEG

hydrogel insertion was uneventful (i.e., no adverse events). Scenario 1 represents a patient with long-standing ulcerative colitis on maintenance mesalamine and intermittent hydrocortisone rectal foam treated with MR guided (MRg) high dose rate (HDR)-BT boost plus whole gland (WG) EBRT for intermediate-risk PCa. Scenario 2 corresponds to a patient with biochemical recurrence following EBRT for localized PCa who subsequently underwent salvage HDR-BT. Scenario 3 is illustrated by a patient with intermediate-risk PCa with PIRADS-5 lesion on diagnostic MR who underwent MRg focal HDR-BT plus whole-gland SBRT. One patient (Scenario 1) experienced transient G2 diarrhea with subsequent resolution of symptoms. No patients have experienced any late G3-4 GI toxicity, with 12, 6 and 6 months follow up respectively in scenarios 1, 2 and 3. **Conclusions:** These clinical experiences illustrate novel applications of PEG hydrogel spacer, where concerns of radiation-induced toxicity may have previously limited the application of RT. Enabled by RT/BT MR-guidance methods, the synergistic use of these novel technologies can expand the indications and therapeutic index of curative-intent radiotherapy treatments, while minimizing the risks of GI toxicity.

95

Experimental Determination and Clinical Validation of Lateral Dose RESPONSE Functions of Photon-Dosimetry Detectors in Magnetic Fields

Ann-Britt Ulrichs[1], Björn Delfs[1], Louisa Brettschneider[1], Ian Hanson[2], Simeon Nill[2], Filipa Costa[2], Uwe Oelfke[2], Björn Poppe[1], Hui Khee Looe[1], (1) Carl-von-Ossietzky University of Oldenburg, Oldenburg, GER, (2) Institute of Cancer Research London, London, ON

Purpose: The dose distribution D(x,y) in magnetic fields is modified from the field-free case due to the action of the Lorentz force on the trajectories of secondary electrons. Furthermore, the presence of a non-water equivalent detector will lead to additional disturbance of the secondary electron transport within the detector that will perturb the measured signal profiles M(x,y). This effect can be characterized using the lateral dose response function K(x, y) according to the convolution model M(x,y) = K(x,y)*D(x,y), where the influence of magnetic fields is incorporated in the shape of the convolution kernel K(x,y). The distortion of K(x,y) in magnetic fields has been previously demonstrated by Monte-Carlo studies (Looe et al. 2017, 2018). In this work, the one-dimensional functions K(x) of clinical detectors were measured in magnetic fields (Delfs et al. 2018). Additionally, experimental validation of these functions was performed at a MR-linac. **Materials and methods:** The functions K(x) of two ionization chambers (Semiflex 3D 31021, PinPoint 3D 31022), a silicon diode (60017), and a diamond detector (microDiamond 60019), all from PTW-Freiburg (Germany) have been determined at a conventional linac equipped with an electromagnet. A 6 MV slit beam geometry similar to a previous study (Poppinga et al. 2015) was used. The functions were obtained using 0.35 and 1.42 T magnetic fields, where the Lorentz force is acting predominantly along the narrow side of the slit beam on forward secondary electrons.

Clinical validation of the experimentally determined K(x) was performed at a MR-linac with 1.5 T magnetic field for one ionization chamber (31021) and the microDiamond detector. The dose profile of a narrow 1 × 20 cm² field was measured using EBT3-films and scanned along its short side with the detectors. The film profile was convolved with the K(x) at 1.42 T, which was then compared directly to detector's measurement. **Results:** The functions K(x) show the distortions due to the magnetic fields as predicted by Monte-Carlo studies. The obtained K(x) of the smaller chamber shows a weaker dependence on magnetic fields, whereas the influence of magnetic fields on the microDiamond detector is also less prominent compared to the silicon diode. Due to the distortions of K(x), the signal profile measured with the ionization chamber is shifted from the film measurement in the preferable direction of the Lorentz force. On the other hand, the profile measured using the microDiamond detector is shifted in the opposite direction due to the higher density detector's components compared to water. The signal profiles predicted by the convolution of film profile and K(x) agree within 3.8% of the maximum value to the measured signal profiles of the Semiflex chamber and within 2.9% of the microDiamond detector. **Conclusions:** The functions K(x) have been determined for four detectors in magnetic fields. Clinical validation has demonstrated that these functions can be applied in conjunction with the established convolution model to describe the distortion of signal profiles in magnetic fields. Correction strategies can be derived based upon this model to obtain the unperturbed D(x,y) from M(x,y) as presented in a separate contribution on this conference.

96

Radiolucency of A 32-Channel High Impedance Coil Receive Array for the 1.5 T MR-Linac

Stefan Zijlema[1], Luca van Dijk[1], Lovisa Westlund Gotby[2], Michel Italiaander[2], Rob Tijssen[1], Jan Lagendijk[1], Nico van den Berg[1], (1) University Medical Center Utrecht, Utrecht, NL, (2) MR Coils, Zaltbommel, NL

Background: The current receive array of the 1.5 T MR-linac (Unity, Elekta AB, Sweden) is insufficient for real-time, highly-accelerated 3D imaging of the anatomy due to its limited channel count (8) and distant placement. Zijlema et al. (2018) proposed a design for a radiolucent and flexible 32-channel on-body receive array that should improve the SNR and parallel imaging (PI) performance of the MR-linac, while not affecting the dose delivery.[1] **Objectives:** Based on the work by Ref. [1], a clinical-grade 32-channel on-body prototype has been designed and a mechanical mockup of the array has been manufactured (MR Coils B.V., the Netherlands). Here, we assess the dose attenuation of the array. We aim to achieve maximal radiolucency for the anterior element such that is can be placed freely on the patient and does not need to be considered in the treatment planning process. **Materials and methods:** The mockups of the anterior and posterior elements consisted of several low-density support layers and two overlapping conductors that are placed between the support layers.

The attenuation values due to the support materials were measured with an ionization chamber that was placed in a phantom at 10 cm depth. A 100 MU 10 × 10 cm² beam was delivered on an Elekta Synergy linear accelerator with and without the mockups present. The mean attenuation value from three acquisitions was reported.

Detecting local dose deviations, for example, due to the thin conductors, required the use of EPID dosimetry. A 10 × 10 cm² beam (250 MU/min) was delivered and the (50-frame average) EPID response was measured at a depth of 10 cm with (S_{mockup}) and without ($S_{no\ mockup}$) the mockup present. The EPID response has been shown to be linear with dose[2] thus the attenuation *A* can be calculated with:

$$A(x,y) = \left[S_{mockup}(x,y) - S_{nomockup}(x,y)\right] / S_{nomakeup}(x,y).$$

Results: Dosimetry revealed the following attenuation values:

Anterior element (support): $0.6 \pm 0.1\%$

Anterior element (support + conductor): $-1.1 \pm 0.1\%$

Posterior element (support): $3.3 \pm 0.1\%$

Posterior element (support + conductor): $-3.9 \pm 0.1\%$

These values are similar to the values that Ref. [1] found, although the posterior element attenuates slightly more. The dosimetric impact of the conductors is very local and acceptably low. The impact of the conductors will be further reduced by anatomical motion and the use of multiple beam angles. The attenuation from the anterior element is sufficiently low that it does not need be included during treatment planning. The relatively homogeneous, but higher, attenuation of the posterior element can be corrected for during treatment planning. **Conclusions:** We presented the design of a clinical-grade receive array for the 1.5 T MR-linac. The anterior element of the new array has a negligible impact on the delivered dose and can thus be disregarded during treatment planning. The posterior element should be incorporated in the treatment planning system, as its attenuation values are slightly higher.

References

1. Zijlema et al. (2019). Procs. ISMRM Benelux Chapter.
2. McDermott et al. (2004). Med Phys 31(2):285–295.

97

Evaluation of Synthetic CT Data in An MR Only Head and Neck Radiation Therpay Workflow

Emilia Palmér[1], Anna Karlsson[1], Fredrik Nordström[1], Carl Siversson[2], Karin Petruson[1], Maria Ljungberg[1], Maja Sohlin[1], (1) University of Gothenburg, Gothenburg, SE, (2) Spectronic Medical AB, Helsingborg, SE

Purpose: An MR only workflow in radiation therapy is based solely on MR data, excluding the standard dose planning CT data. The quality of MR-based

synthetic CT (sCT) data has been thoroughly validated for many anatomical regions, such as prostate and brain, but so far not for the head and neck (HN) region. The aim of this study was to evaluate the feasibility of a novel method for sCT data generation as basis for absorbed dose calculation in radiation therapy for HN cancer. **Materials and methods:** CT and MR data from ten HN cancer patients were included in this pilot study. A Dixon-Vibe sequence (Siemens Healthcare) with 50 cm FOV, enclosing the patient body contour in the HN region, was added to the clinical MRinRT protocol. From this MR data, sCT data was generated using MRI Planner v2 (Spectronic Medical AB), utilizing deep convolutional neural network technology trained on 22 paired CT-MR data sets. To evaluate the sCT in comparison to the standard CT, CT data was deformably co-registered to the MR data using Velocity (Varian Medical Systems). In the deformed CT (CT_{def}) and sCT data, thresholds were set to extract bone (>250 HU), soft tissue (−200–250 HU), and air structures (<−200 HU). Using MATLAB, the mean average error (MAE) between CT_{def} and sCT, the Dice similarity coefficient (DICE) for all structures, and the average symmetric surface distance (ASSD) for body contour were evaluated. For absorbed dose evaluation, sCT data was deformably co-registered to the CT data, and treatment plan and structures for the original CT data were subsequently transferred to the deformed sCT (sCT_{def}) data. Recalculation of absorbed dose with the standard HU-RED calibration curve was performed for sCT_{def} data, and evaluation of the CT and sCT_{def} based absorbed dose plans were carried out by comparing a subset of DVH metrics used in the ARTSCAN III protocol. **Results:** Mean MAE for all patients were 85.05, 217.78, 54.94 and 213.17 HU for body, bones, soft tissue and air respectively. Mean DICE for body, bones, soft tissue and air calculated as mean for all patient were 0.97, 0.81, 0.94, and 0.78 respectively. Mean ASSD for all patients was 4.65 mm for body contour. Differences in absorbed dose calculated using the CT and sCT_{def} data were minor. The mean percentage differences in local dose for all data sets was < 0.6% for all constrains. Two outliers were identified: One was caused by surgery clips present in the CTV, reconstructed as an air cavity in the sCT data, and resulted in −2.95% in CTV $D_{98\%}$. The other was due to that the thermoplastic fixation mask was included in the body contour for the CT but not for the sCT. For one patient with a tumor delineated close to the surface, this resulted in −2.19% in CTV $D_{98\%}$. **Conclusions:** The results indicate that sCT data generated with this AI based method, allows for accurate dosimetric calculations in an MR only workflow for HN radiation therapy.

98

Development of Deep Learning-Based Patient Specific QA for On-Line ART

Noriyuki Kadoya, Seiji Tomori, Kengo Ito, Takahito Chiba, Noriyoshi Takahashi, Keiichi Jingu, Tohoku University Graduate School of Medicine, Sendai, JP

Purpose: Magnetic resonance image-guided radiation therapy (MRIgRT) offers exquisite soft tissue contrast and the ability to image tissues in arbitrary planes. Thus, the interest in this technology has increased dramatically in recent years. MRIgRT system enables us to do on-line adaptive radiotherapy (on-line ART). For patient specific QA for on-line ART, several approaches, such as secondary dose calculation and log-file-based QA, were proposed. However, these approaches could not evaluate the treatment plan before treatment (i.e., after or during treatment). To tackle this issue, we developed the newly deep learning-based patient specific QA method, which can be done before treatment for on-line ART.

In this study, we developed a deep learning-based prediction model for gamma evaluation. We applied the model to a QA measurement dataset of prostate cancer cases to evaluate its practicality. **Materials and methods:** Sixty pre-treatment verification plans from prostate cancer patients treated with IMRT were enrolled. Fifteen-layer convolutional neural networks (CNN) were developed to learn the sagittal planar dose distributions on QA phantom (RT-3000 QA phantom, R-TECH Inc, Tokyo, Japan). The input training data also included the three volumes (PTV, rectum, and overlap regions) and the monitor unit values for each field. The result of patient specific QA (ground truth) was the percentage gamma passing rate (GPR) measured using the QA phantom. Adam, an algorithm for first-order gradient-based optimization of stochastic objective functions, was used for learning and or optimizing the CNN-based model. Fivefold cross-validation was applied to validate the performance of the model. Forty cases were used for training and validation set in fivefold cross-validation, and the remaining 20 cases were used for the test set. **Results:** A linear relationship was found between the measured and predicted GPRs. Spearmen rank correlation coefficients between measured and predicted GPR values with 2%/2 mm criteria were 0.73 (validation set) and 0.62 (test set), respectively. This result demonstrated a strong or moderate correlation between the measured and predicted GPR values. **Conclusions:** CNN-based prediction model for patient specific QA was developed. Our results suggest that our model had the great potential for realizing a patient-specific QA without phantom and beam-on for on-line ART.

99

Development of A Realistic Skull Phantom for RT Planning with Gamma Knife and MR-Linac

Ryan Oglesby[1], Mark Ruschin[1], Wilfred Lam[2], Young Lee[1], Arman Sarfehnia[1], Collins Yeboah[1], Arjun Sahgal[1], Hany Soliman[1], (1) University of Toronto, Toronto, ON, (2) Sunnybrook Research Institute, Toronto, ON

Purpose: Gamma Knife radiosurgery is a high dose per fraction cranial radiotherapy technique that requires submillimeter accuracy in image guidance to ensure safe radiation delivery to patients. A limitation in using commercially available MR distortion phantoms for validating Gamma Knife is that these phantoms do not accurately model the geometry, image contrast and distortion artifacts observed in patient skull landmarks. Therefore, a realistic skull phantom was designed to aid in validating MR image co-registration to CBCT images in Gamma Knife stereotactic space. Use of this phantom ensures that all steps in the co-registration process are robust, including geometric fidelity of images, sequence transfer, and accuracy of registration. Additionally, this phantom can accommodate dosimeters, which will be used to evaluate on-line adaptive radiotherapy in the brain using an MR-linac. **Materials and methods:** A naturally processed human skull was purchased (Osta International, White Rock, BC, Canada), which had not been chemically treated in order to maintain the MR properties of the bone. A 3D CT (CT Big Bore, Philips Medical Systems) was acquired with 120 kVp and 1 mm slice thickness and loaded into 3D Slicer (http://www.slicer.org) to create a surface model. The skull surface model was used as a template to design the skull shell phantom in Autodesk Inventor Pro (Autodesk, San Rafael, CA, USA). The phantom was 3D printed (Viper si, 3D Systems, Rock Hill, SC, USA) out of Accura ClearVue. Nylon screws and EPDM O-rings were used for skull positioning and watertight sealing during assembly.

The size and shape of the phantom was minimized to allow for easy insertion into common MR head coil geometries while retaining an accurate geometrical representation of a head. The skull was suspended in water using nylon screws to minimize contact with the walls of the phantom ensuring realistic skull landmarks for the evaluation of distortion and registration errors. Symmetric positioning lines were placed radially around the outside shell and on the top and bottom of the phantom to ensure laser landmark reproducibility between data acquisitions.

MR images were acquired at 3 T (Achieva, Philips Medical Systems, Best, Netherlands) using a Q-body transmit coil and a SENSE-Head-8 receive coil. 3D T_1-weighted gradient echo images [1 × 1 × 2 mm voxels reconstructed to 0.5 × 0.5 × 1.0 mm, TR/TE1/TE2 = 5.8/1.92/3.5 ms (mDixon: In-Phase and Fat-Sat)] were acquired for the phantom. The phantom was also imaged using the Gamma Knife Icon (Elekta, Stockholm, Sweden) scanner.

Two experiments are currently being conducted to evaluate the performance of the skull phantom: evaluating co-registration accuracy in Gamma Knife and on-line adaptive radiotherapy in the brain using an MR-linac (Unity, Elekta, Stockholm, Sweden). Images will be imported and co-registered using the mutual information algorithm in GammaPlan. Co-registration accuracy will be evaluated by measuring deviations in position of skull-based landmarks and comparisons will be made to recent results on patient images (Ruschin et al., 2018). **Results:** Experiments are currently underway and the results will be presented at the MR in RT symposium.

References

1. Ruschin, M., Sahgal, A., Soliman, H., Myrehaug, S., Tseng, C.,. .. Lee, Y. (2018). Clinical Image Coregistration Variability on a Dedicated Radiosurgery Unit. Neurosurgery. https://doi.org/10.1093/neuros/nyy334.

100

Dosimetric Impact of Daily Plan Adaptation for Magnetic Resonance-Guided Liver Stereotactic Body Radiotherapy

Edward Taylor[1], Andrea Shessel[2], Michael Velec[1], Teo Stanesu[1], Laura Dawson[1], Daniel Letourneau[1], Patricia Lindsay[1], (1) University of Toronto, Toronto, ON, (2) Princess Margaret Cancer Centre, Toronto, ON

Purpose: Liver cancer is challenging for image-guided radiotherapy due to motion and deformation of target volumes and organs at risk (OAR), as well as the difficulty in visualizing these structures using cone-beam computed tomography (CBCT). Liver cancer patients could thus benefit significantly from magnetic resonance (MR)-guided adaptive re-planning at the time of treatment. The purpose of this work was to assess the dosimetric impact of three daily plan adaptation strategies based on daily imaging. **Materials and methods:** Three adaptation strategies were simulated for eight patients who underwent five fractions of CBCT-guided stereotactic body radiotherapy (SBRT) for primary or metastatic liver cancer: (a) couch shifts mimicking standard guidance to match liver (b) modification/adaptation of segment apertures to ensure coverage of lesions imaged on daily imaging, and (c) full re-optimization based on clinical goals and daily contours. Repeat computed tomography scans for six patients for whom it was deemed necessary to replan during treatment and eight serial MR images for two study patients were used in these simulations for a total of fourteen simulated adapted plans and eight reference plans. OAR and target volume dose statistics were calculated for each plan using 2 and 5 mm PTV margins to assess the feasibility of margin reduction in the presence of daily deformations. Respiratory motion was not considered in our margins or modeled in dosimetry simulations. **Results:** Plan adaptation based on segment modification to match the daily target allowed for reduction of the PTV margin to 2 mm without sacrificing coverage: the percent GTV volume receiving the prescription dose was 99% vs 100% for a PTV margin of 5 mm. In contrast, plan adaptation based on liver matching and couch shifts led to 86% and 90% GTV volumes receiving the prescription dose for 2 and 5 mm PTV margins. With segment modification, the mean dose to normal liver was reduced by 0.3 Gys per fraction using a 2 mm PTV expansion as compared to a 5 mm expansion. For all adaptation strategies, PTV margin reduction resulted in decreased non-liver normal tissue doses: using segment modification for instance, maximum dose to 0.5 cc of esophagus, stomach, duodenum, and large bowel were reduced by 0.5, 0.4, 0.3, and 0.3 Gys per fraction, respectively. Full re-optimization ensured OAR dose constraints were met for all fractions; in contrast, segment modification to ensure lesion coverage resulted in OAR constraint violations in 5(3) adapted plans out of 14 using a 5(2) mm PTV margin. **Conclusions:** For patients whose breathing motion can be tightly controlled, online adaptive re-planning of liver cancers based on daily MR imaging may allow for a reduction in PTV volume without sacrificing target coverage, while reducing dose to better spare normal tissues.

101

First 3 T Radiotherapy MRI Coil for MR in RT

Nadia Harhen[1], Dan Coppens[1], Daniel Gareis[2], Hamid Amooi[2], Jeremy Carlson[1], Andrew Johnson[1], (1) Qfix, Avondale, PA, (2) NORAS MRI Products, Höchberg, GER

Background: Most current MRI coils for head and neck provide high signal-to-noise ratios by maximizing the number of distinct coil elements and concentrating their distribution around the crown of the head. While such designs yield excellent image quality, the spatial constraints required in the construction of these coils do not permit the use of patient positioning devices in tandem with the receiver coil, and secondarily, the focusing of the coil elements at the crown of the head further potentially renders lower image quality in the lower portions of the head. A novel 15 channel head coil was developed that enables the use of a commercial SRS Immobilization System for robust, complete immobilization from simulation in MR to treatment with SRS techniques. This presentation describes the design, functionality and utility of a dedicated head and neck coil, enabling MR imaging into an SRS workflow for MR only applications and MR fusion techniques. **Objectives and methods:** An MRI coil system, the Encompass™ 15 Channel Head Coil, consists of 15 receive channels (7 Channel Top Coil, 8 Channel Bottom Coil) and contains overlapping coil elements designed for optimized signal across the entire head for SRS radiotherapy in the brain for use in Siemens 3 T MRI systems. The coil contains a detachable, height-adjustable anterior section which can be placed after the patient is in position with the Encompass™ SRS MR Immobilization device.

Standard safety and performance testing were conducted in accordance with IEC 60601-1 and NEMA standards. MR/CT fusion treatment plans were generated using the Encompass™ 15 Channel Head Coil and the dose distribution was studied. Side by side comparisons with Gamma Knife™ were made to qualify geometric precision. Scans acquired with this coil were compared with those from commercially available coils used in radiotherapy applications. Lastly, under Institutional Review Board approval, human images were acquired for patients immobilized for intracranial stereotactic treatments with the intent of supporting MR-only simulation. **Results and conclusions:** The Encompass™ 15 Channel Head Coil performed well in comparison with commercially available solutions. The measured SNR data for the coils exceeded the QA specifications necessary for diagnostic quality images and the results exhibit good coverage and excellent uniformity and homogeneity.

The testing showed no distortion between CT and MR and also showed positional accuracy <0.1 mm (submillimeter).

A treatment plan was designed using MR and CT Fusion using Varian Eclipse™ Treatment Planning System. The treatment was then delivered using Varian HyperArc™ and the dose distribution of the delivered treatment demonstrated a low margin of error.

A dedicated coil in support of MR-only simulation for immobilized radiosurgery patients has been developed. Tests demonstrate the efficacy of this coil for producing image quality comparable to or better than existing commercial dedicated head coils. Synthetic CT images generated using this coil are similarly of sufficient quality to support MR-only treatment planning and image guidance.

102

Anatomical Changes During MR-Guided Radiotherapy of Prostate Cancer Patients — A Need for Speed?

Emilia Persson[1], Annika Mannerberg[2], Joakim Jonsson[3], Christian Gustafsson[1], Adalsteinn Gunnlaugsson[4], Sofie Ceberg[2], Lars E. Olsson[1], (1) Lund University, Malmö, SE, (2) Lund University, Lund, SE, (3) Umea University, Umea, SE, (4) Skane University Hospital, Lund, SE

Purpose: The development of MR-guided radiotherapy (MRgRT) systems, such as Unity (Elekta) or MRIdian (ViewRay), enables new possibilities to reduce random and systematic deviations. The prostate, with its widely documented inter- and intra-fraction motions (e.g., McPartlin et al., 2016), would benefit of a daily adaptive re-planning strategy (e.g. Pathmanathan et al. 2018). After initial imaging, the daily online adaptive procedure including re-contouring, re-planning and online-QA needs to be carried out. If the time period prior treatment delivery extends, there is an increased probability that the position of the prostate and adjacent organs at risk (OAR) may change. If not accounted for, there is an increased risk of potential under-dosage of the prostate. In order to reach the full potential of MRgRT there might be a need for speed in the adaptive re-planning process. **Objectives:**

1). Quantify anatomical changes for prostate cancer patients occurring during 30 min with the patient in the treatment position on the couch.

2). Investigate how the dose distributions are affected due to these anatomical changes. **Material and methods:** Two large field of view T2-weighted image volumes, MR1 and MR2, were acquired for nine prostate cancer patients. The coil was positioned on a stiff coil bridge not affecting the outer body contour. Time between sequences were approximately 30 min, similar to the time for re-planning reported for MRgRT-systems (Raaymakers et al. 2017, Acharya et al. 2015).

MR1 was used for delineation of the clinical target volume (CTV), bladder, rectum and femoral heads. A planning target volume (PTV) margin of 7 mm was used. For each patient a 7 fraction 42.7 Gy 6 MV flattening filer free (FFF) VMAT treatment plan was created using a synthetic CT (sCT, MriPlannerTM, Spectronic Medical) generated from MR1 resulting in dose distribution D1. The treatment plan was recalculated on MR2 using the corresponding sCT, resulting in D2 which represents the dose distribution after 30 min of adaptive re-planning without accounting for motion prior treatment delivery.

MR2 was deformable registered towards MR1 using Elastix in MICE Toolkit (NONPI Medical). Using this registration, D2 was warped to the geometry of MR1 and compared to D1 using clinical DVH-protocol. The inverse deformation was applied to the MR1 delineations to enable anatomical change quantification. **Results:** Preliminary results showed a mean bladder volume gain of 29.3% (15.7% to 36%). Large volume variations was seen for rectum (−11.0% to 13.6%). The individual anatomical changes identified could result in an under-dosage of the PTV Dmean (−0.3 Gy to 0.0 Gy) assuming the same motion pattern for each fraction. Four patients showed under-dosage >2% of local dose in PTV D98% (−0.5% to -6.8%). Maximum

difference in PTV D98% would mean a −1.0% difference for one fraction. Mean gamma pass rate was 94.2% ± 2.3% (3%/1 mm local dose). **Conclusions:** Preliminary results showed anatomical changes during the time frame corresponding to daily adaptive re-planning procedure in MRgRT for prostate cancer patients. Deformable registration of MR-data and dose calculation on associated sCT-data were used for individual dosimetric evaluation. The resulted PTV under-dosage indicates a need for speed in the MRgRT process.

103

Predicting Radiation Treatment Effect in Extremities/Trunk Soft Tissue Sarcoma Via Radiomics of Quantitative T2 Relaxation Maps

Chenyang Wang, Anusha Kalbasi, Yu Gao, Peng Hu, Daniel Low, Yingli Yang, UCLA, Los Angeles, CA

Purpose: T2 relaxation is the exponential decay of transverse MRI signal after radiofrequency excitation. The rate of transverse signal decay is governed by vibrational and rotational proton motion, which in turn depends on the molecular structure in the proton vicinity. Consequently T2 relaxation should reflect underlying tissue molecular composition. The goal of this study is to apply a deep learning approach to radiomic features of quantitative T2 relaxation constant maps of extremity/trunk soft tissue sarcomas (STS) acquired during neoadjuvant radiation in order to train a deep neural network (DNN) to accurately predict radiation treatment effect. **Materials and methods:** A total of 21 patients with STS of the extremities/trunk underwent neoadjuvant radiation for 30 Gy in five fractions. Each patient underwent MR imaging before the first fraction, at the third fraction and after the fifth fraction, using a turbo-spin-echo pulse sequence with TR = 2000 ms, TE = [24, 61, 97, 109] ms, matrix = 256 × 256 × 10, slice thickness = 1.5 mm, average = 4, and turbo factor = 10. At each time point, a T2 relaxation map was computed via voxel-by-voxel exponential fitting of the four T2-weighted images. After surgical resection, treatment effect was quantified as the percentage of viable tumor cells compared to biopsy sample, with good response defined as <=50% viable tumor cells, and poor response as > 50% viable tumor cells. A total of 487 radiomics features were extracted from each T2 relaxation map. A DNN consisting of two hidden layers and two dropout layers were trained on 80% of the data, and the trained model was tested by predicting for treatment effect in the remaining 20% of the data. This process was repeated for T2 relaxation maps acquired at each time point during neoadjuvant radiation. **Results:** The DNN trained on the radiomic features of T2 relaxation maps before the first fraction, at the third fraction and after the fifth fraction achieved treatment effect prediction accuracies of 0.667, 0.810 and 0.690, respectively. **Conclusions:** The DNN trained on radiomics features of T2 relaxation map acquired at the third fraction of neoadjuvant radiation appears to be most accurate when predicting for good vs poor treatment effect. Additional work is warranted to fine-tune the accuracy of the DNN, and to explore its application in the clinical setting.

104

Investigation of MR-Only Planning in MR Guided Adaptive RT

Anil Sethi, Eenas Omari, Tanesha Beebe, Loyola University Medical Center, Maywood, IL

Purpose: MR-Guided-Adaptive-RT (MRgART) is an emerging technology capable of real-time tumor tracking and gating while adapting daily-delivered dose to patient anatomical changes. MR-only planning, a pre-requisite for adapting, requires fast real-time MR imaging and associated electron density data. We propose a novel method of generating synthetic pseudo-CT (*pCT*) data from MR images to address practical challenges with MRgART, namely, the absence of electron density information for dose calculations and the inability to identify bone/air differences. We hypothesize that the proposed MR-only solution is superior to other methods of acquiring *pCT*, such as, bulk density assignment, atlas based approaches, using ultrashort echo time (UTE) MR images, etc. We further hypothesize that the proposed approach will lead to more efficient, accurate and consistent treatments than those based on conventional MR/CT fusion. **Materials and methods:** Ten brain patients with both CT and MR data sets were selected for this IRB approved investigation. For all patients, MR-T1/T2 axial/coronal scans were acquired on a Siemens 1.5 T scanner with 0.54 mm in-plane resolution and 1 mm slice thickness and CT simulation (*simCT*) performed on a Philips BigBore scanner with 0.68 mm in-plane resolution and 0.75 mm slice width. First, bony structures were outlined on CT images followed by atlas based segmentation of all OARs (brain, brainstem, spinal cord, eyes, optic nerves, optic chiasm, and skull). Second, 15–20 match-points were randomly selected within each structure. Keeping the same window level setting, a structure-specific MR to CT voxel-conversion factor (CF) was determined for each patient. Mean values of CF were used within MATLAB® to derive *pCT* data from MR images and compared with *simCT*. Regions missing MR signal and not overlapping with bone were given air HU value. An additional five SRS patients were chosen to test the validity of *pCT* algorithm. Using the same beam parameters, *pCT* based treatment plans were recreated and compared with original plans based on *simCT via* dosimetric analysis of PTV/OARs. A linear mixed effects model was used to obtain CF and random effects were employed for each patient and structure to account for within observation correlation. Student 2-tail t-test was used for statistical analysis. **Results:** Although both T1 and T2 MR were used to acquire *pCT*, only T1 data are reported as this was primarily used for structure segmentation and planning. Average CF for all structures for the initial patient group was 16.1 ± 6.2 (range: 2.2 bone — 23.9 eyes). For the test patient cohort, voxel based CF generated *pCT* data that differed from *simCT* by <10 HU for all OARs except cerebellum and optic nerves. The largest HU difference was 13.5 ± 5.6 for cerebellum (range 2.4–20.4) and the smallest 5.7 ± 3.5 for eyes (range 1.7–13.5) ($P < 0.001$). Dosimetric analysis showed <1% difference in PTV/OAR doses for conventional vs MR-only plans. **Conclusions:** We have proposed and validated a robust practical solution for MR-only planning within MRgART. The method is easily integrated within clinical workflow and is capable of more accurate, efficient and consistent treatments.

105

Gentle Radiotherapy — The Movie

Christian Gustafsson[1,2], Lars E Olsson[1], Carl Siversson[3], Simon Lindgren[4], Tufve Nyholm[4], (1) Skane University Hospital, Lund, SE, (2) Lund University, Lund, SE, (3) Spectronic Medical AB, Helsingborg, SE, (4) University Hospital of Umeå, Umeå, SE

Purpose: The Gentle Radiotherapy project is part of a Swedish innovation program, funded by the national Innovation Agency VINNOVA. The present phase of the program started 2016 and will end 2019. Members of the project are the Swedish University hospital clinics from Lund, Gothenburg, Umea and Uppsala, in collaboration with their corresponding academic institution. Multiple members from the industry are also working as members of the consortium.

The project strives to create a large-scale national platform, with fully integrated clinical MRI-only radiotherapy. Each participating clinic is implementing a MRI-only workflow for a specific anatomical site (male pelvis, head and neck, female pelvis and brain). Further, the national platform is expected to deliver clinical research, product development and education.

For any new treatment, it can be challenging to get acceptance and reach clinical implementation. Interest and acceptance by many different stakeholders need to be acquired: medical doctors and the clinics in a broad sense, hospital management at different levels and other decision makers in the healthcare system. The aim of this study was to create a dedicated showcase for MRI-only radiotherapy with the purpose to attract the different stakeholders. **Materials and methods:** A digestible format for large and broad scale communication of the project results was desirable. A movie production in English, describing the MRI-only radiotherapy workflow for prostate cancer in Lund (Sweden) was therefore initiated and produced by the movie production company One Two Three Squirrel. The content and outline was drafted in close collaboration with the production company. **Results:** Three short videos (2–3 min/each) were recorded in a hospital environment, describing the MRI-only radiotherapy process for prostate cancer. The movies address clinical motivation, the treatment planning and the treatment delivery. Despite the short format, professional recorded videos during scientific supervision can capture the results from several years of scientific and clinical work. In less than a coffee break, a person can be introduced to MR-only radiotherapy, understand the process and apprehend the take home messages. This is an efficient way of communicate clinical and scientific results.

Videos 1, 2 and 3: https://vimeo.com/315220870, https://vimeo.com/315221834, https://vimeo.com/315222164 (password: GRT123S). **Conclusions:** With online, multi-platform publishing of the videos, we expect the results of the Gentle Radiotherapy project to reach an extended audience beyond the scientific community, that is, healthcare providers, industry including the important decision-making stakeholders as well as the public and the society as a whole. The production, which is in the English language, can be refereed to and used by any research team around the world for the benefit of MRI-only radiotherapy.

106

Implementing Technology to Drive Improvements Within A High Volume Brachytherapy Program

Laura D'Alimonte, Ananth Ravi, University of Toronto, Toronto, ON

Purpose: The introduction of new techniques and technologies in radiation therapy has the potential to improve outcomes; however, initial implementation is often associated with a steep learning curve and decreased efficiencies. We describe the development, implementation and evaluation of implementing an operating room scheduling system, electronic documentation software, patient tracking system and a new patient transfer system within a high throughput, high volume brachytherapy program. **Materials and methods:** In 2017, a small interprofessional team came together to introduce three key technologies into the brachytherapy program; (a) TrackOR to improve patient flow through the unit and (b) PICIS OR Manager to centralize scheduling to provide targeted access to the unit and collect specialized data elements related to the program and provincial initiatives and (c) Qfix Symphony™ patient transfer system to limit uncertainties in applicator position. In addition, the program shifted all documentation to an electronic platform to align documentation practice with the rest of the Radiation Treatment Program and provide access of care notes to healthcare teams across the organization. To promote adoption into clinical practice, a multistep approach was used. Current state workflow maps were created with feedback from all key stakeholders. Future state workflows were created layering the new technologies and process at the key points within the pathway. Training and education was completed with all end users and dry runs of the future state workflow was completed prior to implementation. To ensure success, intensive support was provided during the first two weeks of implementation with debriefs occurring near the end of each clinical day with the interprofessional team to address issues and concerns. **Results:** The implementation of the scheduling and patient tracking software provides the ability to maximize OR utilization through the assignment of procedures in a systematic way. In addition, the program monitors the timing of procedures by physician which allows for optimized daily scheduling. In addition, the system tracks start and stop times to improve throughput and minimizes staff overtime. Challenges were seen in moving documentation practice to an electronic platform as there was a learning curve to using the software in real time. The adoption of the Qfix Symphony™ patient transfer system eased patient transfers and minimized applicator motion. **Conclusion:** Integration of these technologies has allowed for the optimization of brachytherapy OR utilization to nearly 100% month over month and has allowed for provincial access to brachytherapy treatment targets to be reached and maintained.