Adaptive Approaches and Online Monitoring of Radiotherapy Treatment
Wednesday 25th April 2018, Manchester Conference Centre

PROVISIONAL PROGRAMME

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Keri Haselip, Queen Alexandra Hospital, Portsmouth
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Theodoros Christodoulou, University of Glasgow, Beatson West of Scotland Cancer Centre
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Invited Speaker: Geoff Budgell, The Christie NHS Foundation Trust, Manchester
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Styliani Savva, Northampton General Hospital NHS Trust
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Emma Parker, Oxford University Hospitals NHS Foundation Trust
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Organised by IPEM's Radiotherapy Special Interest Group
A pipeline for the validation of motion including dose reconstruction using 4DCT or patient specific motion models
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\textbf{Background.} Lung radiotherapy is challenging due to respiratory motion. The dose actually delivered to the tumour and nearby organs is therefore different from the planned dose\textsuperscript{2} but can be calculated using motion including dose reconstruction (MIDR) with a time-resolved representation of the irradiated anatomy.

Online and offline MIDR methods have been proposed\textsuperscript{1} using the planning 4DCT to estimate the time-resolved anatomy. However, because 4DCTs only represent an average breathing cycle, they suffer artefacts and generally fail to capture breathing irregularities. Patient-specific motion models (PSMM)\textsuperscript{3} may be able to better represent the anatomy at each time point.

MIDR validation is challenging due to the lack of a ground truth for the anatomy. The XCAT – a digital anthropomorphic phantom\textsuperscript{5} – can be animated with irregular breathing and has been used to generate 4DCT in cine mode\textsuperscript{4}.

The aim of this study was to set up a pipeline for the validation of MIDR based on a 4DCT or a PSMM using the XCAT phantom as a ground truth.

\textbf{Methods.} The XCAT was animated with chest (anterio-posterior, AP) and diaphragm motion derived from a lung tumour trace (Fig 1)\textsuperscript{6}. A phase-sorted helical 4DCT was simulated. For each time point, the Structural Similarity Index (SSIM)\textsuperscript{7} between the XCAT and the corresponding 4DCT phase was calculated on coronal and sagittal views centred on the tumour.

\textbf{Results.} The SSIM was phase dependent (Fig 2) and lower towards inhale. Figure 3 shows an example XCAT (green) for the time point indicated in Figure 1 overlaid with the corresponding phase (50\%) of the generated 4DCT in purple.

\textbf{Conclusion.} A pipeline for the validation of MIDR was set-up. The geometric accuracy was quantified with SSIM. Next, a PSMM\textsuperscript{3} will be built based on the unsorted axial slices and the chest motion signal. The PSMM and the 4DCT will be compared based on SSIM. MIDR applied to the different images will allow to evaluate how the differences in geometric accuracy translate dosimetrically.

The authors acknowledge funding from CRUK Programmes C33589/A19727, C33589/A19908 and C33589/CRC521.

\textbf{Key references}
5. Segars WP et al. Med Phys 2010
An Adaptive Strategy for Management of Lung Tumour Shrinkage Using Pinnacle 16
Dynamic Image Registration

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Background.
During radiotherapy for lung cancer, rapid tumour shrinkage may occur\textsuperscript{1,2}. The decrease in tissue density can result in higher doses to adjacent organs at risk\textsuperscript{3}, hence online monitoring and repeat monitor unit adjustment may be required. Here we present 2 case studies demonstrating how the dynamic planning module in Pinnacle v16 can be utilised as part of an adaptive strategy for managing lung tumour shrinkage.

Methods.
Routine daily CBCT imaging for 2 patients receiving radiotherapy treatment for lung cancer identified rapid tumour shrinkage part-way through treatment. In both cases the planned spinal cord dose was near clinical tolerance due to proximity to the target therefore there was a risk that the cord tolerance could be exceeded due to the reduced tissue density. A dosimetry assessment was performed by dynamically deforming the original planning CT to the CBCT so that the original planning structures could be propagated onto the CBCT. By applying a bulk density correction to the CBCT the dose distribution was recalculated and doses to organs at risk (OARs), in particular the spinal cord, were assessed against clinical tolerances to determine if a monitor unit reduction was required. In addition, weekly dose assessments were scheduled in anticipation of further tumour shrinkage to ensure continued online monitoring of the patients’ treatment.

Results.
In the clinical cases presented the use of dynamic planning to assess lung tumour shrinkage was quick and straight-forward to complete. The process enables same-day monitoring of dosimetry changes due to tumour shrinkage, and a monitor unit adjustment could potentially be performed and QA’d in time for the next treatment fraction. For both cases presented, no monitor unit reduction was required.

By scheduling automatic weekly dose assessments it meant that physicists could actively monitor the dosimetry for the duration of the treatment, and initiate corrective action if required, without the need for treatment radiographers to repeatedly seek advice.

Discussion.
The two cases studies presented show that in principle dynamic registration is a useful tool for performing rapid adaptive planning in the event of lung tumour shrinkage. Based on this a process for routine assessment, adaptation and continued monitoring is being developed.

The accuracy of this technique is currently limited by the use of a bulk density correction to override the CBCT densities. Further work is required in order to define a CT-density curve for CBCTs of the thorax

Conclusion.
Dynamic image registration allows for a quick assessment of dosimetry related to lung tumour shrinkage

Key references. In alphabetical order, numbered.
3. T Kataria, MD, D Gupta, MD, S S Bisht, MD, N Karikeyan, MD, S Goyal, MD, DNB, L Pushpan, DNB, A Abhishek, MD, HB Govardhan, MD, DNB, V Kumar, MD, K Sharma, MD, DNB, S Jain, MD, T Basu, MD, and A Srivastava, MD, DNB Adaptive radiotherapy in lung cancer: dosimetric benefits and clinical outcome Br J Radiol. June 2014; 87(1038)
Development and utilisation of a new software for lung cancer patients treated with Stereotactic Ablative Radiotherapy

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Background. Stereotactic Ablative Radiotherapy (SABR), is the main treatment method of treating early-stage peripheral lung cancer in inoperable patients [3,5,6]. Up until now, a quantitative evaluation of the SABR peripheral lung treatment was not possible as the images from on-board image systems taken before and after the treatment fractions could not be used for treatment planning evaluation. With the introduction of Velocity AI, a new software which accurately [1] creates a synthetic CT from an on-board CBCT image, it is possible to compare CBCT generated treatment plans with CT generated treatment plans [2], and also see if it can be use for adaptive planning.

Methods. 16 randomly selected patients had a CBCT ‘pre’ and ‘post’ the delivery of each of their treatments. Each patient had 5 fraction treatments and therefore 160 synthetic CTs were created. Then from the approved treatment plans deformed structures were created (Organs at Risk and Gross Tumour Volume) on the Synthetic CTs, so that verification plans could be assessed. Dose volume histograms (DVHs) were used to assess the radiation doses delivered by the verification plans.

Results. Organs at Risk were inside the proposed dose margins [4] but Gross Tumour Volume (GTV) was not. 40% (64 out of 160) of the patients GTVs received a lower dose than the prescribed dose(fig.1). To be sure that the deformed GTV structures created from Velocity were the same as the original GTV structures created from clinicians, Hounsfield units and volume of the GTVs were assessed (Table 1a and 1b).

Discussion. This study showed that the gross tumour volume received 16.7% less dose than that prescribed. This was investigated as SABR treatments require a high level of accuracy.

Patient movements prior to treatment led to added shifts, resulting in the drop in radiation dose received (fig 2).

Conclusion. Added shifts of 0.6 magnitude and above lead to patient tumour under dose. A quadratic equation was created which can be used to predict the magnitude of shifts when a patient re-plan is needed. Velocity AI can be used as a fast-adaptive planning tool which will assist medical physicists re-plan patient treatments, minutes before the treatments commence.

Assessment of the dose model for the Integral Quality Monitor (IQM)

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Background. The IQM (Integral Quality Monitor) is a head-mounted wedge-shaped transmission ion chamber [1,2,3] mounted below the front face of a linac head which monitors the total radiation fluence coming from the treatment head. The device is designed to be permanently mounted to monitor every fraction and compare against the first fraction delivery. Recently, the manufacturers (iRT Systems GmbH, Koblenz, Germany) have released a new functionality – a dose model (iQM Math) which predicts the IQM signal in advance of the delivery. This introduces new possibilities for the device including the potential ability to replace in vivo dosimetry (IVD) and patient specific verification measurements. This study tested the new dose model to determine its accuracy for a range of different treatment types and determine whether the IQM is suitable as a replacement for IVD and verification measurements.

Methods. The measurements required to create the dose model were measured on an Elekta VersaHD linac and used by the manufacturer to create a 6MV model specific to the linac and IQM device. A series of plans of increasing complexity (conformal, step and shoot IMRT, low modulation & highly modulated VMAT) were exported from Pinnacle 9.8, imported and calculated in the IQM dose model (Math version 1.5.0Beta) and then delivered on the linac with the IQM device mounted. The percentage difference between the final cumulative IQM signal calculated and measured was recorded for each treatment field, and then the average, range and standard deviation for all fields of that treatment site were calculated.

Results. The results are shown in the table. For step & shoot IMRT, low complexity fields show good agreement between calculated and measured values, whilst medium complexity fields have a mean difference of +1.5 - 2%. For VMAT, low complexity fields again show good agreement whilst medium/high complexity field gave an underestimate of 1.1 - 3.6% per beam, with a mean difference of 2.5%.

<table>
<thead>
<tr>
<th>Site (No. fields)</th>
<th>Technique</th>
<th>Complexity</th>
<th>Cumulative IQM signal compared to calculated (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Mean</td>
</tr>
<tr>
<td>L Breast (12)</td>
<td>2 or 3 field S&amp;S</td>
<td>Low</td>
<td>0.9</td>
</tr>
<tr>
<td>R Breast (12)</td>
<td>2 or 3 field S&amp;S</td>
<td>Low</td>
<td>0.0</td>
</tr>
<tr>
<td>Lung (90)</td>
<td>MLC and S&amp;S</td>
<td>Medium</td>
<td>1.5</td>
</tr>
<tr>
<td>Sarcoma (9)</td>
<td>MLC and S&amp;S</td>
<td>Medium</td>
<td>2.0</td>
</tr>
<tr>
<td>Rectum (3)</td>
<td>VMAT</td>
<td>Single arc, low modulation</td>
<td>0.5</td>
</tr>
<tr>
<td>Cervix (2)</td>
<td>VMAT</td>
<td>Double arc, medium modulation</td>
<td>-1.6</td>
</tr>
<tr>
<td>H&amp;N (20)</td>
<td>VMAT</td>
<td>Double arc, high modulation</td>
<td>-2.5</td>
</tr>
</tbody>
</table>

Conclusion. The IQM dose model is sufficiently accurate to allow consideration of using it to replace IVD and/or patient specific verifications for some patient groups.

Key references.
The use of an EPID in-vivo dosimetry solution to triggering adaptive intervention for H&N weight loss cases

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Aims The aim of this work was to determine whether EPID based in-vivo dosimetry software PerFRACTION (Sun Nuclear) could be used to passively monitor Head and Neck (H&N) patients for weight loss, and alert for further assessment and intervention when a set tolerance is breached.

Background. Over 300 H&N patients are treated with radiotherapy at Clatterbridge Cancer Centre (CCC) each year. Weight loss is common in this patient group, with 16% of patients being referred to physics for adaptive assessment. However following these assessments only 5% of H&N patients require a re-plan.

PerFRACTION analyses integrated MV images from each fraction against a baseline image, acquired at fraction 1. Images are analysed in pseudo real-time via a DICOM query/retrieve against the OMS. In addition to 2D gamma analysis, PerFRACTION will also perform a 3D plan recalculation on the CBCT for review.

Methods. 5x3mm superficial water equivalent plastic layers were vacuum moulded to an anthropomorphic H&N phantom. Each layer represented an effective 6mm lateral weight loss. The layered phantom was scanned, outlined and planned using a typical CCC H&N VMAT protocol. The plan was delivered to the phantom on a Varian TrueBeam and integrated images acquired on an AS1000 EPID. To simulate weight loss, one layer was removed for each subsequent fraction, until no layers remained. 2D gamma analysis against the fraction 1 baseline image was automatically performed by PerFRACTION. The results of the simulation were used to determine sensitive criteria, such that a fail result was yielded when the plan would be considered clinically unsuitable. The same criteria were then retrospectively applied to three historic clinical cases for initial validation.

Results. 2D gamma analysis (4%, 2mm) of the integrated images showed pass % decreased with increasing weight loss, with an 80% pass tolerance corresponds to 1.5cm weight loss, which was felt to be clinically significant. Retrospective patient analyses against these criteria correctly triggered a fail result at fraction 12 for a patient with clinically significant weight loss (fig.1). This alert came 2 fractions prior to the historic manual assessment confirmed the need for a re-plan. No false positives were generated for the two patients showing nil weight change.

Conclusion. Results indicate PerFRACTION will alert patients likely to require intervention. The 3D CBCT recalculation could prove a convenient tool to review the clinical suitability of the current plan, following an automated 2D gamma result. The physics resource should reduce by way of only reviewing the most critical cases, through a reduction of false positive referrals.
Review of departmental clinical use of diodes for in vivo Dosimetry
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Background. Towards Safer Radiotherapy [1] recommends that in vivo Dosimetry measurements should be performed to verify that the plan is being delivered correctly to the patient. At Imperial College Healthcare NHS Trust diodes were used for all conformal 3D planned patients and hand calculated palliative patients since 2007. Diode measurements were not used for VMAT and IMRT plans instead patient verification methods using the PTW Octavius array and Portal Dosimetry are used pre-treatment to check machine delivery capability. An audit on diode use was performed to look at compliance in the department and evaluate protocol.

Methods. An audit was performed of clinical diode measurements over a 3 month period Jan-March 2017. The results for 803 diode measurements from 366 patients were reviewed. All diode measurements which were out of our local tolerance of ±7% were investigated. The aim was to see why diodes where failing, and if protocols were being followed.

Results.

All out of tolerance diode measurements were supposed to be investigated by physics. Of the 803 measurements, 200 (24.9%) failed our local tolerance of +/-7%. Of these, 49% were either corrected to in tolerance by physics or passed a repeat measurement. Leaving 17% that were never repeated or followed up. The remainder (34%) failed either due to incorrect positioning of the diode (either in the plan to obtain the predicted dose or on the patient to obtain the measured dose). Or they failed due to complex set up DIBH/personalised bolus, change in patient contour, software errors. The Audit found that due to the high frequency of out of tolerance readings, diodes were frequently (27%) being ignored or dismissed (17% not repeated, 5% out of tolerance accepted by physics, 5% rounded down by radiographers).

Discussion. Based on the results from the audit and following a risk assessment it was decided to reduce the frequency of diode measurements. 3D conformal plans would no longer require a diode measurement as the audit and routine linac QA over time has shown the machine is able to deliver complex plans accurately. Diodes would only be performed on manually calculated plans where there is still a user risk of manually entering the monitor units incorrectly into Aria. For single fraction treatments it was also decided to introduce a split field diode measurement so that a reading could be taken before the whole treatment was delivered. CPD training was offered to all staff and simultaneously a paperless option using patient alerts and dynamic documents was rolled out for all diode measurements.

After 3 months of the new protocol implementation 83 patients have had diode readings with a total of 121 fields. Of these 14 fields failed (12%). 6 (42%) of the failed readings were corrected by physics, 3 fields (21%) had been positioned incorrectly during treatment and required a repeat measurement. 1 diode (7%) measurement failed was a conformal plan that didn't require a measurement but was corrected into tolerance by physics. 1 reading had the wrong expected dose entered into the software, 1 reading was accepted by physics due to difficulty in positioning and 1 reading the dynamic document was not completed. The new protocol has saved physics and radiographers time, far fewer diodes are failing allowing a more thorough investigation of those that do fail.

Background
The introduction of two new sources in EGSnrc has permitted the Monte-Carlo (MC) simulation of dynamic arcs (Lobo, 2010). In a single run, these dynamic arcs may include variable gantry angle, MLC position, couch rotation, collimator angle and dose-rate. These additions have since made MC a practical solution for calculating VMAT dose distributions.

Method
An in-house Python toolkit is used to convert a DICOM radiotherapy plan into a format required by the EGSnrc user codes (BEAMnrc and DOSXYZnrc). This toolkit has been updated to obtain individual control points from a VMAT plan and for each control point, simple transformations convert between the IEC-defined rotations and the DOSXYZnrc coordinate system. These form the basis of the MC input file. Files for both the MLC and Jaw positions are also created to model the shape of the radiation source during treatment delivery.

To compare the MC and treatment planning system (TPS) distributions, the VMAT plan is delivered to a simple geometry. It has been decided that a homogenous cylinder of water would be sufficient. A simple python script has been created that will output an anti-aliased, cylindrical, voxel phantom. A phantom with identical dimensions has also been created in the TPS. The VMAT plan is then simulated using the DOSXYZnrc user code, input file and cylindrical phantom. The resulting dose distribution is saved in a .3ddose format. The python toolkit has since been modified to obtain a slice along the axis of the cylinder and a separate script has been developed to obtain a 3D dose cube. At present, commercial software, OmniPro I’mRT, is used to compare distributions with gamma analysis. However, this project fully intends to use a modified, in-house solution that is already implemented for 6MV IMRT plans.

Results
Preliminary results have been displayed using the OmniPro I’mRT software.

Figure 1 shows that the MC dose distribution has the correct orientation when compared to the TPS plan but exhibits a noisier distribution. This noise will be improved when the number of histories in the MC simulation is increased.
Fig. 2: The signal from a slice demonstrates good correlation between the two distributions (left); Gamma Analysis (DD: 3%; DTA: 3mm) has been used to assess agreement (right). There is generally good agreement. However, there is poor agreement where dose-gradients are large, indicated by the red regions.

Figure 2 shows the two dose distributions which generally correlate well despite some uncertainty around large dose gradients.

Discussion
It can be seen that there is good agreement between the two distributions, with some possible artefacts due to high dose gradients. This may be due to a misalignment between dose grids and a noisy MC distribution. It is planned to resolve any differences between the dose grids and increase the numbers of MC histories used in order to overcome these issues.

Conclusion
The preliminary results demonstrate a promising approach to the checking of VMAT plans using an independent and dosimetrically competent system based on EGSnrc. It is planned to develop the process to allow automation and comparison with the planned distribution using gamma analysis, and validate the distributions for a range of treatment sites.

References


The development and applications of glass beads as novel dosimeters in radiotherapy

Jafari S.M.  
1 Department of Radiotherapy Physics, Portsmouth Hospitals NHS Trust, UK.  
2 Medical Physics Department, University of Surrey, UK.

Background

An inexpensive, high performance, low maintenance thermoluminescent dosimetry (TLD) system developed using micro size jewellery silica beads for in vivo dosimetry that would comply with the requirements of modern radiotherapy technology. This has led to the formation of a spinout company (TruelInvivo Ltd) from The University of Surrey to commercialize the products and building a fast automated reader to obtain the results in less than 15 min. post irradiation.

Methods

Characterization measurements have been performed utilizing a range of modalities and energies of clinical beams; photons, electrons, proton, carbon ions and HDR brachytherapy sources of ⁶⁰Co and ¹⁹²Ir [1-9].

Results and Discussion

The initial results were promising, offering in many cases a better performance in comparison with other commonly available TL dosimeters; a better batch homogeneity, a linear response over a large dynamic range from mGy to more than 100 Gy that covers the whole radiotherapy dose range, a response independent from dose rate and angle of incident beam, lower fading and an almost flat energy response over the megavoltage energy beams. These results encouraged investigation into their different clinical dosimetric applications in which the results proved their suitability in small field dosimetry, patient specific treatment plan dosimetry verification by performing point dosimetry, a postal dosimetry audit programme of lung SABR techniques within 20 radiotherapy departments in UK, invivo dosimetry for patients treated with kV X-ray beams and experimental dosimetry of HDR brachytherapy.

Conclusion

The dosimetric characteristics and the small size of dosimeters made them suitable for accurate dose determination from simple to complex beam arrangements and dose distributions covering different radiation therapy techniques and modalities particularly when high spatial resolution at a high dose gradient and complex treatment delivery is required, as well as their low cost, robustness, inert nature and minimal fading characteristics when it is difficult to control the environmental factors such as light exposure, humidity and temperature. Further work is ongoing to use silica beads for 2D and 3D invivo dosimetry arrangements.

The project has received great interest and supports from NPL, presented at The Royal Society of Medicine 2015 Innovation Summit, encouraged by SETsquared Partnership and UKTI and awarded £100k funding for commercialization and a market research, won an innovation voucher from InnovateUK, being the sole winner of 2015 Grant Thornton Entrepreneurial Excellence Award, and being winner of InnovateUK "women in innovation" award (£50k). Portsmouth Radiotherapy Physics and The University of Surrey are continuing research projects to exploit the applications of glass bead dosimeters in radiotherapy.

Key references

5- Jafari S.M. et al. 2017. Feasibility study of silica bead thermoluminescence detectors (TLDs) in an external radiotherapy dosimetry audit programme Radiation Physics and Chemistry 141, 251-256
8- Thomas R. et al. 2014 Dosimetric characterisation of glass bead TLDs in proton beams. European society for radiotherapy and oncology conference 33 (ESTRO33) 4-6 April 2014
9- Douralis et al. 2018 HDR Brachytherapy dosimetry: clinical use of micro-silica bead TLD & Gafchromic EBT3 film. ESTRO 37, 20-24 April 2018
Clinical outcomes with daily online MRI-guided adapted radiation therapy
Invited Speaker: Dr Michael Roach, Washington University School of Medicine, St Louis, USA

Washington University in St. Louis implemented online adapted radiation therapy in 2014 with ViewRay’s MRIdian®, a 0.35 T MRI and cobalt 60 treatment device. This talk will walk the audience step-by-step through the current workflow and on-screen tools used by therapy, physics, and physician staff for these complex treatments that involve both online adaptation and respiratory gating. The time involved and the practical challenges with this workflow will be explored, as well as planned improvements. Clinical outcomes using these online adapted treatments to dramatically improve overall survival for locally advanced pancreatic cancer will be highlighted, as this is a disease for which some consider radiation therapy futile. High local control of abdominal metastases in organs like the adrenal gland will also be shown. Finally, ongoing and planned clinical trials at our and our collaborating institutions will be discussed.
Adaptive on-line planning and patient position monitoring with the Elekta Unity MR Linac

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1Christie Medical Physics and Engineering, The Christie NHS Foundation Trust, Manchester, UK
2Manchester Cancer Research Centre, Division of Molecular & Clinical Cancer Sciences, School of Medical Sciences, Faculty of Biology Medicine & Health, University of Manchester, Manchester Academic Health Science Centre, The Christie NHS Foundation Trust, Manchester, UK

The Elekta Unity MR Linac has been designed as a fully on-line adaptive planning and monitoring radiotherapy delivery system. Patients will be CT scanned and a step-and-shoot IMRT reference plan created in Monaco in advance of treatment accounting for the effects of the permanent B field on electron dose deposition using Monte Carlo calculations. Patients will then be set-up on the MR Linac couch and MR scanned. An automatic rigid registration between the MR and reference CT scans is performed.

If changes are small and the original contours are still valid then a re-optimization starting from the reference plan can be made of either the segment weights or segment shapes and weights, but accounting for the positional shift. In this case calculations are made on the original CT scan. If there is a large positional shift or the planning contours have changed significantly then deformable registration is used to adapt the original contours to the new MR. Once the user is happy with the new contours a re-optimization based on the original reference plan is done but calculating on the MR scan using bulk density over-rides for electron densities.

A traffic light system is used for selected parameters to ensure the new plan meets required constraints before sending the new plan for delivery. Intra-fraction motion is monitored either using a second MR scan for positional verification after the plan is complete or using live 2D MR motion monitoring to ensure the patient is not moving. This can also be used during treatment delivery.

The Utrecht group carried out a first in man study last year for a limited number of patients using the pre-clinical MR Linac and using their own software. The system is due to be CE marked in June with other sites being upgraded to the clinical version over the coming months.

This presentation will outline the clinical workflow, outline some of the challenges to be overcome to allow clinical use and present some of the work done towards meeting those challenges.

Key references.

Automated monitoring of every treatment fraction using SNC PerFraction


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Background. Contemporary radiotherapy treatments are typically monitored on the first few fractions and periodically thereafter. However, with hypofractionated treatments becoming more common, deliveries more complex and replanning more prevalent, there is a greater need to monitor every fraction. In addition to image-guidance for patient set up, our centre utilises the automated commercial software PerFraction (Sun Nuclear Corporation, Florida) to monitor every treatment fraction. The web browser platform provides a convenient environment to monitor all stages of patient treatments, including pre-treatment quality assurance tests, with email alerts to the physicist for out of tolerance results. Since our centre commenced operation in September 2017, all treatments delivered (which includes 3DCRT, IMRT, VMAT and SABR) have been monitored using the PerFraction software.

Methods. After exporting the patient plan and dose file from the treatment planning system (TPS), the DoseCHECK software (part of the PerFraction suite) performs an independent dose calculation. Commissioning was simple and involved choosing an appropriate beam model, defining the reference dose and the CT-RED curve. This has since been implemented for all treatments. Pre-treatment QA is also incorporated into the software by recalculating the treatment plan on a virtual water phantom, extracting the 2D planar dose at the radiological depth of the EPID, and performing a comparison with a measured EPID image. This has been implemented for all IMRT/VMAT deliveries. Thereafter all fractions of the patient treatment are monitored automatically. For all fractions, the server generates a log file from the treatment delivery that provides time-stamped information about the dose rate and gantry angle. For fractions without EPID images, the log file is used together with the plan file to reconstruct a 3D dose on the planning CT or CBCT. For fractions in which an EPID image is acquired during delivery, the plan file is not needed but rather the MLC positions, jaw positions and collimator angles are extracted from the image. This information, together with the log file, is used to reconstruct a 3D dose on the planning CT or CBCT. Additionally, for the EPID fractions, a 2D transmission fluence image can be used to monitor inter-fractional changes. Tracking of treatment fractions with logs has been implemented for all patients and the additional use of EPID images has been implemented for all IMRT/VMAT patients.

Results. An example set of patient results can be seen in the figure on the right. The mean agreement between the TPS and DoseCHECK for the 76 treatments to date is 1.2±0.9% for point doses (all errors quoted here are the standard deviation) and the mean 3D local gamma passing rate (3%/3 mm) is 90.1±10.5%. Pre-treatment QA with the EPID has been conducted for all IMRT/VMAT treatments we have delivered to date. The mean agreements with planned dose are: 1.3±1.1% for point doses; 98.5±3.0% for 2D analysis; and the mean 3D local gamma (3%/3 mm) is 91.7±8.1%. Assessment of individual fractions has been very useful in identifying errors in patient alignment and/or changes in patient anatomy, which were alerted to the physicists by email, and this has led to the necessary replanning procedure.

Discussion. The SNC PerFraction software is easy to use and set up and provides a complete environment for tracking patient treatments. Improvements are still possible and include (among others) more accurate modelling of couch structures and absolute in vivo dose monitoring for treatment fractions (currently only inter-fractional changes can be detected).

Conclusion. SNC PerFraction has the ability to detect potential failures in radiotherapy at a number of levels: secondary dose calculation; pre-treatment measurements; and EPID and log measurements of every treatment fraction. It is an essential component of our practice.
Incorporating changes in patient anatomy into *in-vivo* EPID dosimetry using commercially available software

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**Background:** At our centre Dosimetry Check (Lifeline Software Inc.) is used for routine *in-vivo* dosimetry. Per the standard work-flow for this software, transit EPID images are acquired during treatment and used to reconstruct the delivered dose on the original planning CT. This process goes some way to providing an independent assessment of whether treatment has been delivered as intended. A shortcoming, however, is that interfractional variations in patient anatomy are neglected in the dose reconstruction. These can be complex, and may significantly impact dose distributions [1], as well as increasing the number of incorrectly flagged reports [2].

In this presentation we will share a method we have developed to incorporate CBCT images into the above work flow. By reconstructing the dose using transit EPID images and the actual anatomy on-treatment, we aim to achieve a dose distribution that more accurately represents the delivered dose for any given fraction. We will present some initial results to demonstrate proof of concept, and explore the feasibility of employing this process regularly as a means of near real-time *in-vivo* dosimetry.

**Methods:** In our method we use Raystation (Raysearch Labs) as a means of registering the CBCT to the planning CT, and mapping ROIs. A modified patient plan is then produced by copying the original plan onto the CBCT. All relevant DICOM objects are subsequently exported to Dosimetry Check where the delivered dose distribution is calculated on the CBCT using EPID images from the same fraction.

Several CBCTs and transit EPID image sets acquired during prostate treatments have been processed using the above method. In each case we have compared the results to our conventional *in-vivo* dosimetry method. Data acquisition and analysis is also being carried out for some other treatment sites where anatomical changes might occur during the course of treatment, including head and neck.

**Results & Discussion:** CBCTs have successfully been brought into Dosimetry Check for computation of dose distributions using the method outlined above. This method appears, in principle, to provide a workable means of near real-time *in-vivo* dosimetry, taking the fraction-specific anatomy on each treatment into account. Future work is required, however, to establish whether automation of the process would be possible to make this method usable routinely.

For the patients analysed thus far, there appears to be an advantage in using the CBCT rather than the planning CT. Changes in both machine delivery and in patient anatomy can be combined to reconstruct the delivered dose distribution as realistically as possible. We will present and discuss some specific results which highlight the difference from using the planning CT using gamma maps and by DVH statistics. For example, when the bladder volume differs from that at planning by 10%, the V40 of the bladder changes by 1.8% on average (n = 8, Pearson’s R = 0.96). In some cases, for this reason, the volume constraints for the bladder appeared to be met when the dose was computed on the planning CT, but were exceeded when the dose is computed on the CBCT. The dose to the PTV remains remarkably similar, however, with the median dose being changed by only 0.5% on average when the CBCT is used instead of the planning CT.

**Conclusion:** EPID dosimetry which incorporates variations in patient anatomy can be achieved using currently available commercial solutions. Results indicate value in this process, particularly for the organs at risk. Further work remains to automate the work-flow but near real-time *in-vivo* dosimetry may be possible.

**References:**


Background. Electronic portal imaging devices (EPIDs) have been used for radiotherapy monitoring purposes for a while. In-vivo dosimetry is strongly encouraged, and an area where the use of EPID is considered promising [1], [2], [3], [4]. In Northampton General Hospital we have replaced diodes with transit in-vivo dosimetry using the EPIgray system, for most of our radical patients. This has changed the workflow of the department, for both treatment and physics teams. This talk will present the challenges met during this transitional stage and the difference in the capabilities of the two systems, showing some representative case studies in which transit dosimetry offered enough information to avoid considerable deviations of the delivered treatment from the planned one.

Methods. EPIGray uses the planning CT, structure set and plan for each treatment to back-project the dose into the patient, using the integrated image acquired during the field. The reconstructed dose is then compared with the planned one. This is currently done on the first fraction of treatment of each patient of all the radical photon treatments except arc treatments, for practical reasons. After the system’s commissioning and testing, EPIGray was used in just one of the three linear accelerators for a trial period before expanding to all three of them. The results presented are clinical cases where discrepancies in the EPIgray output have shown potential errors in treatment that would not have been found by diodes alone.

Results. There were some challenges met during the transition to the new system were the training of staff (radiographers and physicists), as executing and reconciling the verifications were much different than the existing process. Another important issue was the simultaneous need for both positioning and dosimetric image acquisition according to some particular site-specific imaging protocols. The dosimetric response of the EPID needed to be investigated and decisions had to be taken about the quality assurance needed; as well as setting a limit on the useful area of the EPID for the verification images. After a year of use of EPIGray in our department we have noticed an advantage of transit dosimetry over the diodes, as far as the amount of information offered by the two systems is concerned. Internal patient movement and anatomy changes can be detected, additionally to external movement/positioning errors. Two case studies will be presented highlighting the last statement. The first one is the case of a lower oesophagus patient for which EPIGray demonstrated partial geographical miss; The second case is a breast photon boost, for which EPIGray showed that the patient was not treated in breath hold as treatment planned. The treatments were corrected for the remaining fractions for both cases.

Conclusion. In depth knowledge of each technique, which comes with experience, is needed to establish a smooth workflow, understand the results sufficiently, and to develop the correct quality control. Although departmental understanding of the system is still ongoing, and improvements could yet be made, transit dosimetry has proved to be a useful tool for detecting treatment discrepancies.

Key references.


Online prostate plan adaptation for simulated volume changes on the 1.5T MR-Linac  
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Background. On the MR-Linac 1,2 (Elekta AB, Stockholm, Sweden) any change in patient set-up will be corrected for using a ‘virtual couch shift’ 3, where the defined MLC aperture shifts, rather than the couch. Additionally, segment weights and shapes may be re-optimised to account for daily anatomical changes. This study investigates methods for re-optimisation of treatment plans for set-up and rectum volume changes for prostate patients.

Methods. Four 60 Gy in 20 fraction prostate IMRT plans were created using an MR-Linac beam model on a research Monaco system (v5.19.02) (Elekta AB, Stockholm, Sweden). This allows the 1.5 T magnetic field to be included in the optimisation 4. To investigate adaptive workflows, the planning CT was re-imported into Monaco with two changes introduced; 1) either a 5 mm or 10 mm setup error in x, y or z, 2) rectal volume variation, ±20% uniform increase or decrease in volume, simulated by deforming the CT using ImSimQA. To correct for translational and anatomical changes, three re-optimisation methods were tested: Shift-only (SO); Segment Weight Optimisation (SWO); and Segment Weight and Shape Optimisation (SSO). The time to re-optimise and the DVH statistics were recorded, with the change in dose from the original plan calculated.

Results. The difference in D95% PTV coverage and V40 Gy for the Rectum from the original plan using the three re-optimisation methods were investigated with setup errors of 5 mm and 10 mm. For all rectal filling states the SO plan showed the largest difference with the original plan. The largest mean difference was -4.2 Gy and -14.0 Gy for SO with a decreased rectum with a set-up error of 0.5 cm and 1.0 cm respectively. Using a SWO reduced these differences to -1.8 Gy and -6.1 Gy, with SSO reducing this further to -0.5 Gy and -0.6 Gy. The V40 for the rectum does not vary greatly between the three different re-optimisation methods with differences being due to the size of the rectum and magnitude of the set-up error. The mean time taken to complete each of the 3 methods of plan re-optimisation were 61, 64 and 239 seconds for SO, SW and SSO respectively.

Discussion and Conclusion. This preliminary study suggests available optimisation methods can be used for daily strategies. SO was not able to recover the PTV dose when translations of 1 cm were introduced. SSO was the optimal method for recovering the original PTV coverage whilst not adversely affecting the dose to the rectum. However, there was a mean time increase of 3 minutes between this and the other methods and set-up errors less than 5 mm could be recovered using SWO with little additional detriment to the rectal dose. This work is being extended to real changes in patient anatomy using CBCTs and an in-house shading correction 5 to investigate adaptive planning workflows.

Quantification of changes to dose distribution caused by positional corrections for verification image matching to rectal and anal cancer patients during IMRT treatment

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Background Image guided radiation therapy (IGRT) is currently a standard for patients treated for rectal and anal cancer (ca) using intensity modulated RT (IMRT). In our Centre (OUH), the patient’s position is verified using cone beam computed tomography (CBCT) and corrected if needed by shifting the couch [2], according to image matching to bony anatomy. This introduces dose delivery discrepancies which, in theory, can be addressed by re-planning [1]. This study aims to quantify the differences and estimate their clinical significance. The null hypothesis is that there is no difference between the original and matched dose distribution.

Methods Nine patients completing treatment between 2015 and 2017 were eligible and selected (five with anal ca and four with rectal ca). Organs at risk (OARs) and target volumes were contoured following ICRU guidelines [4] and were used for dosimetric analysis.

Mirada RTx software was used to do two rigid registrations of the CBCT to the CT: to the isocentre, and manual rigid image alignment simulating couch shifts. Dose statistics from exported dose volume histograms (DVHs) for key structures were used to compare the two alignments. The median dose to each organ from each plan was compared using Wilcoxon matched pairs signed ranks test with the doses before and after manual alignment compared with a statistical significance threshold of p=0.05.

In addition, EUD and NTCP were calculated for both alignments using a free Matlab script [3] to determine the likelihood of OAR damage. The logit-EUD model was used having been found to give as good a description of the data as more complex methods for an end point of late rectal bleeding [5]. \[ \Delta \text{NTCP} = \text{NTCP1} - \text{NTCP2} \] was calculated for comparison between the two samples, where NTCP1 is that with the isocentric alignment and NTCP with manual alignment.

The Wilcoxon test was used for NTCP statistical analysis before and after the intervention of couch movement. The values were not able to be calculated for all patients due to time constraints (but will be presented in the final paper). Here we present the outcome of 84 fractions analysed.

Results Both DVH and radiobiological analysis showed some statistical significance for the doses to certain organs; however, this was not consistent across all patients. Twenty (20) out of 84 fractions analysed, manual alignment led to constraints being breached due to imposed shifts: 10 for small bowel D20Gy, 4 for left femoral head D50%, and 6 for bladder V40Gy.

The results from EUD and NTCP work reflect those from the DVHs, with the same OARs showing statistically significant difference between the alignments (e.g. for patient ‘rectum1’, bladder significance = 0.007; and \( \Delta \text{NTCP} = -0.07% \), the manual giving the higher values.

Discussion The results show that despite the movements made the dosimetry changes are small but in some cases significant. The NTCP for bowel is high showing the radiosensitivity of such structures is important in the analysis. Further work including using deformable image registration and dose surface maps would improve how this work can be applied to adaptive radiotherapy in the future. Limitations of the work include the small population sample, the smaller number for which the EUD and NTCP was calculated, and that results from DVHs were only drawn from individual dose levels which may not represent the whole organ’s response. Increasing the number of patients would improve the power of this study and is suggested as further work.

Conclusion Dosimetric changes caused by verification image matching on set can lead to significant increases in dose to OARs and the probability of complications is in some cases increased. The null hypothesis is thus rejected on the basis that it cannot be retained for all cases. Therefore, online adaptive radiotherapy (or re-planning) should be considered for future clinical practice.

Key references