A new methodology for inter- and intrafraction plan adaptation for the MR-linac

To cite this article: C Kontaxis et al 2015 Phys. Med. Biol. 60 7485

View the article online for updates and enhancements.

Related content
- Towards adaptive IMRT sequencing for the MR-linac
  C Kontaxis, G H Bol, J J W Lagendijk et al.
- Towards fast online intrafraction replanning for free-breathing stereotactic body radiation therapy with the MR-linac
  C Kontaxis, G H Bol, B Stemkens et al.
- Fast online Monte Carlo-based IMRT planning for the MRI linear accelerator
  G H Bol, S Hissoiny, J J W Lagendijk et al.

Recent citations
- MR-guided radiation therapy: transformative technology and its role in the central nervous system
  Yue Cao et al
- An MRI-compatible patient rotation system - design, construction, and first organ deformation results
  Brendan Whelan et al
- Investigation of undersampling and reconstruction algorithm dependence on respiratory correlated 4D-MRI for online MR-guided radiation therapy
  Nikolai J Mickevicius and Eric S Paulson
A new methodology for inter- and intrafraction plan adaptation for the MR-linac

C Kontaxis, G H Bol, J J W Lagendijk and B W Raaymakers

Department of Radiotherapy, University Medical Center Utrecht, Heidelberglaan 100, Utrecht 3584 CX, The Netherlands

E-mail: c.kontaxis@umcutrecht.nl

Received 12 June 2015, revised 23 July 2015
Accepted for publication 30 July 2015
Published 15 September 2015

Abstract

The new era of hybrid MRI and linear accelerator machines, including the MR-linac currently being installed in the University Medical Center Utrecht (Utrecht, The Netherlands), will be able to provide the actual anatomy and real-time anatomy changes of the patient’s target(s) and organ(s) at risk (OARs) during radiation delivery. In order to be able to take advantage of this input, a new generation of treatment planning systems is needed, that will allow plan adaptation to the latest anatomy state in an online regime. In this paper, we present a treatment planning algorithm for intensity-modulated radiotherapy (IMRT), which is able to compensate for patient anatomy changes. The system consists of an iterative sequencing loop open to anatomy updates and an intra- and interfraction adaptation scheme that enables convergence to the ideal dose distribution without the need of a final segment weight optimization (SWO). The ability of the system to take into account organ motion and adapt the plan to the latest anatomy state is illustrated using artificial baseline shifts created for three different kidney cases. Firstly, for two kidney cases of different target volumes, we show that the system can account for intrafraction motion, delivering the intended dose to the target with minimal dose deposition to the surroundings compared to conventional plans. Secondly, for a third kidney case we show that our algorithm combined with the interfraction scheme can be used to deliver the prescribed dose while adapting to the changing anatomy during multi-fraction treatments without performing a final SWO.

Keywords: adaptive, sequencer, intrafraction, interfraction, anatomy changes, IMRT, MR-linac

(Some figures may appear in colour only in the online journal)
1. Introduction

The University Medical Center Utrecht (Utrecht, the Netherlands), in cooperation with Elekta AB (Stockholm, Sweden) and Philips (Best, the Netherlands), is building an MRI linear accelerator (MR-linac) for real-time anatomy visualization during radiation delivery. The prototype combines an Elekta 8 MV linear accelerator system with a Philips 1.5 T MRI scanner (Lagendijk et al. 2002, Raaymakers et al. 2009, Crijns and Raaymakers 2014).

More hybrid systems have been developed in the same direction including the ViewRay™ system which combines three equidistant 60Co beam setup with an open 0.35 T MRI system (Mutic and Dempsey 2014) and the system combining a biplanar 0.6 T MRI with a 6 MV linac (Fallone 2014).

The MR-linac will monitor the changing patient anatomy during treatment and thus the target and organ at risk (OAR) anatomy deformations that occur will be available through image registration algorithms.

In our previous work (Kontaxis et al. 2015), we presented a new IMRT optimization system, the adaptive sequencer (ASEQ), specifically suited for this new generation of radiotherapy machines, like the MR-linac. ASEQ features a novel sequencing algorithm which enables online replanning based on incoming anatomy deformations. Given a desired dose distribution, every iteration calculates one segment as well as the dose it will deliver and decreases the current dose total accordingly. The residual dose distribution will be the target of the next iteration of the algorithm. This loop is repeated several times until dose convergence is achieved. At the core of this algorithm is the full fluence optimization which is performed during every iteration. Every fluence optimization targets the remaining dose distribution and optimizes the dose influence data of the respective anatomy. In this way, each segment is calculated from this updated fluence distribution, specifically targeting the current anatomy state. We showed that our sequencer can produce clinically acceptable results when used as conventional treatment planning software by performing standard clinical quality assurance (QA). Furthermore, we proposed a new interfraction scheme which transfers the missing/excess dose to the planning of the subsequent fraction and can be used to ensure convergence to the prescribed dose without the use of a segment weight optimization (SWO) enabling direct delivery of the treatment.

The purpose of this work was to further develop our system by adding all the modules needed in order to facilitate anatomy deformations during delivery. Moreover, we wanted to verify that given a set of anatomy deformations, the pipeline can accurately track the previously delivered dose and deliver the prescribed dose to the target(s) while minimizing the dose to the surrounding structures during treatment.

Two variations of this treatment were tested. In the first one, a single-fraction treatment is simulated while on-the-fly intrafraction plan adaptation is used. In the second one, a multi-fraction treatment is assumed, during which both intrafraction adaptation and the interfraction scheme are utilized. Kidney tumor sites with an experimental IMRT setup suitable for the MR-linac (Stam et al. 2013a) were selected to give a proof of principle for the system. For each kidney case, artificial baseline shifts were created that produce an incremental shift of the target during the treatment fraction. We compared our adaptive approach to static radiotherapy plans with no extra margins and to static radiotherapy plans with Internal Target Volume (ITV) structures that include the motion of the target.

These results show that this new planning system implements the complete pipeline needed, in order to successfully facilitate online-replanning IMRT treatment in the context of hybrid radiotherapy machines like the MR-linac.
2. Materials and methods

2.1. Algorithm

2.1.1. Pipeline. In this work we extended the pipeline originally presented in Kontaxis et al (2015) (figure 1). Given a desired dose distribution ($dose_{ideal}$), the original ASEQ performs in every iteration a fluence optimization targeting the remaining $dose_{ideal}$. Then, the resulting fluence maps of all beams are segmented to their respective beam’s eye view (BEV) and the best segment among all beams is selected (Kontaxis et al 2015). The dose of that segment is calculated and subtracted from the $dose_{ideal}$ distribution. This updated dose distribution forms the target of the next iteration of the algorithm. The above loop is repeated multiple times until dose convergence is achieved. Dose convergence is defined by the following equation:

$$convergence = \frac{dose_{delivered}}{dose_{prescribed}}$$

where $dose_{prescribed}$ is the average dose value of the target voxels in the original $dose_{ideal}$ and $dose_{delivered}$ is the average delivered dose from the segments calculated so far to the target voxels, excluding the overdosage of any voxels that have exceeded their ideal dose.

The dose influence data is generated by GPU-based Monte Carlo dose (GPUMCD) calculation engine (Hissoiny et al 2011a, 2011b) and the fluence optimization is done by a fast inverse dose optimization method presented in Ziegenhein et al (2013).

In order to introduce anatomy changes into the pipeline extra modules were added to the main algorithm. In contrast to the static anatomy of the previous algorithm, we now split our calculations in either reference or dynamic space calculations. The first CT/MRI exam of the patient used for conventional treatment planning forms the reference anatomy and the changing anatomy, as determined from the online MRI, corresponds to the dynamic anatomy. The fluence optimization, segmentation and dose calculation are performed in the dynamic space while the update of the prescribed $dose_{ideal}$, the dose accumulation and dose convergence statistics are performed in the reference space. Figure 2
shows the modified ASEQ algorithm which is able to facilitate anatomy updates. The solid and dashed borders indicate that the module operates on the reference and dynamic grid space respectively.

The input of the algorithm is a voxel-by-voxel dose prescription calculated on the reference grid, the constraints used by the optimizer and the MLC related parameters (leaf width etc). Moreover, for these experiments the precalculated data of all intermediate anatomy sets is used including the three-dimensional deformation fields and the dose influence data corresponding to each anatomy. Then, during each iteration of ASEQ the following steps are performed:

(i) Load new anatomy: The anatomy, deformation fields and dose influence data corresponding to the new anatomy is loaded. The deformation fields, consist of the three-dimensional field that transforms the reference anatomy to the dynamic anatomy as well as its inverse field which transforms the dynamic anatomy to reference space. The target of the following fluence optimization is replaced by the remaining $dose_{ideal}$ distribution after it has been warped to the new dynamic grid using trilinear interpolation.

(ii) Fluence Optimization:
A full fluence optimization is performed to produce a new set of optimal beamlet weights. (Dynamic space)
(iii) **Segmentation:**

The fluence maps of all beams are segmented and one segment among them is selected. The segment evaluation criteria consist of the area of the open field of the segment which favors larger fields, the discrete intensity of the segment which ensures that the final segment intensity will be as high as possible and the average value of the beamlets that are included in this segment and implicitly adds the actual contribution of the included beamlets to the full three-dimensional fluence. (Dynamic space)

(iv) **Segment dose calculation:**

The dose of the selected segment is calculated using Elekta’s research software tools taking into account the MLC settings. (Dynamic space)

(v) **Dose warping:**

The dose of the selected segment is warped to the reference grid using trilinear interpolation. (Reference space)

(vi) **Dose accumulation:**

The dose of this segment is added to the dose accumulation grid (dose\_acc) used to track delivered dose, penalise over-dosed voxels for the next iteration and acquire the convergence statistics. (Reference space)

(vii) **dose\_ideal update:** The dose of this segment is also subtracted from the dose\_ideal distribution resulting in an updated goal for the new iteration. (Reference space)

The above steps are repeated until either a certain percentage of the ideal dose has been accounted for or a certain number of segments has been calculated.

2.1.2. **Interfraction scheme.** The above loop accounts for the intrafraction anatomy changes but can also be used to facilitate interfraction adaptation. In current treatment planning systems, convergence to the prescribed dose is not fully achieved after sequencing. This is typically tackled by employing Segment Weighted Optimization (SWO) as a post processing step which guarantees dose convergence. In order to perform online replanning, ASEQ should fully converge during the treatment without the need for a SWO.

For this purpose, we have developed an interfraction scheme (figure 3) able to converge to the prescribed dose without the need of a final segment weighting during the course of the treatment (Kontaxis et al 2015). More specifically, given the initial dose prescription, ASEQ (figure 1) was used to generate a treatment plan for every treatment fraction. The difference between the prescribed dose and the calculated dose was acquired after every fraction and added to the prescription of the subsequent fraction. In this way, the missing/excess dose was taken into account during the sequencing of treatment fractions and convergence to the initial prescription was achieved without a final SWO. We showed that this was feasible for several different treatment sites used in current clinical practice.

This interfraction algorithm was adapted to use the modified ASEQ presented in this work, enabling the transfer of missing/excess dose to the next fraction while also adapting to the inter- and intrafraction anatomy updates.

2.2. **Anatomy**

Three kidney cases were selected to introduce anatomy changes to our pipeline. This treatment site has been extensively researched under the context of MRI-guided radiotherapy and has been demonstrated as a possible candidate for MR-linac treatments (Stam et al 2012, 2013a, 2013b).
For each case, we produced artificial intrafraction motion data that demonstrate a linear gradual shift in the cranial-caudal (CC) inferior direction during treatment. Every motion set consists of several intermediate anatomy sets that together describe the final shift at the end of the fraction. Each anatomy instance is shifted by 0.2 mm in the CC direction compared to the previous state. This motion discretization was selected, in order to stress test our pipeline by changing the anatomy after every iteration of the sequencer. The target is thus gradually shifted during treatment and every calculated segment targets the most recent anatomy state. Every anatomy set was generated by shifting the whole patient volume in order to have a verifiable accurate dose accumulation. In this way, we were able to assess the performance of our system while excluding possible artifacts and uncertainties of image registration.

Every intermediate anatomy set includes the three-dimensional grid containing the new patient anatomy, the three-dimensional deformation fields that describe the above mentioned linear shifts and are used to transform the anatomy between the reference and dynamic grids, the propagated contours and the pre-calculated dose influence data corresponding to the respective anatomy.

The grid spacing for all cases was $3 \times 3 \times 3$ mm$^3$ and the calculations were done using the MR-linac prototype’s specifications (Crijns and Raaymakers 2014), an MLC with 80 leaf pairs and 7 mm leaf width using 8 MV energy beams at 1.5 T.

The Gross Tumor Volume (GTV) of each one of the three cases used was 2.3 ml (Case 1), 9.1 ml (Case 2) and 12.7 ml (Case 3) respectively.

The GTV was prescribed with 25 Gy and no additional margins were used for the adaptive ASEQ plans. For these experiments the GTV (target), ipsilateral kidney (OAR) and body (OAR) volumes were included in the optimization and the resulting plans satisfied all experimental constraints (table 1) proposed in Stam et al (2013b), with kidney mean dose adjusted from Dawson et al (2010). The beam setup used is shown in table 2.

Furthermore, in order to assess the adaptive plans we also generated conventional radiotherapy plans with no additional margins (Static) and plans with ITV structures (ITV). The ITV volume of interest was generated by only applying the tightest necessary margin in the CC inferior direction ensuring that the GTV was always fully inside the planning target.

The first two kidney cases were used in a single fraction treatment. Case 1 was planned using 60 segments and underwent a 1.2 cm shift, while Case 2 was planned using 62 segments and underwent a 1.24 cm shift.
Case 3 was used to test the interfraction adaptation ability of our system in a hypo-fractionated kidney treatment of five fractions without the use of SWO. Every fraction was sequenced using 40 segments during which the target exhibits a shift of 0.8 cm. In order to introduce an interfraction variation in addition to the intrafraction shift, the initial target position in every fraction is shifted by 1 mm in CC direction relative to the previous one. This leads to a shift of the initial GTV position, that ranges from 1 mm in the first fraction to 5 mm in the fifth fraction, when compared to the reference position.

3. Results

For all cases one adaptive plan using ASEQ was generated that passed the contraints shown in table 1. Figure 4 shows one transversal slice of the dose for one kidney case.

### Table 1. Constraints of the kidney cases.

<table>
<thead>
<tr>
<th>Volume of interest</th>
<th>Constraints</th>
</tr>
</thead>
<tbody>
<tr>
<td>GTV</td>
<td>99% vol &gt;= 20 Gy</td>
</tr>
<tr>
<td>Kidney</td>
<td>25% vol &lt;= 5 Gy</td>
</tr>
<tr>
<td></td>
<td>Mean dose &lt;= 8 Gy</td>
</tr>
<tr>
<td>Liver</td>
<td>30% vol &lt;= 2.5 Gy</td>
</tr>
<tr>
<td>Bowels</td>
<td>5% vol &lt;= 20 Gy</td>
</tr>
<tr>
<td></td>
<td>Maximum dose &lt;= 21 Gy</td>
</tr>
<tr>
<td>Stomach</td>
<td>5% vol &lt;= 22.5 Gy</td>
</tr>
<tr>
<td>Spinal cord</td>
<td>Maximum dose &lt;= 13 Gy</td>
</tr>
</tbody>
</table>

### Table 2. Beam angles used for the kidney cases.

<table>
<thead>
<tr>
<th>Case</th>
<th>Beam angles</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kidney</td>
<td>0°, 24°, 48°, 72°, 96°, 120°, 144°, 168°, 192°, 216°, 240°, 264°, 288°, 312°, 336°</td>
</tr>
</tbody>
</table>

3.1. ASEQ

Figures 5(a) and (b) show the intrafraction convergence for the first two kidney cases. The Adaptive dashed line is the result of ASEQ that adapts every segment to the moving anatomy while the Static dotted line is the result of a conventional segment weighted plan when delivered to the moving anatomy.

In Case 1, Adaptive is on average 12.3% higher than Static and at the end of fraction successfully converges to 98.7% compared to 88.9% for Static, while in Case 2 Adaptive is on average 10.3% higher than Static and at the end of fraction converges to 97.5% compared to 90.1% for Static (table 3).

The above differences show a significant dose decrease in the Static plan due to the intrafraction motion. More importantly, we observe that ASEQ converges close to 100% of the prescribed dose in a single fraction, very close or higher than their initial segment weighted plans, 97.7% and 98.3% respectively (represented in the plot with a square). These results confirm the findings presented in Kontaxis et al (2015), that showed that SWO plans do not fully converge to 100% but still deliver the desired dose when the initial ideal prescribed dose safely ensures the clinical constraints.
In order to qualitatively verify the dose distributions we also generated an ITV plan for each case of figure 5. Since the direction and range of the motion for these cases were now known, the ITV for both cases was created by extending the GTV only in the CC inferior direction by approximately 1.2 cm to tightly encompass the GTV during treatment. The convergence

**Figure 4.** Transversal slice of the dose for one kidney case in reference space (x axis range: 40 cm, y axis range: 37 cm).

**Figure 5.** Intrafraction convergence for Cases 1 and 2. (a) Case 1. (b) Case 2.

**Table 3.** Inter- and intrafraction convergence: intrafraction adaptation was performed for Cases 1 and 2 while both inter- and intrafraction adaptation was performed for Case 3.

<table>
<thead>
<tr>
<th>Case</th>
<th>Static (%)</th>
<th>Adaptive (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case 1</td>
<td>88.9</td>
<td>98.7</td>
</tr>
<tr>
<td>Case 2</td>
<td>90.1</td>
<td>97.5</td>
</tr>
<tr>
<td>Case 3</td>
<td>89.6</td>
<td>98.3</td>
</tr>
</tbody>
</table>

In order to qualitatively verify the dose distributions we also generated an ITV plan for each case of figure 5. Since the direction and range of the motion for these cases were now known, the ITV for both cases was created by extending the GTV only in the CC inferior direction by approximately 1.2 cm to tightly encompass the GTV during treatment. The convergence
achieved by the ITV plans when delivered to the moving anatomy, represented in the plot with a triangle, was 98.6% and 99% respectively, very close to the adaptive regime.

Figures 6 and 7 show a coronal slice for each one of the above kidney cases. Figures 6(a) and 7(a) show one slice of the dose delivered by the Adaptive scheme and figures 6(b) and 7(b) show the absolute dose difference for the respective slice between the Adaptive scheme and the ITV plan delivered in the moving anatomy, both in reference space. For both cases, we observe that the tight ITV plans caused a significant overdosage in the region of the ITV below the GTV as well as in the region above the GTV due to motion of the anatomy in the inferior direction. The dose differences in the remaining regions are small and show that the adaptive sequencer is able to efficiently deliver the required dose in a comparable way to conventional plans.

### 3.2. Multi-fraction ASEQ

Figure 8(a) shows the intrafraction convergence of the first fraction for Case 3. Adaptive reached 95.8% after 40 segments, 1.5% less than the SWO plan (represented with a cross in the plot). Figure 8(b) shows the interfraction convergence for Case 3, in which the Adaptive dashed line
is the result of the adaptive treatment when intra- and interfraction adaptation is performed and the missing/excess dose is transferred to the next fraction. The Static dotted line is the result of a conventional segment weighted plan of this case when delivered to the anatomy sets of every fraction. The $y$-axis shows the convergence of both regimes, calculated using the delivered dose up to the respective fraction in the $x$-axis, relative to the initial prescribed dose that ideally should be have been delivered so far. Both Adaptive and Static start from the convergence values reached at the end of the first fraction (figure 8(a)) and then diverge during the treatment fractions. After five fractions, Adaptive converges to 98.3% compared to 89.6% of Static (table 3) and higher than the initial static SWO plan (represented with a horizontal line in the plot).

This result confirms that ASEQ is not affected by the addition of interfraction motion and that, by transferring the dose to the next fraction, it can be used in a multi-fraction treatment without relying on any final calculation step like SWO.

### 3.3. Timings

Table 4 shows the calculation time of the individual steps of our pipeline for each one of the three kidney cases. The columns ‘Fluence Optimization’, ‘Dose calculation’ and ‘Segmentation’ cover the respective pipeline blocks of figure 2. The column ‘Anatomy/Grid Operations’, shows the combined time spent on loading the new anatomy (which includes the dose influence data and anatomy grid) as well as the time spent on grid operations like dose warping (from reference space to dynamic space and vice versa), dose accumulation and dose update.

These timings reflect the performance of the first functional prototype of our pipeline. Each individual step includes several variables that could be tweakable to improve its speed, e.g. number of iterations for the fluence optimization and Monte Carlo uncertainty for the dose calculation. Moreover, a significant overhead caused by file input/output operations, dose engine initialization etc is included in these results and can be easily minimized in the future. Better integration and parallel implementations of the individual steps taking advantage of multi-core/GPU systems will also lead to a significant speed increase that will bring the system close to clinical application.

Figure 8. Convergence for Case 3. (a) Intrafraction convergence for the first fraction. (b) Interfraction convergence ($y$-axis starts at 88%).

phys. med. biol. 60 (2015) 7485

C Kontaxis et al

7494
The calculation of the dose influence data for the new anatomies, which were precalculated for these experiments, is a computationally demanding task. We used GPUMCD with Monte Carlo uncertainty set to 3% and the calculation time for every beam in 1.5 T magnetic field was 43 s on average among all cases, leading close to 11 min per new anatomy given the 15-beam configuration used in these cases.

4. Discussion

In this work we presented a treatment planning system that implements the complete pipeline needed to perform online plan adaptation. Given the appropriate anatomy input from new radiotherapy machines, like the MR-linac, it incorporates these changes into the calculation of subsequent segments. The experiments with kidney baseline shifts showed that the system is able to adapt the segment to the moving anatomy and thus to deliver the intended dose distribution to the patient without the use of any additional margins. Conventional radiotherapy plans with no margin fail to deliver the intended dose when the same motion is applied and when ITV structures are used for planning, the plans severely overdose regions outside of the GTV in order to reach the desired target coverage. In addition, following our previous work (Kontaxis et al 2015), we show that the system can still ensure convergence for multi-fraction treatments without the use of SWO, while adapting the radiation to the moving anatomy.

Kidney cases have already been suggested that will greatly benefit from future MR-linac treatments compared to the current standard of care (Stam et al 2013a). The range of motion of kidney has been studied, with its principal component being in the cranial-caudal direction (Wysocka et al 2010, Stam et al 2013b). In this work we investigated the possible baseline-shifts that could hamper both breath-hold and free breathing treatment variations that have been proposed for this treatment site.

For the purposes of this paper, we generated changing anatomy input sets by creating artificial linear baseline shifts of several kidney cases as we wanted to verify the performance of our system unbiased from possible image registration uncertainties. These shifts were described by full body deformation vectors in order to have an accurate dose accumulation. The magnitude of the shift in between segments in these data is conservative and serves to generate the above mentioned overall linear shift. These data provided a proof of principle and verified the stability of the system. This means that the same performance is expected in less uniform shifts in terms of direction, range and frequency of motion.

In the future, we plan to test our pipeline with deformation vectors calculated by image registration on actual MR acquisitions. Having verified that our pipeline successfully works when provided with accurate deformation fields, we can now focus on testing different image registration algorithms and the minimum acceptable field of view for the deformation fields in order to have accurate dose accumulation and ensure that the replanning can correctly include the previously delivered dose into its calculations. Moreover, when non-artificial deformation fields are available, we will investigate the additional margins that a static approach should employ in order to match the convergence of our system and assess their impact on the OARs.

<table>
<thead>
<tr>
<th>Case</th>
<th>Fluence optimization</th>
<th>Dose calculation</th>
<th>Segmentation</th>
<th>Anatomy/Grid operations</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>6</td>
<td>13</td>
<td>4</td>
<td>16</td>
<td>39</td>
</tr>
<tr>
<td>2</td>
<td>7</td>
<td>13</td>
<td>5</td>
<td>16</td>
<td>41</td>
</tr>
<tr>
<td>3</td>
<td>9</td>
<td>16</td>
<td>5</td>
<td>24</td>
<td>54</td>
</tr>
</tbody>
</table>

Table 4. Pipeline timings per iteration (seconds).

The calculation of the dose influence data for the new anatomies, which were precalculated for these experiments, is a computationally demanding task. We used GPUMCD with Monte Carlo uncertainty set to 3% and the calculation time for every beam in 1.5 T magnetic field was 43 s on average among all cases, leading close to 11 min per new anatomy given the 15-beam configuration used in these cases.
The introduction of online replanning to the clinic will require that all components of this pipeline are fast enough to match the input from the MRI. The results presented in this work tested the feasibility of this pipeline with the extreme scenario of changing the anatomy after every delivered segment. This update frequency heavily depends on the motion pattern, range and frequency which greatly varies between different treatment sites and will be researched in future work. Several improvements, that range from multi-threaded/GPU implementations to parameter tweaking, can be made to improve the speed of each iteration of our method and thus bring it close to clinical application. Regarding the calculation of dose influence data of the incoming anatomies which is the most time consuming step, this has been shown that can be done in real-time (Bol et al. 2012).

In order to take full advantage of the future radiotherapy machines in the clinic, a move from CT-based to MR-based planning should also be made. Several techniques that can provide electron density information from acquired MR data have been researched (Devic 2012).

Furthermore, a new set of quality assurance (QA) procedures should be developed. Full online replanning, is also restricted by the plan approval policy currently granted by the physician prior to treatment. These clinical procedures are currently being investigated in order to allow adaptive treatments while maintaining all patient safety protocols.

We consider this work as the first steps towards adaptive treatments enabling inter- and intrafraction plan adaptation for the MR-linac.

5. Conclusion

In this paper, we have presented a treatment planning system for IMRT that is able to facilitate online replanning under the context of the new hybrid MRI-radiotherapy machines, like the MR-linac. Its algorithm enables the inclusion of anatomy changes during sequencing that will be provided by the online and real time MRI embedded in these machines. Furthermore, we have coupled our sequencer to a novel interfraction scheme that guarantees convergence to the prescribed dose without the need of a segment weighted optimization. We have created interfraction baseline shifts for three kidney cases and demonstrated that the system can account for motion and converge to the desired dose, while the static plans with no additional margins showed a severe decrease in the expected target dose when delivered to the moving anatomy. This was demonstrated in both single and multi fraction kidney treatments where the interfraction scheme is also utilized. For two cases we showed that while ITV plans could achieve the desired dose coverage, they produced a significant overdosage in regions outside of the GTV. These results confirm that our system can accurately adapt the treatment to the moving anatomy and pave the way for future highly hypofractionated boost treatments in the MR-linac.

Acknowledgments

This research is financially supported by Elekta AB, Stockholm, Sweden. The authors would like to thank Elekta AB, Stockholm, Sweden for providing some of their research software tools.

References


Crijns S and Raaymakers B 2014 From static to dynamic 1.5T MRI-linac prototype: impact of gantry position related magnetic field variation on image fidelity Phys. Med. Biol. 59 3241

Devic S 2012 MRI simulation for radiotherapy treatment planning Med. Phys. 39 6701–11

Fallone B G 2014 The rotating biplanar linac-magnetic resonance imaging system Semin. Radiat. Oncol. 24 200–2


Raaymakers B W et al 2009 Integrating a 1.5 T MRI scanner with a 6 MV accelerator: proof of concept Phys. Med. Biol. 54 N229–37


