

ORIGINAL ARTICLE

The contribution of on-line correction for rotational organ motion in image-guided radiotherapy of the bladder and prostate

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Abstract

Background and purpose. Current IGRT protocols only correct for organ motion through a 3D translational movement of the treatment couch. The aim of this study was to quantify the relative importance of rotational vs. translational corrections in bladder and prostate IGRT. **Materials and methods.** The data available consisted of a set of 9 bladder cancer patients each having a planning CT scan and between 3 and 8 repeat CT scans throughout their treatment course, with the bladder and prostate (for 5 of the 6 male patients) outlined on all scans. An algorithm was written to determine both the optimum translation and rotation angles required to align the repeat CTVs with their planning CTV. Angles considered were those possible through couch roll, rotation and tilt. The optimum shifts and angles were determined as those that minimised the volume of the repeat scan CTV lying outside the volume of the planning CTV. Two different situations were investigated: 1) 3D translation only (3 degrees of freedom (DoF)) and 2) rotation after applying the optimum 3D translation (6 DoF). Those repeat scans where rotation provided the greatest increase in CTV coverage were further investigated by determining the effect of rotation on the size of the treatment margins required and the volume of the resulting PTV. **Results.** For the bladder, the overall average volume percentage (across scans and patients) of the repeat CTV included in the planning scan CTV was increased from 85.7% without IGRT to 89.5 and 90.1% with 3 DoF and 6 DoF, respectively. The corresponding results for the prostate were 79.4, 86.9 and 87.5%. The resulting decrease in treatment margins required was determined for the 3 bladder and 3 prostate situations where including rotation had the largest impact. In 2 of the 6 situations the resulting PTV volume was reduced by approximately 20% when using an isotropic margin, but this reduction was considerably less when the margins were individually optimised. **Conclusion.** When treating either the bladder or prostate alone, translational IGRT correction was by far the most important action necessary to ensure alignment of the repeat CTV with the planning CTV.

Radiotherapy (RT) is an important treatment modality in the treatment of both bladder and prostate cancer. However, the considerable geometrical uncertainties caused by pelvic organ motion represent major challenges in RT for these two tumour sites. Such uncertainties have until recently been accounted for by merely adding a population-specific margin around the clinical target volume [1–10]. In recent years, however, the use of fiducial (gold/titanium) markers together with on-line 2D imaging and isocentre repositioning has developed into the state-of-the-art approach for prostate RT, allowing for use of sub-cm prostate to PTV margins [11]. Fiducial markers have also been tested in bladder RT, although not yet with the same widespread adoption

[12]. However, the introduction of so-called image-guided RT (IGRT) equipment designed for on-line volumetric imaging is now opening possibilities for frequent CTV imaging and re-positioning for a range of tumour sites, including bladder cancer. A technical solution that is currently given a lot of attention is cone-beam CT imaging (CBCT), where a full 3-D CT data set is reconstructed from multiple cone-beam x-ray transmission projections through the patient. In a recent study we showed that there is considerable theoretical potential in terms of margin reduction resulting from the use of translational isocentre corrections based on CBCT-guidance in bladder RT [13]. However, rotations have been shown to play a role in the geometric precision of pelvic RT

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[14] and could be accounted for if using both translational and rotational corrections based on on-line imaging. The aim of the present study was therefore to quantify the relative importance of translational vs. rotational corrections in IGRT for bladder and prostate targets, focusing on treatment of bladder and prostate alone.

Materials and methods

Patient and CT material

The patient data available consisted of nine bladder cancer patients (6 men, 3 women; average/range age: 74 years/63 to 81 years) that were treated at Edinburgh Cancer Centre (ECC). A detailed presentation of this material can be found in a previous publication [15], but the main points are described in the following: All patients were scheduled for twice-weekly repeat CT scanning and both the planning scan and the repeat scans consisted of 3 mm thick contiguous slices throughout the bladder volume. The planning scans were all acquired with an empty bladder. All repeat scans were registered on bony anatomy to the corresponding planning scan, including rigid body translations and rotations (Advantage Fusion software, GE Medical Systems, Milwaukee, WI, USA), isolating the internal organ motion only. Subsequently, the bladder and the prostate (for five of the six male patients) were outlined in all relevant slices in all scans. All bladder structures and all prostate structures were outlined by a single operator, a physician in training in radiation oncology for the bladder outlines and a radiation oncologist specialised in prostate cancer for the prostate outlines. The outlines were stored as DICOM RT structure sets using the same coordinate system as the corresponding planning scan.

Determination of translations and rotations

The planning CT and the related bladder and prostate repeat scan outlines were imported into in-house developed software where the IGRT translations were determined using a previously described methodology [13] and briefly, the following approach was taken. The 3D shift required to find the optimal isocentre position of the repeat scan bladder volume was determined as that which resulted in the smallest volume of the repeat scan bladder volume lying outside the planning scan volume and that was used as the objective function of a minimisation problem. The minimum was found by an iterative method employing a fast simulated annealing algorithm. The planning and repeat CTVs were represented by 3D binary matrices and moved relative to each other according to

the values of the 3 directional shifts at each iteration of the algorithm. The values of the shifts were not constrained. As this is a well-defined problem, an optimum solution was usually obtained in less than 100 iterations of the algorithm. Current IGRT protocols stop there and only correct for organ motion through a 3D translational movement of the treatment couch. The object of this study was therefore to determine if rotation of the CTV could provide any further improvement after the optimum 3D translation has been applied.

A similar algorithm was used to determine the optimum rotation angles. After applying the optimum 3 directional shifts, the conventional technique of forward mapping can be used to rotate a 3D binary matrix representing the repeat CTV (about its centroid) through the values of couch roll, rotation and tilt angles in that specific order for each iteration of the algorithm. The axes of rotation and the coordinate system used are shown in Figure 1. The problem with forward mapping is that 'gaps' or 'voids' can occur within the rotated CTV and to avoid this problem, the 3D binary matrix representing the repeat CTV was constructed by a spatial transformation using inverse mapping. In this procedure, each voxel in a 3D array that will represent the rotated CTV undergoes an inverse rotational transformation (i.e. with the rotation angles in the reverse order to that mentioned above) in order to determine the corresponding voxel in the 3D array representing the non-rotated CTV. If the voxel lies within the non-rotated CTV, it will also lie within the rotated CTV. This procedure completely avoids the problems with gaps occurring within the rotated CTV as happens with conventional forward mapping.

The algorithm then proceeded in the same manner as for the determination of the optimum shifts. The values of the rotational angles were nominally constrained to lie within $\pm 10^\circ$ of their starting value

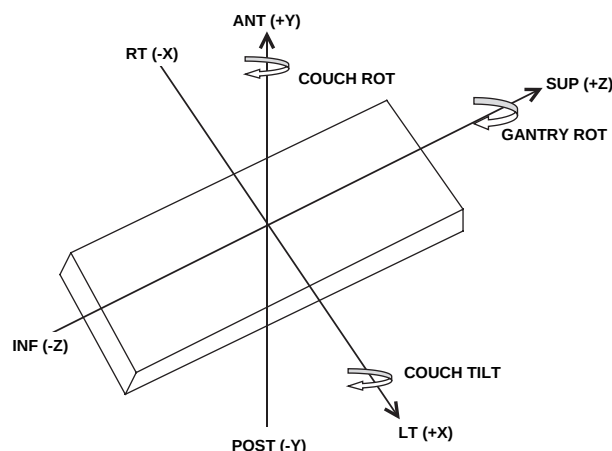


Figure 1. Axes of rotation and coordinate system used.

(=0, i.e. no rotation) as that was arbitrarily chosen to be the maximum value that would be clinically acceptable. The problem of determining the optimum rotation angles is not well defined and the algorithm normally required around 200 iterations to obtain a solution.

Using these algorithms, we investigated two different situations for both the bladder and prostate outlines: 1) 3D translation only (3 DoF) and 2) rotation after applying the optimum 3D translation (6 DoF).

Margin calculations

Determination of the optimum treatment margins was performed for selected cases where rotational corrections were found to have the greatest effect in terms of the increase in the volume of the repeat scan CTV coverage. These were determined using a previously described algorithm [7]. Having positioned (i.e. translated, and also rotated in the 6 DoF case) a bladder/prostate repeat CTV to its optimal position, all margins (inf, sup, left, right, ant, post) were increased in size in 1 mm steps and added to the planning CTV until complete coverage of the repeat CTV was obtained. This gives the optimum isotropic margin and then the algorithm subsequently proceeded to determine the optimum values of all 6 margins such that the volume enclosed between the PTV and the repeat CTV was minimised.

Results

Translations and rotations in bladder RT

The results are shown in Table I for the bladder CTVs. The overall average percentage volume (across scans and patients) of the repeat CTV included in the planning scan CTV was increased from 85.7% without IGRT to 89.5 and 90.1% with 3 DoF and 6 DoF, respectively. Therefore the average increase in volume covered due to translation was

3.8% that only increased to 4.4% when rotation was included. An increase greater than 1% in the volume covered (maximum 2.4%) was obtained for 14 of the 62 repeat bladder CTVs when including rotation.

Translations and rotations in prostate RT

Table II shows the results for prostate CTVs. The overall average percentage volume (across scans and patients) of the repeat CTV included in the planning scan CTV was increased from 79.4% without IGRT to 86.9 and 87.5% with 3 DoF and 6 DoF, respectively. The average increase in volume covered due to translation was 7.5%, considerably larger than found for the bladder, but again only showed a small increase to 8.1% when rotation was included. An increase greater than 1% in the volume covered (maximum 1.9%) was obtained for 7 of the 39 repeat prostate CTVs when including rotation.

The impact of rotations in terms of margins

The 3 bladder treatment situations (from patients 2 and 5) and the 3 prostate situations (from patients 2, 5 and 6) having the largest benefit when rotation was added were selected for margin investigation. The results are shown in Table III. The optimum isotropic margin was seen to decrease in 4 of 6 situations and a reduction in PTV volume in excess of 20% was noticeable in 2 of these. However when the margins were optimised individually both the excess volume outside the repeat CTV and the volume of the PTV were much lower than for an isotropic margin.

Discussion

This study has quantified and compared the relative importance of translational versus rotational corrections in RT of the bladder and prostate. Our main finding was that translational IGRT correction was by far the most important action necessary to ensure

Table I. Bladder: Average percentage repeat CTV coverage and the improvement obtained with 3 and 6 DoF IGRT corrections.

Patient Number (Number of repeat scans)	No translation or rotation	3 DoF (Trans)		6 DoF (Trans+Rot)	
1 (8)	77.7	88.4	10.7	89.0	0.6
2 (7)	74.6	76.7	2.1	77.8	1.1
3 (3)	91.2	94.7	3.5	94.9	0.2
4 (8)	70.0	75.0	5.0	75.9	0.9
5 (8)	86.5	91.5	5.0	92.8	1.3
6 (8)	87.7	92.4	4.7	92.8	0.4
7 (8)	99.0	99.9	0.9	99.9	0.0
8 (7)	85.3	87.3	2.0	87.8	0.5
9 (5)	99.5	99.9	0.4	99.9	0.0
Mean	85.7	89.5	3.8	90.1	0.6

Table II. Prostate: Average percentage repeat CTV coverage and the improvement obtained with 3 and 6 DoF IGRT corrections.

Patient Number (Number of repeat scans)	No translation or rotation	3 DoF (Trans)		6 DoF (Trans+Rot)	
1 (8)	75.0	86.9	11.9	87.3	0.4
2 (7)	80.3	86.9	6.6	87.7	0.8
4 (8)	89.5	91.1	1.6	91.5	0.4
5 (8)	80.2	86.5	6.3	86.9	0.4
6 (8)	72.0	83.3	11.3	84.0	0.7
Mean	79.4	86.9	7.5	87.5	0.6

alignment of the repeat CTV with the planning CTV. Rotational corrections have an impact in a small fraction of treatment situations when treating either the bladder or prostate alone, mainly when treating the bladder.

The problem of calculating the effect of rotation on a 3D structure is considerably more difficult than for 3D translation. Couch roll (i.e. gantry rotation) about the sup/inf axis of the patient presents no problem, as it is simply a rotation of any outline in the transverse plane. Couch rotation (about the ant/post axis) and couch tilt (about the left/right axis) provide a more complex problem as these rotate an outline out of the transverse plane on which it was drawn. As described in the second section of Materials and Methods, this problem has been addressed digitally by determining the coordinates of all the voxels in a 3D binary matrix that will hold the rotated repeat CTV volume and using the technique of inverse mapping to determine which of these voxels will lie within the rotated 3D volume.

This study has quantified the additional benefit of rotations after an initial translation. The point used for the rotation was taken as the centroid of the repeat CTV after the optimal translational correction. In the absence of an isocentre (this was a purely geometrical study), this was the most logical point to

select. However, finding the best point for rotations could actually be considered an optimisation problem on its own [14]. The implications for the findings in the present study would probably still be small.

The volume of the repeat CTV not covered by the planning CTV was used as the objective function in the described optimisation process. This objective function is both computationally straightforward and will also produce the best possible 'volumetric coverage'. However as the volume not covered will have to be accounted for by the addition of margins, an alternative solution would therefore be to minimise the maximum distance between the planning CTV and repeat CTV outlines, on the basis that the margins required to expand the planning CTV to the PTV should also be minimal. We have performed some initial work using a simplified multiple 2D approach (rather than 3D) by calculating the maximum axial separation on all slices. The approach was found to be computationally feasible, but will require more investigation and refinement before it can be compared to the current method.

In a parallel study we have investigated various image-guided adaptive strategies for bladder cancer. As an intermediate step in this study we have quantified the rotation of the bladder and prostate

Table III. Margins for repeat scans where including rotation had the greatest impact on coverage.

Patient Number	Site		Isotropic margin (mm)			Individual Margins (mm)							
			Margin (mm)	PTV Vol (cc)	% volume reduction	Inf	Sup	Lt	Rt	Ant	Post	PTVVol (cc)	% volume reduction
2	Bladder	3 DoF	9	226.2		5	10	5	2	3	0	175.5	
		6 DoF	6	184.4	22.7	5	7	3	4	5	3	163.5	7.3
5	Bladder	3 DoF	18	838.8		0	5	9	9	17	21	546.7	
		6 DoF	17	799.2	5.0	0	0	16	7	15	18	535.7	2.1
5	Bladder	3 DoF	8	213.3		8	10	7	0	9	5	202.4	
		6 DoF	8	213.3	0.0	10	10	4	0	3	6	201.4	0.5
2	Prostate	3 DoF	11	146.9		0	9	5	4	14	5	89.7	
		6 DoF	9	115.8	26.9	0	9	6	5	9	4	82.7	8.5
5	Prostate	3 DoF	7	136.9		7	5	2	3	3	7	109.2	
		6 DoF	6	124.4	10.0	9	5	2	3	3	3	103.0	6.0
6	Prostate	3 DoF	5	48.6		5	3	5	3	2	3	38.4	
		6 DoF	5	48.6	0.0	6	1	3	0	2	5	37.7	1.9

3 DoF = Translation only; 6 DoF = Translation followed by Rotation.

centres of mass, showing that the amount of rotation is relatively limited. The further comparisons of various strategies for adaptive RT (also based on the use of fiducials for daily positioning according to the tumour motion) were therefore based on translations only [16].

The possibilities for correction of internal organ rotations and the related benefit have been investigated in a few previous studies. Rijkhorst and colleagues [14] investigated the possibilities of correcting for prostate and seminal vesicle rotations around the left-right axis (due to rectum filling variations) through collimator rotation for any beam direction and showed that a perfect correction was only possible for a lateral beam. However, using a Monte Carlo simulation involving sampling of errors throughout treatment for a set of patients in order to calculate dose-population histograms, they found that with their IMRT set-up the effect of the rotations could be accounted for and resulted in a 2 mm reduction in the margins required. A similar correction strategy was proposed by Wu and colleagues [17] in a study of prostate-only treatment; however they limited the collimator rotations to the lateral beams only. A variety of sophisticated methods for on-line IGRT corrections have also been proposed, with approaches ranging from modification of MLC shapes [18], through deformation of beam intensity fluences [19] to full 6 DoF rigid body corrections [20].

The findings of this study imply that the current approach of on-line translational corrections based on fiducial markers in prostate-only IGRT is adequate in most situations. However, when the seminal vesicles are included the likelihood of rotations playing a role increases considerably. Furthermore, irradiation of pelvic lymph nodes is performed for advanced stages of both prostate and bladder cancer. Although the effect of target rotations was found to be small in this study, we expect rotations to play a larger role for the lymph node targets in these patients. A repeat pelvic MRI study is underway at Aarhus University Hospital where the algorithm presented here will be applied to answer this question.

A large reduction in the volume of the target was found when using individually optimised non-isotropic margins (Table III). However, as can be seen in our results, the individual margins required are highly dependent on both the patient and their individual scan. Use of an isotropic margin can reduce the dependence and although that should be safer in terms of target coverage, it will irradiate a larger volume of normal tissue. In a previous study using repeat CT scanning for bladder patients [7], the margins required for all directions were quantified in terms of their size against the percentage of

repeat CTVs that would be covered during their treatment course, allowing for selection of appropriate individual margins.

In conclusion, this study has evaluated translational versus rotational corrections in bladder and prostate IGRT. It was found that translational corrections are by far the most important action with rotational corrections having an impact in only a small fraction of treatment situations, mostly when treating the bladder. The intention is to apply the procedures developed in this work to the acquisition of repeat cone beam CT scans that are now available in both centres.

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