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Original Article

Prostate irradiation in patients with hip prostheses – a retrospective analysis

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Abstract

There are several clinically useful techniques for delivering radical radiotherapy to the prostate. One such beam arrangement is a conformal four-field box technique. Patients who have undergone a total hip replacement have in place a metallic prosthesis, which presents challenges in achieving a homogenous dose distribution. This is due to the increased density of the metal in comparison to bone and soft tissue. The resultant effect is additional attenuation of the X-ray beam as it passes through the prosthesis. The interaction of the photons with the metal also causes increased scatter. Thus, the dose delivered to the tumour is reduced if it is not corrected for. Due to the uncertainty in the amount of attenuation, it is recommended to avoid irradiating through the hip concerned. This means that the four-field box technique cannot be used. Instead, different field arrangements are used such as three or four oblique fields. This is a retrospective investigation into which field arrangement would be the most appropriate for early stage prostate cancer patients. Ten previously treated prostate patients were planned with different beam arrangements avoiding the prosthesis. The results were analysed and are presented with reference to the doses to the organs at risk and the planning target volume. The results indicate that the beam arrangement of choice should be three fields (anterior, posterior and lateral) or a three-field oblique beam arrangement. It has been proved that these plans are acceptable as a solution in this scenario.

Keywords

Hip; prostate; total hip replacement; prosthesis; dosimetry; heterogeneity

INTRODUCTION

Osteoarthritis is a type of degenerative joint disease affecting mostly elderly people.[1] It is mainly implicated by joint stress, the major causes of which are strenuous labour, obesity, previous trauma and athletics. In the UK over 5 million people suffer with pain and disability caused by osteoarthritis.[1] Total hip replacement (THR) is indicated when patients present with discomfort and disability within the hip joint.[2]

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There are currently many different types of prosthetic hip joints available for use within the UK. Murray et al.[3] identified not less than 62 different hip replacement devices, manufactured by 19 different companies. Not only are there different mechanical and dimensional variations, but also variations in composition. The most commonly used metals are titanium, cobalt, chromium, molybdenum alloy and steel. Some are hollow, some are solid. The density of these metals ranges from 4.5 to 8 times that of water.[4]

The American Association of Physicists in Medicine (AAPM) established a task group (TG 63) to address concerns regarding the dosimetric

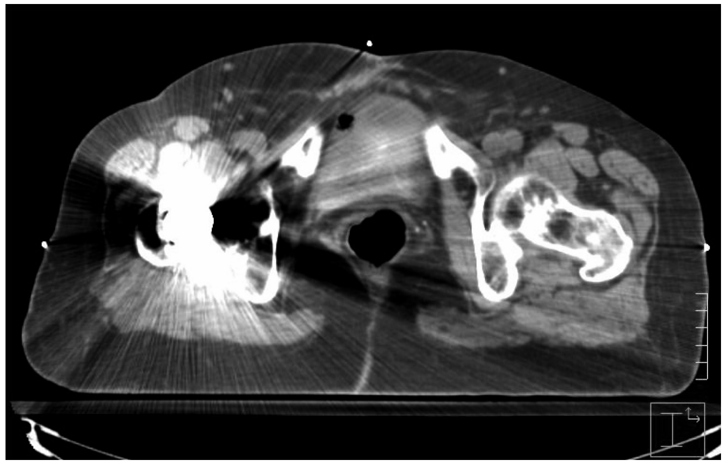

Figure 1. CT Scan of a patient with an artificial hip.

effects of irradiating patients who have in place a metallic prosthesis. They identified that the number of patients with prosthetic devices, which could affect the accuracy of their radiation dosimetry, was between 1 and 4% of the total number of patients.[5] The dosimetric effects of a prosthesis are discussed.

Dosimetric effects of irradiating an artificial hip

Hip replacements cause problems for computerised tomography (CT) planning in several ways.[6] Artefacts on the CT scan cause a loss in image quality. This is illustrated by the streaking effects seen on CT scans of patients with artificial hips (Figure 1). The artefacts are caused by "aliasing".[7] This is the lack of arrival at the detectors of the X-rays as they are absorbed by the prosthesis.

This "starburst" streaking leads to a loss in image detail, making it more difficult to identify anatomy and disease. Clinically, it can become difficult to contour the gross tumour volume (GTV) with confidence. Additionally, the geometry and density of the offending prosthesis cannot be accurately defined due to these artefacts. This prevents any density overrides to allow compensation for the extra attenuation caused by metal.

The presence of a prosthesis also causes a reduction in the accuracy of CT numbers, making any dose calculations based on relative electron density (RED) inaccurate. This is caused by both artefacts degrading the image and because the CT scanner cannot accurately report the density of the prosthesis. The CT scanner is not designed or calibrated to record such high-density metals. The scans become "saturated", white areas seen may not all be of the same CT number but the scanner can no longer report them accurately as they are above the threshold limit. Additionally, uncertainties exist when planning with the dose algorithm's ability to model both the interaction of the metal prosthesis with soft tissue, and in the attenuation of the X-ray beam.[8] Carolan et al.[8] found that "CT images of a phantom containing a hip prosthesis were so degraded by artefacts that no reliable density data could be taken from them for planning purposes". As a result, heterogeneity corrections should not be applied for these patients.

Attempts have been made to apply different image reconstruction methods to CT data sets containing prostheses but as yet no methods are commercially available.[7] If rigorously tested, these reconstructions could offer superior GTV delineation and lead to more accurate density corrections.

Management options

The options for the management of these cases are discussed. Agapito.[6] explained that "the typical

Table 1. Results of different experimental studies

Study	% Dose reduction	Method	Sample size
Agapito et al.[6]	10–55	Review	1
Alecu et al.[18]	55	Measured	1
Burleson et al.[14]	10–15	Measured, in vivo	2
Carolan et al.[8]	52	Measured	2
Ding and Yu[19]	5–25 titanium 10–45 steel alloy	MC/TPS	8
Erlanson et al.[12]	10–40	Measured	1
Hazuka et al.[13]	39	Measured	1
Kung et al.[10]	10–40	Review	3
Roberts[20]	40 steel 22 titanium	Measured	2
Sibata et al.[9]	Up to 50 Co–Cr Alloy 32–64 titanium	Measured	7

MC = Monte Carlo modelling; TPS = treatment planning system.
Note: Phantom studies included.

technique for standard radiotherapy for this site is the four-field "box" which requires two lateral fields that pass through the head and neck of both femurs." In THR patients, this technique for prostate radiotherapy is no longer practical. This is because of the previously identified problems that occur when the radiation interacts with the metallic prosthesis.

The alternative options available are compensation, avoidance of the prosthesis, or intensity modulated radiotherapy (IMRT). In the author's experience, compensation was rejected as it proved to be too complex. Extra dose would be passed through the prosthesis so that the planning target volume (PTV) behind it would still receive an adequate dose. It requires an exact reproduction of patient position both around the PTV, organs at risk (OAR's) and at the prosthesis. This would be both costly and time consuming in terms of planning and set-up; requiring on-line imaging or three-dimensional (3-d) image analysis. The differing alloys and varying size and structure of prosthesis creates further uncertainty. It has been demonstrated experimentally that each prosthesis attenuates the beam in varying amounts. Table 1 illustrates the vast differences in results of experiments attempting to detail attenuation values. Sibata et al.[9] stated that it was "virtually impossible to provide dosimetric information for each individual implant".

Table 1 demonstrates that it is difficult to obtain a reproducible value for the amount of attenuation through a prosthesis. This is because each design of THR has different dimensions and a different metallic composition and density. The positioning of the recording equipment and method of dose detection also plays an important role. If the dose was recorded in an area of rapidly changing dose then the results will be quite varied. The equipment used also varied and its reliability may differ. The studies shown in Table 1 have small sample sizes; larger sample sizes may increase the reliability of the results. These results, confirm the concern expressed by Reft et al.[5] that compensation, would be difficult and potentially hazardous.

Carolan et al.[8] suggested the investigation of using IMRT in conjunction with oblique fields (avoiding the prosthesis). Kung et al.[10] retrospectively planned 3 patients using IMRT. They were treated using six and nine co-planar fields. The beams were positioned to avoid the prosthesis. The doses received by bladder and rectum were reduced. One disadvantage observed during their investigations was that a larger than normally acceptable dose inhomogeneity was observed across the PTV. It ranged from 95% to 115%. This does not fulfil the ICRU 50 recommendations.[11] The time taken to plan and carry out quality assurance (QA) checks on these patients was not mentioned but in terms of resources may be more costly than the avoidance option. However, it may offer superior results in terms of OAR sparing. This retrospective research is welcomed as it is promising for the future as it offers the opportunity to both avoid OAR's, the prosthesis and to adequately treat the PTV. It needs testing in each institution before implementation.

Reft et al.[5] recommended that "the first option to consider when treating a patient with a metal prosthesis is to design a treatment plan with beams that do not pass through the device." Kung et al.[10] highlighted that they were not aware of any published study critiquing the merits of the different beam configurations. This was confirmed[5] because "no general consensus on how to manage the treatment of these cases was observed." This forms the basis of the current study.

The alternative beam arrangements were discussed by Erlanson et al.[12] who concluded that: "the most simple and possibly the safest way to avoid the dose distortions would be to use techniques not including prosthesis by using isocentric three- or four-field techniques." Hazuka et al.[13] suggested reducing the lateral field weights and to use oblique fields in "extreme" cases. Burleson et al.[14] advised that tumour under dose can be prevented "by using an oblique four-port technique". Carolan et al.[8] also suggested that oblique fields could be used, but warned that this leads to an increased rectal and bladder dose. Other alternatives include bilateral arcs or increasing the weighting of the anterior and posterior beams with the standard four-port pelvic technique while decreasing the lateral contribution.[13] Eng[15] proposed a six-field conformal technique with high energy beams, or increased ant and post weights on a box technique or four-field obliques. In the author's opinion, it is preferable to avoid irradiating through a prosthesis at all, even with a low-weighted beam. The plan should represent as closely as possible, the actual situation, particularly when considering doses to OAR's. The situation is increasingly difficult when the patient has two artificial hips because neither right nor left lateral fields can be used; this further limits the options available.

These suggestions mean that many combinations of fields could be used (to avoid the hip). This reflects the author's current clinical practice. Several alternative beam arrangements are trialled and the best is selected. Reft et al.[5] did offer alternative beam arrangements similar to those discussed above but they did not propose in further detail, an optimum technique. Instead, they suggested that an optimal plan would depend on the individual anatomy and the extent and location of the disease. However, if there was just one-stage and one-disease site (i.e., early stage prostate cancer) would an optimum plan exist?

The principal aim of this study was to identify if an optimum beam arrangement exists to enable accurate and safe delivery of radiotherapy to patients who have undergone THR. A suitable technique should be both affordable and achievable with the resources currently available.

METHOD

A retrospective experimental investigation was used. The different interventions were the different field arrangements. Ten early stage prostate cancer (<T3) patients were randomly selected. They were from a selection planned by several consultants. They had been previously CT planned in the preceding month. They did not have artificial hips. Retrospective planning enabled the plans to be produced without the problems of artefacts and loss of detail in the CT data caused by metallic prostheses. The hips, PTV and OAR's were outlined and the Beam's eye view (BEV) facility enabled the author to verify that the hip to be avoided was outside the radiation portal. It was acknowledged that the outline of the real hip would vary from that of a prosthesis. If the results suggest an optimum technique, this could be further tested on patients with artificial hips to see if the results were in agreement. The names of the patients and the clinicians treating them were removed from the plans to protect the patient's identity. The local ethics committee were consulted who deemed full ethical approval unnecessary. The planning part of this study was conducted over a period of 2 months. The overall time to plan the patients was 4 h per patient and therefore 40 h in total.

Dose values collected were the minimum (to 1% volume), maximum (99% volume), and mean dose and the standard deviation values for PTV, rectum, bladder and contra-lateral hip. Additionally, the V95 for rectum and bladder and the V50 for contra-lateral hip were recorded. These values were selected to enable comparison with previously conducted studies, in particular that of Fiorino et al.[16]

Contouring protocol

CT slices were at 5 mm intervals. This was the clinical standard at the author's centre for pelvis planning and provides adequate information for both planning and digitally reconstructed radiograph (DRR) viewing. The OAR's of concern were the rectum and bladder and femoral head. Contouring of OAR's was undertaken by treatment planning radiographers. The anatomical limits for the rectum were the rectum-sigmoid colon junction superiorly and inferiorly approximately 20 mm inferior to the apex of the prostate. This was in agreement with Fiorino et al.[16] The whole bladder was contoured. In the author's department,

Table 2. *A summary of the different beam arrangements*

Plan name	Technique	Number of beams	Example gantry angles
Final	4 field box	4	0, 180, 270, 90
3FAPL	3 field ant, post and lateral	3	0, 180, 90
3FOBS	3 field oblique	3	30, 150, 270
4FDIA	4 field diamond	4	340, 50, 130, 210
4FOBS	4 field oblique	4	0, 90, 180, 210

patients are asked to empty their bladders before treatment and prior to a planning CT scan. It is acknowledged that this does increase bladder dose but the rationale for this is a stable and reproducible bladder volume. Additionally, both femurs were contoured. The femurs were outlined, from the superior margin of the femoral head to the shaft of the femur, until the inferior end of the CT data set. One hip was randomly selected as the artificial hip (and avoided by the beam). The other was used to provide dose volume information for plan evaluation.

The clinical target volume (CTV) was contoured by the radiation oncologist. The CTV was then expanded by 1 cm superiorly, inferiorly, anteriorly, and laterally and 0.7 cm posteriorly. This takes into account set up errors both random and systematic and CTV movement due to internal organ motion, as per department protocol. 0.7 cm is chosen posteriorly to reduce the rectal dose. These values were determined by the clinicians.

Beam arrangement

Each patient had four different plan combinations plus the control. The control was the original clinically used plan (the four-field box). This plan is referred to as final. The additional plans are described. Table 2 summarises the different field arrangements.

Three-field anterior, posterior and lateral fields

Three fields enter at a gantry angle of 0, 180 and 90 (or 270) degrees. This avoids the prosthesis and attempts to keep a flat edge at the posterior part of the PTV to shield the rectum. The contra-lateral hip dose should be observed as it can increase. This plan is referred to as 3FAPL.

Three-field oblique

Fields enter the patient as obliquely as possible, ensuring that they do not pass through the prosthesis. For a prosthesis on the left side, the gantry angles are approximately 30, 150, and 270 degrees. This plan is referred to as 3FOBS.

Four-field diamond

The beams enter the patient 90 degrees apart to form a diamond shape. However, this is modified to avoid the prosthesis. This arrangement typically gives rise to a diamond shaped high-dose region which can lead to a pointed region of the rectum getting a high-dose. This plan is referred to as 4FDIA.

Four-field oblique

The four-field oblique is a combination of the three-field arrangements but with an extra field. The fields avoid the prosthesis and are arranged to obtain the best dose distribution possible. This plan is referred to as 4FOBS.

Planning

The planning process is outlined. Co-planar planning was utilised for simplicity and to match current clinical practice in the author's department. Additionally, heterogeneity correction was not applied. Energy was either 8 or 18 MV. This was randomly allocated, to identify if the energy affected the dose to OAR's. Conformal plans were produced by using 1 cm multi-leaf collimators (MLC). A penumbra margin of 7 mm was used for 18 MV and 6 mm for 8 MV. This is the margin from the PTV edge to the MLC leaf edge. The MLC leaves are automatically placed by the treatment planning system (TPS) but were individually moved as required to obtain an optimum plan. To obtain an optimum plan, the following variables were adjusted; beam weightings, wedges, MLC leaves, jaws, gantry angles.

The TPS used is Pinnacle[3] (Philips Medical Systems, Andover, MA). The 3-d dose algorithm used for routine pelvis plans is adaptive convolution superposition. However, heterogeneity corrections were not applied as if metallic prostheses were in place. This is due to reasons discussed earlier and as discussed by Carolan et al.[8] The dose distribution

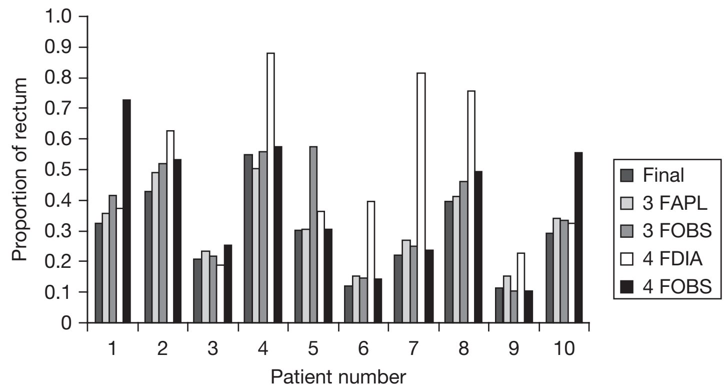

Figure 2. Graph to show V95 for Rectum. Results are shown as proportion of the rectal volume.

was normalised to the isocentre and the reference dose was 95% of the isocentre dose. DVH's were produced of OAR's (bladder, rectum and contra lateral femoral head) and PTV. Plans were evaluated using DVH's. They were then compared.

Statistics

The results were statistically analysed using the Paired T Test[17] to identify if the sample represented the population. The paired T test can be used in small sample sizes[17] which helped to decide whether a mean is representative of the population. This enabled a comparison of the doses received to each OAR for each different plan. If the mean of each set of plans (for the ten patients) is different to the final (four-field box) plan, the T test identifies the significance.

RESULTS

The results are presented in sections with regards to the contours.

Dose to the PTV

In 96% of plans, the minimum dose to the PTV was 95% (of the isocentre dose). In all plans it was greater than 94.8%, the mean dose was approximately 99% and the maximum dose was less than 103%. This matches the results presented by Fiorino et al.,[16] who achieved mean doses of around 98–100%, and a similar 95% coverage. It also achieves the ICRU 50 recommendations.[11] This means that the PTV was adequately covered in all the plans.

Dose to the rectum

The results are compared by considering the mean dose and the proportion of the rectum receiving 95% (V95), see Figure 2. This is the proportion of rectum receiving 47.5 Gy or more. This follows other plan comparison studies.[16]

When analysing the data, the plan with lower dose to the rectum in seven out of ten cases was the final plan. The plan delivering the lowest dose to the rectum *and* avoiding the site of the THR was the 3FAPL ($p = 0.023$). It gave the lowest or second lowest rectal dose in five out of ten cases. The 3FOBS plan ($p = 0.038$) was in first to third best place in 80% of patients.

When considering mean dose (Figure 3), the plan with the lowest mean dose is the final plan, but the second lowest mean dose is delivered by the 3FOBS plan ($p = 0.030$), followed by the 3FAPL ($p \leq 0.001$).

Dose to the bladder

The results for the bladder doses are presented in a similar way to those for the rectum. Firstly, the V95 is presented (Figure 4). The results for V95 of the bladder show that the four-field diamond is not significantly better or worse than the final plan. The 3FAPL plan delivers a higher dose to the bladder ($p = 0.020$). This is because there are only three beams, and one beam enters through the bladder. One-third of the dose is delivered

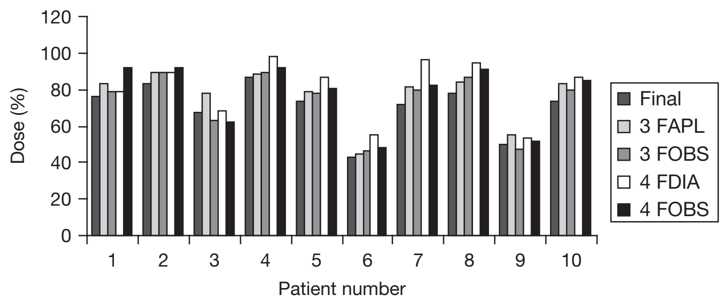

Figure 3. *Graph to show mean dose to the rectum dose is displayed as a percentage of the dose to the isocentre.*

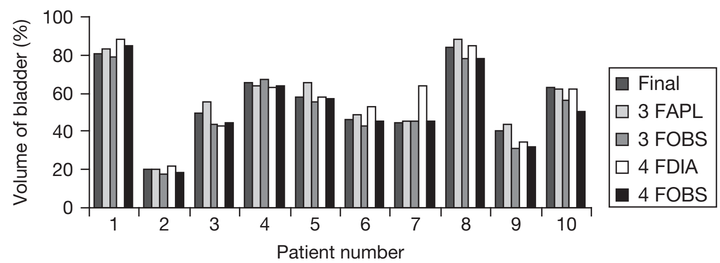

Figure 4. *Graph of V95 for bladder.*

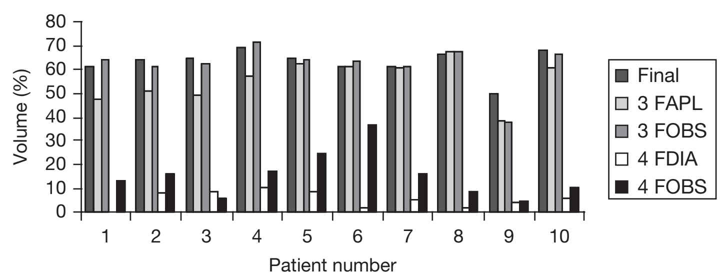

Figure 5. *V50% for the contra-lateral hip.*

Table 3. *Mean dose to bladder (%)*

Patient	Final	3FAPL	3FOBS	4FDIA	4FOBS
Mean values for bladder (%)					
1	95.4	96.5	95.3	96.6	97.4
2	55.6	59.6	52.0	52.0	60.4
3	83.9	89.5	80.5	82.5	81.0
4	90.8	90.7	92.6	91.1	91.2
5	87.0	91.7	88.1	88.5	86.5
6	85.1	88.9	83.4	89.6	86.2
7	78.4	84.6	83.6	92.1	82.6
8	96.9	97.8	96.2	97.3	96.0
9	80.2	84.7	74.8	76.2	79.2
10	89.5	91.2	87.0	90.5	86.1
Mean	84.3	87.5	83.4	85.6	84.7
T-test		0.001	0.358	0.416	0.677

through the bladder as opposed to one-quarter in the original (final) plan. The 3FOBS plan delivered a lower dose to the bladder (p = 0.004) this is because its beam arrangement avoided entering through the bladder. The same is true (only less significant p=0.030) for the 4FOBS plans. For the mean dose to the bladder (Table 3), the 4FOBS, 4FDIA and 3FOBS did not show any significant difference. The 3FAPL delivered a higher mean dose to the bladder (p = 0.001). This confirms the results for the V95.

In summary, the order of preference when considering the bladder dose (V95) is firstly 3FOBL, and secondly 4FOBS. The mean dose does not provide any conclusive results for which plan is best, but the 3FAPL is the worst plan as it had the highest mean dose to the bladder.

Dose to the contra-lateral hip

The contra-lateral hip dose is discussed (Figure 5). As mentioned previously, the V50 is quoted as the hip is outside the high dose volume, making a V95 value meaningless. It is chosen as a suitable alternative and matches the plan analysis study done by Fiorino et al.[16]

The graph of V50 for the contra-lateral hip (Figure 5) illustrates that in all cases, a four field approach gives a significantly lower dose to the femoral head. The mean doses were also lower for the four-field plans ($p < 0.001$ for both). This is because in the four-field plans, only one out of four beams or parts of two beams passes through the contra-lateral femoral head.

The V50 for the final plan was 62.9%. The 3FAPL was 55.5% ($p = 0.005$). The 3FAPL has a lower dose as there is no dose contribution from an exit dose from any beams coming from the opposite side of the patient. When considering the contra-lateral hip dose, a four-field plan gives the lowest dose to the hip. However, it can be observed that none of the plans give a notably worse plan than the clinically used 4 field box plans.

Energy

Another issue to be considered is that of energy. Some of the patients were planned at 8 MV, and some at 18 MV. Patients 1–4 and 9 were planned at 18 MV. The others were planned at 8 MV. No significant effect on the dose to the rectum or bladder was identified. However, for the femoral head, the differences were not significant except for the 3FAPL plan, for which 18 MV gave a lower dose to the hip. The V50 for 18 MV for the hip was 48.6% compared to 62.4% for 8 MV.

DISCUSSION

The study and literature review demonstrate that there are many options available when planning a patient with an artificial hip. The simplest method identified was to avoid irradiating through the metallic device. In this section the findings and limitations are discussed in relation to the literature.

Using plans in patients without artefacts caused by a prostheses, made it possible to identify the structures for contouring more precisely. However, heterogeneity correction could still not be applied as this would not be possible when a prosthesis was in situ.[5]

In this investigation, the optimal beam arrangements identified were the 3FOBS and the 3FAPL. The 3FAPL gave the lowest V95 dose to the rectum and the 3FOBL offered the lowest dose (V95 and mean dose) to the bladder and the lowest mean dose to the rectum. Therefore the 3FOBL plan is suggested. However, the clinical relevance of V95 and mean dose with regards to toxicity is still uncertain. When the femoral head is considered, all of the plans gave a lower dose in terms of V50 than the 4f box. If the 3FAPL arrangement is applied then it is recommended to use a higher energy where available to reduce as far as possible the dose to the femoral head. Agapito[6] compared different plans for just one patient. He reported similar results and commented that the use of a lateral beam enables sparing of the rectum. Plans with five or more field numbers were not investigated as current practice at the author's centre does not use these plans. However, if IMRT were to be implemented for these patients, an increase in fields would be adopted as for conventional prostate IMRT.

It is acknowledged that in this report, the dose to the PTV was hypofractionated at 50 Gy in 16 fractions. Doses are presented in percentage of dose to the isocentre. Comparisons in terms of tolerance to OAR's with other studies are limited. However, the principle in all cases is to minimise the volumes of normal tissue receiving a high dose.

Figures 2 and 4 show the V95 for the rectum and bladder. It must be recognised that using DVH's has a limited role in that the structures of the bladder and rectum are either hollow or filled organs and as such it is the dose to the mucosa that is of primary concern. The DVH serves merely as an illustrative guide to enable volume comparison on a snapshot image. The use of 3-d imaging studies during a course of radiotherapy will further guide us with regards to organ motion. Dose wall histograms do identify the dose to the walls of structures but they are still only an illustrative guide due to being derived from one set of images. Agapito[6] identified that using the two different methods of dose volume evaluation provided different results. Therefore, each should be tested with caution before adapting current practice. Another consideration should be that of normal tissue complication probabilities (NTCP). There should be consideration of all the OAR's together with a weighting for each organ's relative susceptibility based on dose and volume. This is beyond the scope of this article. Here the aim was to limit the high-dose volume as far as possible in all cases.

In the author's clinical setting, patients are requested to empty their bladders when undergoing prostate radiotherapy. The rationale for this has been explained in the contouring protocol section. This will provide higher values for the DVH to bladder; this is because the overall volume of the bladder is smaller. When comparing results between studies,[6] the three-field oblique plan gave the lowest dose to the bladder in both empty and full situations.

It has been shown in other studies that the use of IMRT can reduce normal tissue toxicity.[10] This is welcomed and the author intends to investigate this clinically. The implications are an increase in planning resources but the number of patients is fairly small. Reft et al.[5] quoted the number in the US as 1–4% of radiotherapy patients.

Recommendations

Further work should include a feasibility study on the use of IMRT to improve conformality of the high-dose region to the PTV and to avoid the OAR's.

The ability of CT scanners to accurately record the CT number for metals used in a prosthesis needs to be developed. Additionally, artefact smoothing algorithms should be developed to enable heterogeneity corrections to be used where appropriate. This correction should be done with the use of Monte Carlo modelling techniques which have been shown to provide superior dose distribution information, particularly at areas of complex interaction such as the prosthesis–tissue interface.[7]

Patients with bi-lateral hip replacements further reduce the options for beam entry points. Avoidance of the prostheses is difficult and IMRT for this group of patients would help to reduce normal tissue toxicity.

CONCLUSION

Avoiding the prosthesis as opposed to IMRT and compensation has been shown by this study to be a viable option. The plans were produced within an acceptable time frame and could be delivered within the time scale available when planning patients. However, sometimes the different beam arrangements have provided inferior results compared with the original beam arrangement. This could be improved by using IMRT. Currently IMRT is being used clinically for prostate patients in dose escalation studies. IMRT which avoids the prosthesis is one area where IMRT is beginning to be utilised to produce an optimised plan which also avoids the prosthesis.

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