Phys. Med. Biol. **52** (2007) 2147–2156 doi:10.1088/0031-9155/52/8/007

A feasibility study of using conventional jaws to deliver IMRT plans in the treatment of prostate cancer*

Yongbok Kim, Lynn J Verhey and Ping Xia

Department of Radiation Oncology, University of California, San Francisco, Comprehensive Cancer Center, 1600 Divisadero Street, Suite H1031, San Francisco, CA 94143-1708, USA

E-mail: PXia@radonc.ucsf.edu

Received 11 December 2006, in final form 1 February 2007
Published 27 March 2007
Online at stacks.iop.org/PMB/52/2147

Abstract
The aim of this study is to investigate the feasibility of using conventional jaws to deliver inverse planned intensity-modulated radiotherapy (IMRT) plans for patients with prostate cancer. For ten patients, each had one three-dimensional conformal plan (3D plan) and seven inverse IMRT plans using direct aperture optimization. For IMRT plans using conventional jaws (JO plans), the number of apertures per beam angle was set from two to seven while three apertures per beam angle were set for the multi-leaf collimator (MLC) plans. To evaluate each planning method, we compared average dose volume histograms (DVH), the conformal index (COIN), total number of segments and total number of monitor units. Among the JO plans with the number of apertures per beam angle varying from two to seven, no difference was observed in the average DVHs, and the plan conformal index became saturated after four apertures per beam angle. Subsequently, JO plans with four apertures per beam angle (JO-4A) were compared with 3D and MLC plans. Based on the average DVHs, no difference was found among 3D, JO-4A and MLC plans with regard to the planning target volume and rectum, but the DVHs for the bladder and penile bulb were significantly better with inverse IMRT plans than those with 3D plans. When compared with the plan conformity, the average COIN values for 3D, JO-4A and MLC plans were 0.61 ± 0.07, 0.73 ± 0.05 and 0.83 ± 0.05, respectively. In conclusion, inverse IMRT plans using conventional jaws are clinically feasible, achieving better plan quality than 3D-CRT plans.

(Some figures in this article are in colour only in the electronic version)

* The abstract was presented at the 48th Annual Meeting of the AAPM (American Association of Physicists in Medicine) in Orlando, FL, July 2006.

1. Introduction

Although intensity-modulated radiotherapy (IMRT) has been widely implemented and has become a mature treatment modality for many well-equipped medical centres, many radiation therapy centres worldwide still use cobalt-60 machines or early versions of linear accelerators without multi-leaf collimators (MLC) (Webb 2002, Webb *et al* 2003, Anderson *et al* 2006a, 2006b). For these centres, a simple collimator with conventional jaws (or independent jaws) would be much more affordable and easier to maintain. With conventional jaws, Dai and Hu (1999) demonstrated that IMRT plans can be delivered using the step and shoot delivery method with a significant increase in treatment times. For the three selected clinical cases of the breast, the prostate and the nasopharynx, they estimated that the delivery time could be about four to seven times longer than the delivery time using modern multi-leaf collimators. The purpose of the study was to investigate whether it is possible to reduce delivery time while using conventional jaws to deliver IMRT plans.

The intensity patterns used in Dai and Hu's study (1999) were generated through the traditional two-step optimization process, in which the optimizer did not consider the constraints of the delivery systems during optimization and then a leaf sequencer decomposed the ideal intensity patterns into deliverable MLC shapes while considering those constraints. Recently, Shepard *et al* (2002) and others (Bedford and Webb 2006) proposed to use a one-step optimization by directly optimizing MLC shapes and weightings while considering constraints of the delivery systems and user-defined complexity of intensity modulation, referred to as direct aperture optimization (DAO). They demonstrated that this one-step optimization method resulted in a significant reduction of the number of beam segments and the number of monitor units while maintaining the full dosimetric benefits of IMRT. The DAO algorithm was implemented in a commercial planning system (Prowess Inc., Chico, CA), capable of using either MLCs or conventional jaws for IMRT delivery. A similar yet different one-step optimization has also been implemented in another commercial treatment planning system (Pinnacle, Philips Medical Systems), referred to as the direct machine parameter optimization (DMPO).

The purpose of this study is to investigate whether it is feasible to use one-step optimization methods to reduce delivery time for IMRT plans using conventional jaws. Our approach is different from Dai and Hu's approach (1999) since they attempted to use the conventional jaws to deliver intensity patterns without considering the special limitation of the conventional jaws during optimization. Using the DAO optimization method implemented in a commercial planning system, the optimizer in our approach directly produces apertures using conventional jaws with optimized weighting factors. Therefore, we hypothesized that the delivery time for an IMRT plan using conventional jaws may be significantly reduced with the DAO optimization. In this paper, we conducted a planning study for ten patients with prostate cancer. For each patient, eight plans were generated using conventional jaws and MLC with inverse planning techniques and the conventional 3D conformal planning technique.

2. Methods and materials

Ten patients (later referred to as patients A to J) with prostate cancer were randomly selected for this study. The clinical plans for these patients were generated with a total number of segments set to 25 and a seven beam angle arrangement (a planning protocol developed in our institution (Xia *et al* 2001)), delivered with Siemens linear accelerators with MLCs.

2.1. Treatment planning

For each patient, eight plans were generated using Prowess Panther^{TM} 4.21, including a conventional three-dimensional conformal plan (3D plan), and seven inverse DAO IMRT plans using either conventional jaw-only (JO plan) or multi-leaf collimator (MLC plan). The planning goal was to deliver 72 Gy to $\geqslant$95% of the planning target volume (PTV) while keeping 10% of the rectum and 15% of the bladder receiving $\leqslant$60 Gy and mean dose of the penile bulb $\leqslant$30 Gy. The maximum point dose to the PTV was limited to $\leqslant$82.8 Gy (115% of the prescribed dose).

For all patients, a set of clinical beam angles (0°, 55°, 90°, 135°, 225°, 270° and 305°, IEC convention) was used for all plans with 6 MV photon energy (Primus, Siemens Medical Solutions, Concord, CA). For 3D plans, nine apertures were manually designed, with one aperture for each beam angle except for the two posterior oblique beam angles, which used two apertures per beam angle to protect the rectum. The beam weights for each aperture in the 3D plans were manually adjusted. For IMRT plans using either JO or MLC, a set of planning dose constraints was adjusted for each patient until the plan met the planning goals. The same dose constraints were used subsequently for both JO and MLC plans. Three apertures per beam angle were set for all MLC plans based on the clinical experience for IMRT plans using MLC (about 25 segments) for prostate cancer treatment. Because of limited degrees of freedom in the conventional jaw when compared to MLC, six different numbers of apertures per beam angle were set, from two to seven, to determine the optimal number of apertures for the JO plans.

2.2. Plan evaluation

All plans were evaluated based on plan quality and delivery efficiency. The plan quality was measured by (i) whether or not they met the treatment planning goals (described above) and (ii) the dose conformity index (COIN). The plan delivery efficiency was measured by the total number of segments and the total MUs per fraction. The dose conformity index proposed by Baltas *et al* (1998) was calculated using the following equation:

$$\mathrm{COIN} = c_1 \times c_2 \qquad \text{where} \qquad c_1 = \mathrm{PTV_{ref}}/\mathrm{PTV}\; c_2 = \mathrm{PTV_{ref}}/V_{\mathrm{ref}}. \quad (1)$$

$\mathrm{PTV_{ref}}$ is the fraction of the PTV that is enclosed by the prescribed isodose line of 72 Gy and V_{ref} is the tissue volume that is enclosed by the prescribed isodose line. The ideal case is for both c_1 and c_2 to be equal to 1.

We first compared JO plans with six different numbers of apertures per beam angle, determining the best number of apertures' setting and choosing this for JO plans for subsequent plan comparisons. After choosing the best JO plan setting for each patient, we compared 3D plans, JO plans and MLC plans, using the above-defined endpoints as well as group average cumulative dose volume histograms (DVH) of the PTV, the rectum, bladder and penile bulb. To obtain the group average DVH, dose bins of each DVH were rebinned with the same bin size for a group of patients; thus dose in each bin was summed up for ten patients and divided by the total number of patients.

2.3. Delivery efficiency

Treatment delivery efficiency for IMRT plans depends on the delivery method employed by each specific manufactured linear accelerator. Our centre is equipped with six Siemens linear accelerators, and thus the delivery efficiency is based on this type of linear accelerator. With its auto-sequencing delivery system, Siemens' linear accelerators can automatically deliver

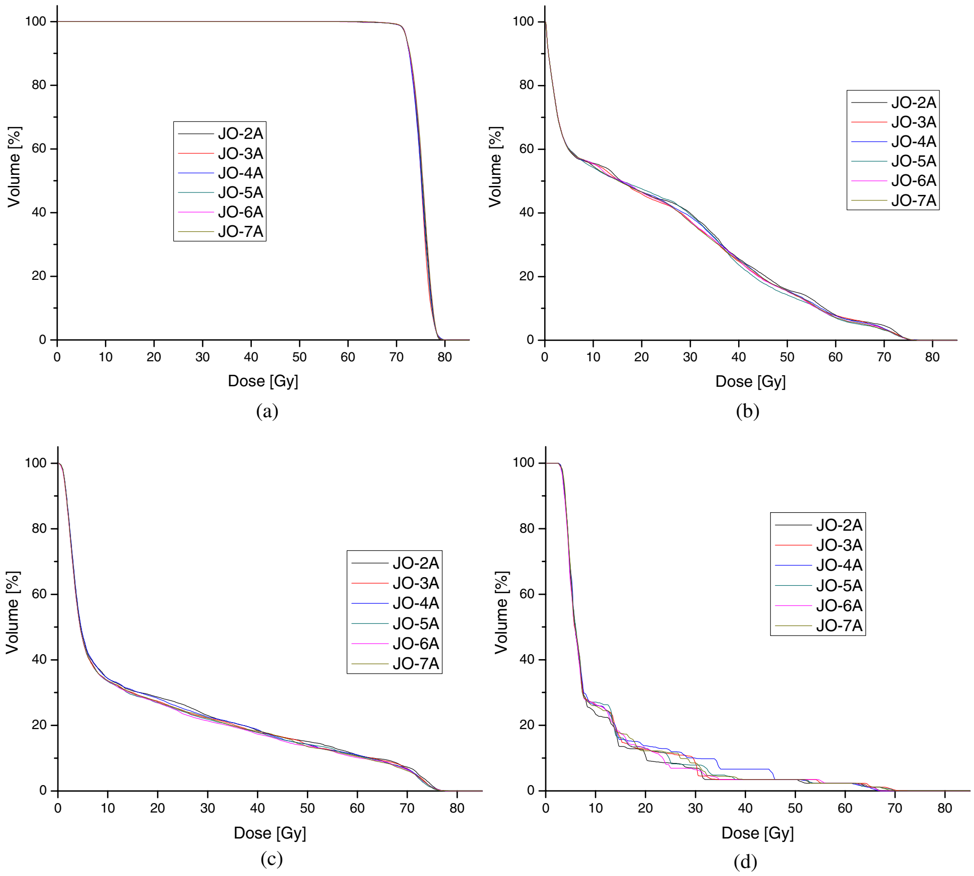

Figure 1. A comparison of average DVHs (from ten patients) between six different JO plans using various numbers of apertures per beam angle (from two to seven) for (a) PTV, (b) rectum, (c) bladder and (d) penile bulb.

non-IMRT plans from one gantry angle to another without human intervention. It takes about 12 s from the beam-off of the current gantry angle to the beam-on of the next gantry angle. For IMRT delivery, this type of linear accelerator supports step and shoot delivery, in which the conventional jaws (Y jaws) conform to the shape of each segment to minimize radiation leakage through the MLC leaves. Because the MLC is static, the radiation pause time between segments is about 4 s with the newest delivery software. Based on these delivery parameters, the delivery time was estimated as

$$\text{Time (seconds)} = (\text{Ng} - 1) \times 12 + (\text{Ns} - \text{Ng}) \times 4 + (\text{MU}_\text{T}/300\,\text{MU/min}) \times 60, \qquad (2)$$

where Ng is the total number of gantry angles used for the plan, Ns is the total number of segments and MU_T is the total number of MUs. 300 MU/min is the dose rate for 6 MV photons.

3. Results

3.1. Plan acceptance based on treatment goals

The mean value of the PTV is 57.3 ± 15.0 cc with a minimum of 38.0 cc to a maximum of 89.3 cc. Seven out of ten 3D plans met the planning goals. Two 3D plans (for patients D

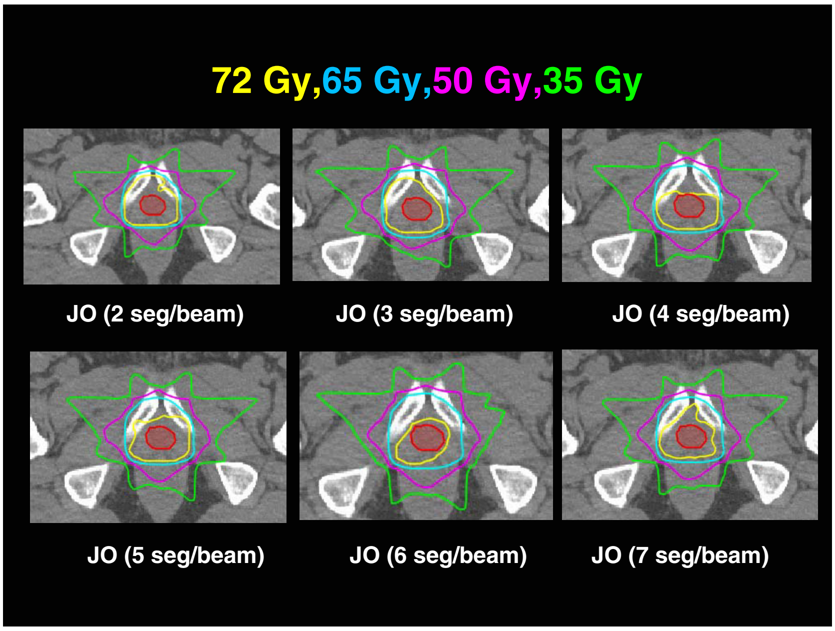

Figure 2. Dose distributions from jaw-only plans with two to seven apertures per beam angle, displayed in an axial image of a selected patient. The red line and red colour shade represent the prostate contour.

and H) slightly exceeded the mean dose criterion of a penile bulb (⩽30 Gy), 30.11 Gy for patient D and 30.94 Gy for patient H. One 3D plan (for patient F) exceeded the bladder dose criterion (D15% ⩽60 Gy), with D15% = 63.9 Gy. Although a set of patient-specific dose constraints must be carefully adjusted, all IMRT plans using the conventional jaws or MLC met the planning goals.

3.2. Comparison of JO plans

The number of the apertures per beam angle was a parameter set by the planner, and the inverse planning system considered this number as the maximum number of apertures permitted for each beam. While setting two to seven apertures per beam angle, the resultant average numbers (± standard deviations) of apertures per beam angle for JO IMRT plans were 1.9 ± 0.14, 2.7 ± 0.21, 3.6 ± 0.28, 4.4 ± 0.6, 5.3 ± 0.46 and 6.1 ± 0.82, respectively.

Figures 1(a)–(d) show the group average DVHs for the ten patients using the conventional jaws as a delivery hardware with six different numbers of apertures per beam angle (from two to seven), respectively. As shown in figures 1(a)–(d), the mean DVHs were almost identical for the PTV, rectum, bladder and bulb of penis. Figure 2 shows dose distributions of an axial image for a selected patient, planned with two to seven apertures per beam angle. As one can see from figure 2 and more quantitatively in figure 3(a), although the DVHs of these JO plans were similar, the values of COIN, a conformal index of the plan, were different. The mean value of the COIN was gradually improved from 0.67, 0.71, 0.73, 0.74, 0.76 to 0.76 as the number of apertures per beam angle increased (from two to seven), but became rather flat after four apertures per beam. In the meantime, however, the average MUs per fraction also gradually increased (from 491, 542, 537, 557, 571 to 569) as the number of apertures per beam angle increased (from two to seven) (shown in figure 3(b)). When comparing among these

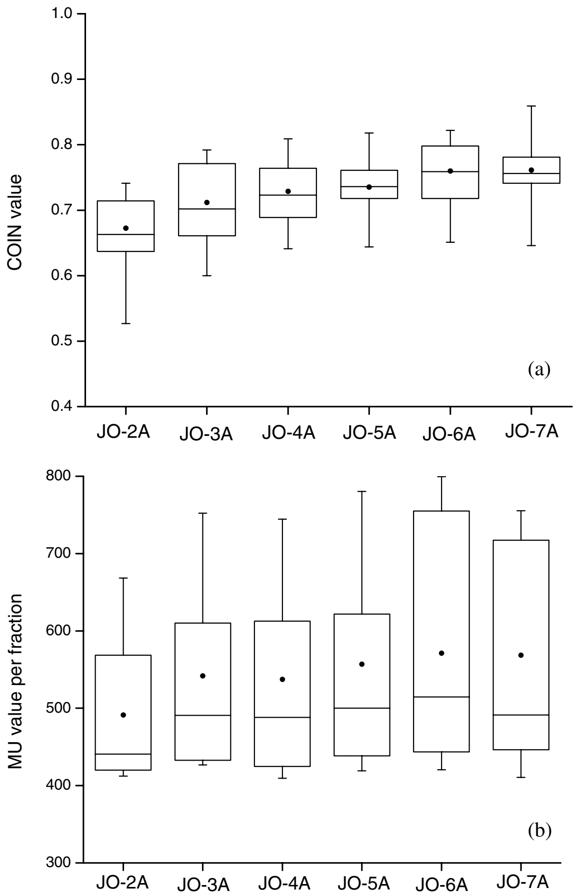

Figure 3. A comparison of (a) COIN and (b) MU value per fraction between six JO plans using different numbers of apertures per beam angle (from two to six) for ten patients. Each parallel bar in the box graph represents minimum, 25, 50, 75 percentiles and maximum values in order, and the dot inside the box is the mean value.

six different JO plans with respect to the total number of segments, MUs for each fraction and the COIN values, we decided that JO plans with four apertures per beam angle (JO-4A plans) were the best compromise plans, balancing good plan conformity and efficient delivery parameters.

3.3. Comparison of 3D, JO-4A and MLC plans

For a selected patient, figures 4(a) and (b) show dose distributions from 3D, JO-4A and MLC plans, displayed in two axial images. Figures 5(a)–(d) show comparisons of the group average DVHs among ten patients for 3D, JO-4A and MLC plans for the PTV, rectum, bladder and bulb of penis, respectively. As shown in figure 5(a), the DVHs of the PTV for 3D, JO-4A and MLC plans were nearly superimposed on each other. The DVHs for the rectum were also very similar among these three types of plans. The DVHs of the bladder with JO and MLC plans were better than those of the 3D plans. A similar trend was also observed for the DVHs of the penile bulb. When compared with the plan conformity, the average ($\pm$ standard deviation) COIN values for 3D, JO-4A and MLC plans were 0.61 ± 0.07, 0.73 ± 0.05 and $0.83 \pm$

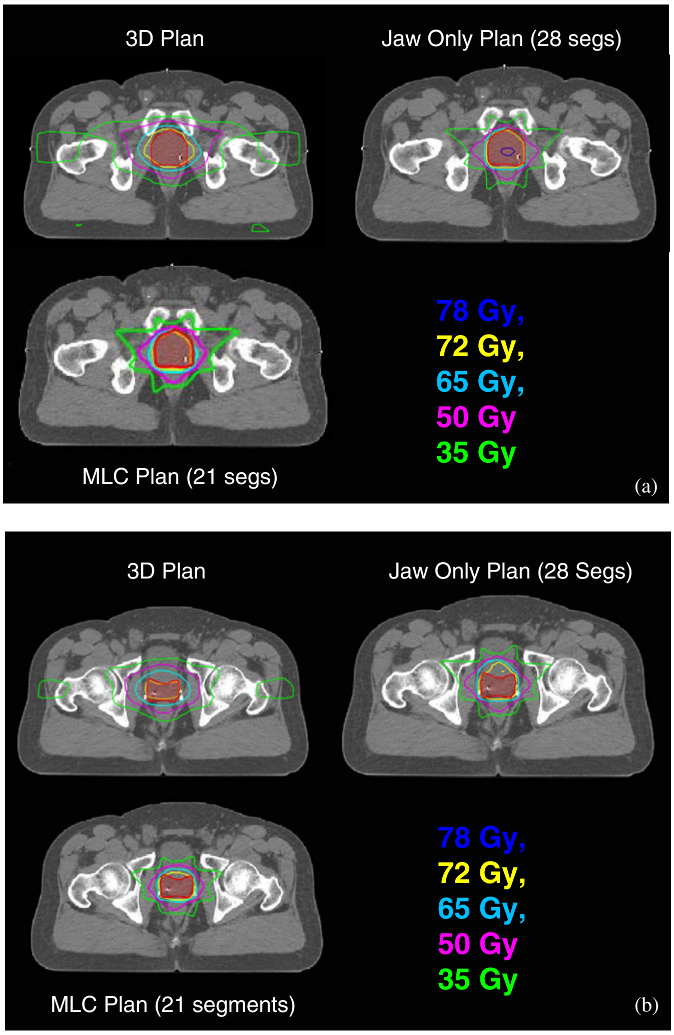

Figure 4. Dose distributions from 3D, JO-4A and MLC plans, displayed in two axial images (a) and (b) for a selected patient. The red line and red colour shade represent the prostate contour.

0.05, respectively. As shown in figure 6(a), the MLC plans achieved the highest conformity with the smallest standard deviation. On the other hand, conformity of the JO-4A plans was significantly better than the 3D plans ($p = 0.002$ using Wilcoxon matched-pairs signed-ranks test).

3.4. Delivery efficiency

Figure 6(b) plots the average MUs per fraction for the 3D, JO-4A and MLC plans. The average delivered MUs per fraction of JO-4A plans (537 MUs) was significantly higher than that of the 3D plans (378 MUs) ($p = 0.002$ using Wilcoxon matched-pairs signed-ranks test) and it was insignificantly different from that of the MLC plans (472 MUs) ($p = 0.1309$). Using equation (2), the estimated average delivery time is 2.6 ± 0.1 min, 4.4 ± 0.5 min and $3.7 \pm$

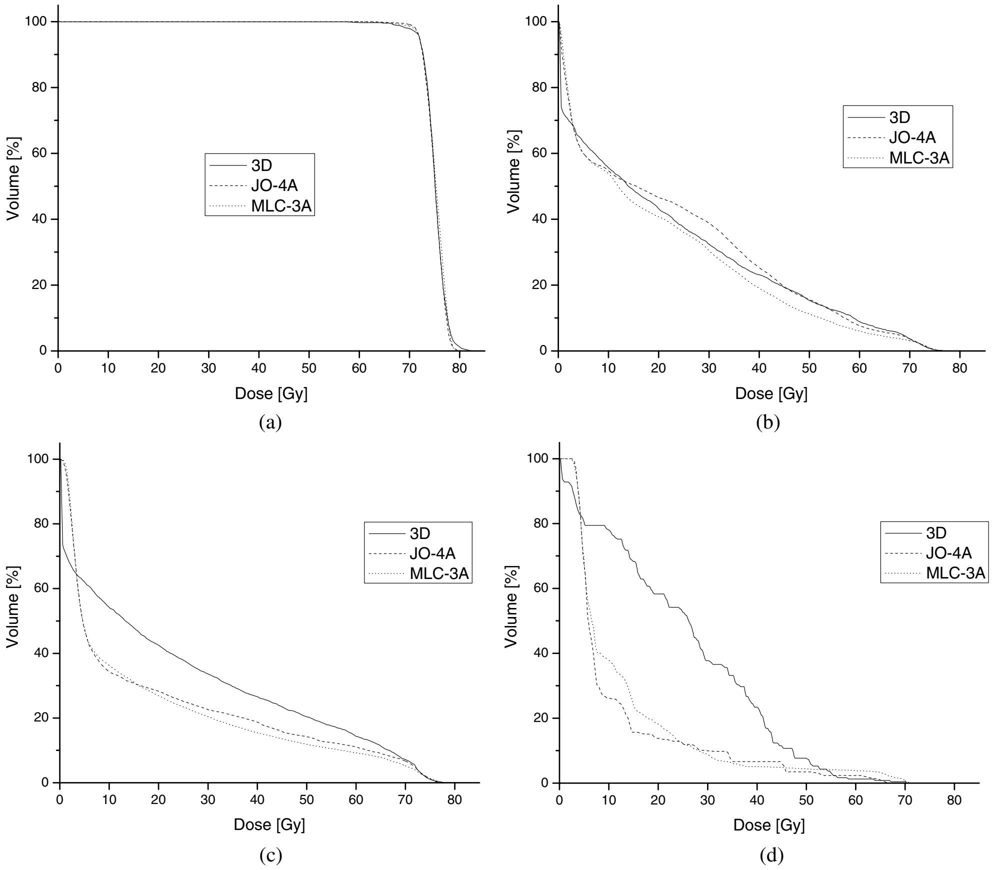

Figure 5. A comparison of group average DVHs (from ten patients) between three plans (3D, JO-4A and MLC-3A plan) for (a) PTV, (b) rectum, (c) bladder and (d) penile bulb.

0.1 min for 3D, JO-4A and MLC plans, respectively, as shown in figure 7. In fact, the delivery time for 3D plans could be even longer than the estimated time if dynamic wedges were used for some fields, or cut blocks were used for the treatment.

4. Discussion and conclusions

It has been generally believed that MLC is essential for IMRT delivery. On the other hand, the designs of MLCs are initially intended for replacement of cerrobend blocks although later designed MLCs, especially dynamic MLCs, are intended for IMRT delivery. The fundamentals of IMRT collimators have been systematically investigated by Webb and his colleagues (Anderson *et al* 2006a, 2006b) with ten collimator models, among which conventional jaws were considered as the simplest collimator and MLCs were considered as the most complicated collimator. As they pointed out, one advantage of considering simple collimators was to provide a greater insight into the fundamentals of IMRT collimation, and to design more efficient collimators of interest in all IMRT treatment centres (Anderson *et al* 2006a, 2006b). In 1999, Dai and Hu (1999) developed an algorithm to decompose the intensity patterns using independent jaws, the first study to demonstrate the feasibility of using conventional jaws for

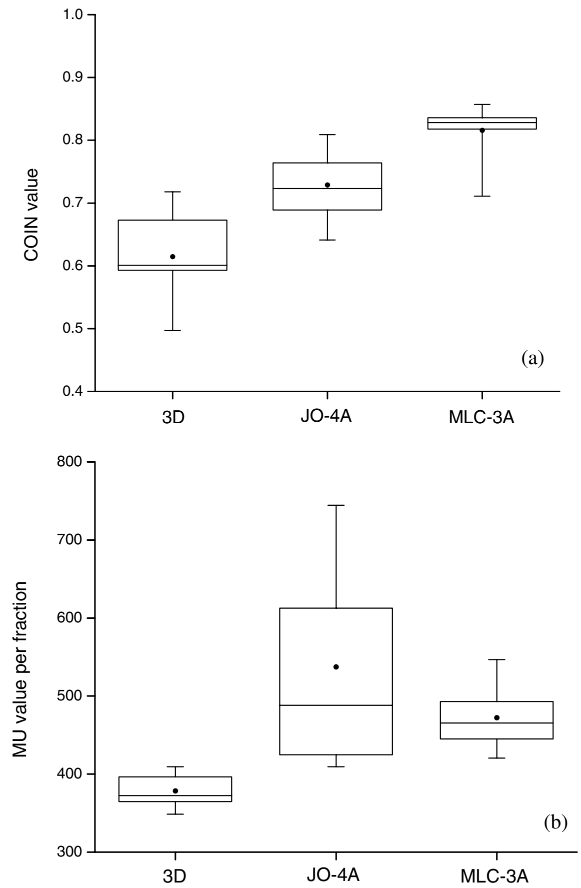

Figure 6. A comparison of (a) COIN and (b) MU value per fraction between three plans (3D, JO-4A and MLC-3A plan) for ten patients. Each parallel bar in the box graph represents minimum, 25, 50, 75 percentiles and maximum values in order, and the dot inside the box is the mean value.

IMRT delivery. Although their results were promising, the prolonged delivery time (a factor of 4 to 7) was a concern. In this study, we demonstrated that using direct aperture-based optimization instead of pixel-based optimization, the delivery time of using conventional jaws is only slightly longer than the delivery time using MLC for the treatment of prostate cancer. Recently, at the time of the final revision of this paper, Earl *et al* (2007) published their research results of jaw-only IMRT using direct aperture optimization and concluded that for prostate cases, both MLC and jaw-only IMRT plans provided similar target coverage with slightly improved sparing of the rectum and bladder with MLC IMRT plans.

The advantages and disadvantages of using conventional jaws have been summarized in Dai and Hu's paper (1999). The advantages using conventional jaws include continuous jaw positions, sharper beam penumbra, no interleaf leakage or tongue and groove effect and easy maintenance. The disadvantages of using conventional jaws include the requirement of relatively higher MUs, more segments and less conformal plans when compared with MLC IMRT plans. The limitation of this study is that we chose a relatively simple clinical site (prostate) although this site is one of the most applicable sites using IMRT. With conventional

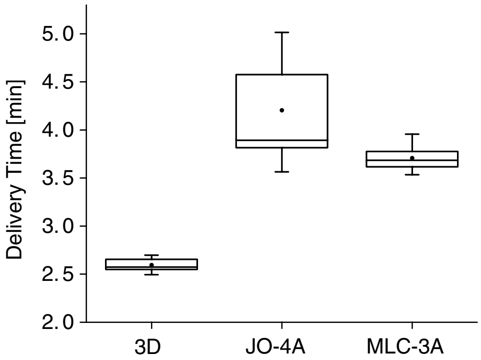

Figure 7. A comparison of delivery time between three plans (3D, JO-4A and MLC-3A plan) for ten patients. Each parallel bar in the box graph represents minimum, 25, 50, 75 percentiles and maximum values in order, and the dot inside the box is the mean value.

jaws, further study on the more complicated tumour shapes such as head and neck tumours are underway. In conclusion, inverse IMRT plans using conventional jaws are clinically feasible, achieving better plan quality than 3D-CRT plans. For centres where MLCs are not available, using conventional jaws to deliver IMRT plans can be a great option for treatment of prostate cancer and possibly for cancer in other sites as well.

Acknowledgment

The authors would like to thank Prowess, Inc. for its research support and technical assistance.

References

Anderson J W, Symonds-Tayler R, Hartmann G, Echner G, Lang C, Schlegel W and Webb S 2006a Comparative efficiency of the multi-leaf collimator and variable-aperture collimator in intensity-modulated radiotherapy *Phys. Med. Biol.* **51** 1725–36

Anderson J W, Symonds-Tayler R and Webb S 2006b Investigating the fundamentals of IMRT decomposition using ten simple collimator models *Phys. Med. Biol.* **51** 2225–36

Baltas D, Kolotas C, Geramani K, Mould R F, Ioannidis G, Kekchidi M and Zamboglou N 1998 A conformal index (COIN) to evaluate implant quality and dose specification in brachytherapy *Int. J. Radiat. Oncol. Biol. Phys.* **40** 515–24

Bedford J L and Webb S 2006 Constrained segment shapes in direct-aperture optimization for step-and-shoot IMRT *Med. Phys.* **33** 944–58

Dai J R and Hu Y M 1999 Intensity-modulation radiotherapy using independent collimators: an algorithm study *Med. Phys.* **26** 2562–70

Earl M A, Afghan M K N, Yu C X, Jiang Z and Shepard M D 2007 Jaws-only IMRT using direct aperture optimization *Med. Phys* **34** 307–14

Shepard D M, Earl M A, Li X A, Naqvi S and Yu C 2002 Direct aperture optimization: a turnkey solution for step-and-shoot IMRT *Med. Phys.* **29** 1007–18

Webb S 2002 Intensity-modulated radiation therapy using only jaws and a mask *Phys. Med. Biol.* **47** 257–75

Webb S, Hartmann G, Echner G and Schlegel W 2003 Intensity-modulated radiation therapy using a variable-aperture collimator *Phys. Med. Biol.* **48** 1223–38

Xia P, Pickett B, Vigneault E, Verhey L J and Roach M III 2001 Forward or inversely planned segmental multileaf collimator IMRT and sequential tomotherapy to treat multiple dominant intraprostatic lesions of prostate cancer to 90 Gy *Int. J. Radiat. Oncol. Biol. Phys.* **51** 244–54