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A comparison between cobalt and linear accelerator-based treatment plans for conformal and intensity-modulated radiotherapy

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ABSTRACT. The simplicity of cobalt units gives them the advantage of reduced maintenance, running costs and downtime when compared with linear accelerators. However, treatments carried out on such units are typically limited to simple techniques. This study has explored the use of cobalt beams for conformal and intensity-modulated radiotherapy (IMRT). Six patients, covering a range of treatment sites, were planned using both X-ray photons (6/10 MV) and cobalt-60 gamma rays (1.17 and 1.33 MeV). A range of conformal and IMRT techniques were considered, as appropriate. Conformal plans created using cobalt beams for small breast, meningioma and parotid cases were found to compare well with those created using X-ray photons. By using additional fields, acceptable conformal plans were also created for oesophagus and prostate cases. IMRT plans were found to be of comparable quality for meningioma, parotid and thyroid cases on the basis of dose–volume histogram analysis. We conclude that it is possible to plan high-quality radical radiotherapy treatments for cobalt units. A well-designed beam blocking/compensation system would be required to enable a practical and efficient alternative to multileaf collimator (MLC)-based linac treatments to be offered. If cobalt units were to have such features incorporated into them, they could offer considerable benefits to the radiotherapy community.

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With the advance of increasingly complex treatment techniques in radiotherapy, there is a tendency to move towards ever more sophisticated and expensive external beam delivery equipment. The use of conformal radiotherapy (CFRT) is now routine in most centres, with intensity-modulated radiotherapy (IMRT) also becoming more widespread. Both CFRT and IMRT are usually implemented using a linear accelerator fitted with a multileaf collimator (MLC), to create the conformality and fluence variations necessary [1]. However, the complexity of such machines leads to high maintenance costs and significant planned and unplanned downtime [2, 3].

The advantages of cobalt units, with their very low maintenance costs and minimal need for engineering support, are well known to the radiotherapy community. The net gains in reviving a safer generation of such simple, economical machines could be considerable in a world with increasingly stretched health-care resources. The current generation of three-dimensional treatment planning systems, networked to commercial block and compensator cutters, could provide a practical means of delivering high-quality, radical radiotherapy treatments on cobalt units.

A planning study has therefore been carried out to compare cobalt-60 (Co-60) plans, using conformal blocks and/or compensators, with those created using a 6/10 MV linear accelerator and MLC.

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Methods and materials

Planning comparisons were carried out for seven clinical sites using both photons (6/10 MV) and Co-60. Cobalt plans used data from a Theratron Elite cobalt unit (MDS Nordion, Kanata, Canada) and photon plans used data from an Elekta SL15 dual energy accelerator (Elekta, Crawley, UK). The clinical sites were chosen to cover a range of plan complexity, from conventional planning to IMRT, using divergent blocks and compensators for the cobalt unit and a MLC for the accelerator. Planning was carried out on a Helax-TMS system (v6.0.2) (Nucletron UK, Cheshire, UK) using CT scans from previously treated patients. Dose distributions were calculated using a pencil beam calculation algorithm [4]. Conformal plans were normalized such that the planning target volume (PTV) doses were within 95–107% of the prescription dose, ideally with a median dose of 100% [5]. IMRT optimizations also aimed to fulfil these goals although a minimum dose of 90% was considered acceptable provided that 95% of the PTV was enclosed within the 95% isodose; if necessary, IMRT plans were normalized after optimization to achieve this. For the PTVs, minimum and maximum doses (defined as the dose received by 99% and 1% of the volume respectively) were recorded, as were the median dose and the volume covered by the 95% isodose (V95%). For organs at risk

(OARs), dose–volume parameters appropriate for the particular organ, based on the tolerance values, were recorded.

Breast

A patient with right-sided breast cancer was considered for this comparison. The patient separation at the base of the breast was 17 cm, representing a small breast [6], and the maximum lung depth encompassed by the standard tangential fields (measured in beam's eye view) was 1.1 cm. The whole of the breast, excluding the 5 mm beneath the surface of the skin, was contoured as the PTV. Plans were created for Co-60 and 6 MV photons using opposing rectangular wedged tangential fields, angled to give a non-divergent posterior edge. The prescribed dose was 50 Gy.

Oesophagus

The clinical target volume (CTV) for this site comprised the oesophageal tumour with a margin for microscopic spread and the adjacent lymph nodes. This was extended by 3 cm in the superior/inferior direction by contouring, tracking along the oesophagus, and then a 15 mm margin was added circumferentially to create the PTV. Planning was carried out using four conformal fields (gantry angles 0°, 90°, 180°, 270°), shaped using a MLC and blocks for 6 MV and Co-60, respectively. The prescribed dose to the PTV was 54 Gy. The OARs were the spinal cord, to which a maximum dose of 46 Gy was allowed, and the lungs, 20% of which were required to remain below 20 Gy [7].

Meningioma

The CTV in this case was an irregularly shaped base-of-skull meningioma to which a 5 mm margin was added in three dimensions to create the PTV. The prescribed dose was 55 Gy. The brain and brainstem were considered as OARs; although the dose employed was within tolerance limits for these structures [8], functional damage to the brain is both dose and volume dependent and hence it is desirable to limit the volume of normal brain irradiated. Dose to the eyes was minimized by avoiding beam directions that passed through them. CFRT plans were created for Co-60 and 6 MV photons using four and six non-coplanar fields with conformal blocks. Use of conformal blocks for this treatment site is normal clinical practice at our centre because of their superior shaping ability compared with the 1 cm MLC leaves. Additionally, IMRT plans were created for both modalities using the six-field arrangement, using conformal blocks and compensators. In practice, intensity modulation on the accelerator could be achieved using the MLC; however, the planning system would not allow the use of both a MLC and blocks on the same beam.

Parotid

The CTV for this case consisted of the radiographically visible parotid gland surgical bed and the ipsilateral upper cervical lymph nodes, to which a 5 mm margin was applied in three dimensions, excluding the 5 mm beneath the skin surface, to create the PTV. The main OARs under consideration were the ipsilateral cochlea, which lay very close to the PTV, and the contralateral parotid gland. Dose to the eyes was minimized by avoiding beam directions that passed through them, and doses to the oral cavity, brain and brainstem were also considered. Conformal wedged pair and four-field IMRT plans (gantry angles 15°, 40°, 140° and 170° [9]) were created using 6 MV photons with a MLC, and Co-60 with blocks or compensators. The prescribed dose was 60 Gy.

Prostate

The CTV in this case consisted of the prostate plus seminal vesicles, to which a 10 mm margin was added in three dimensions to create the PTV. The prescribed dose was 70 Gy. The main OAR of concern was the rectum, although bladder and femoral heads were also considered; planning goals for the OARs can be seen in Table 1 [10]. A standard three-field conformal plan (gantry angles 0°, 90°, 270°) was prepared using 10 MV photons and a MLC, and then compared with a five-field Co-60 plan (gantry angles 30°, 90°, 180°, 270°, 330°) prepared using conformal blocks. More fields were necessary for the Co-60 plan to keep the doses near the surface of the patient to an acceptable level. Additionally, a six-field non-coplanar Co-60 plan was created, using an anterior and posterior field and lateral fields with the couch twisted by $\pm 30°$ (the maximum couch twist possible avoiding collision with the treatment head).

Table 1. Planning goals and dose statistics for prostate plans

Organ at risk	Dose (Gy)	Maximum volume (%)	Volume achieved (%)		
			10 MV	5f Co-60	6f Co-60
Bladder	50	50	17.3	14.0	14.9
	60	25	13.7	9.4	10.0
	70	5	3.6	3.4	3.2
Rectum	50	60	36.0	35.3	37.6
	60	50	30.6	29.6	30.6
	65	30	27.3	26.5	25.5
	70	15	12.5	11.6	7.2
Femoral heads	50	50	0.0	0.0	0.0

5f, five-field; 6f, six-field.

Thyroid

For this case the CTV consisted of the thyroid bed and immediately adjacent lymphatics, to which a 5 mm margin was added in three dimensions, excluding the 5 mm beneath the skin surface, to create the PTV. In this situation, where the PTV wraps around the spinal cord, conventional and conformal techniques are unable to deliver the prescribed dose of 60 Gy to the target without exceeding the spinal cord tolerance of 46 Gy [11]; hence, only IMRT plans were considered. Five coplanar fields were used for both Co-60 with compensators and 6 MV photons with a MLC.

Results

Breast

The minimum and maximum PTV doses for the 6 MV plan were 97.2% and 105.3% (median 100.0%) of the prescribed dose respectively; those for the Co-60 plan were 94.5% and 105.7% (median 101.1%) respectively. As the PTV coverage was slightly lower for the Co-60 plan, a second plan was created in which a low-weighted segment was added to the anterior oblique beam with a wedge in the cranio-caudal direction. This second plan had a minimum PTV dose of 95.8% and a maximum of 106.3% (median 101.0%). The volume of lung receiving doses below 25 Gy was slightly increased in the Co-60 plans; however, the lung doses were still perfectly acceptable (volume receiving >20 Gy (V20 Gy) was 2.2% for 6 MV, 3.4% for both Co-60 plans).

Oesophagus

Table 2 lists the dose statistics for the oesophagus plans. Spinal cord and lung doses were both within tolerance; however, the cobalt plan showed poorer target coverage and homogeneity than the 6 MV plan. This was partly due to the large variation in effective path length across the anterior field, where the central part of the beam passes through soft tissue and bone, and the edges pass through a large proportion of lung. This gives rise to large hotspots at the lateral sides of the PTV (see Figure 1a). A second cobalt plan was created, which delivered part of the anterior beam dose through a rectangular segment that included the mediastinum but not the lungs (see Figure 1b). This led to improved target homogeneity as indicated in Table 2.

Meningioma

Table 3 shows the PTV dose statistics for the meningioma plans. In all cases the median dose was 100.0%. The PTV was fully encompassed by the 95% isodose for all conformal plans (V95%=100.0%); for the IMRT plans, V95% was 98.6% for 6 MV and 97.8% for Co-60. Figure 2 shows the dose–volume histograms (DVHs) for the brain and brainstem.

Parotid

Table 4 shows the dose statistics for the parotid case. The minimum PTV dose for the 6 MV IMRT plan was below the goal of 95%; V95% for this plan was 96.4%. The OAR doses were similar between the two modalities. The IMRT plans showed reductions in the doses to the cochlea, oral cavity and contralateral parotid whereas the brainstem doses were increased; however, the brainstem doses were still well within the tolerance of 55 Gy for this structure.

Prostate

Figure 3 shows the DVHs for the PTV, rectum and bladder. The minimum and maximum PTV doses for the 10 MV plan were 97.0% and 105.4% (median 100.0%) of the prescribed dose, respectively; those for the five-field Co-60 plan were 95.0% and 105.3% (median 100.7%), respectively, whereas those for the six-field Co-60 plan were 95.2% and 105.0% (median 100.0%) respectively. Table 1 gives the dose statistics for the OARs compared with the plan acceptance criteria.

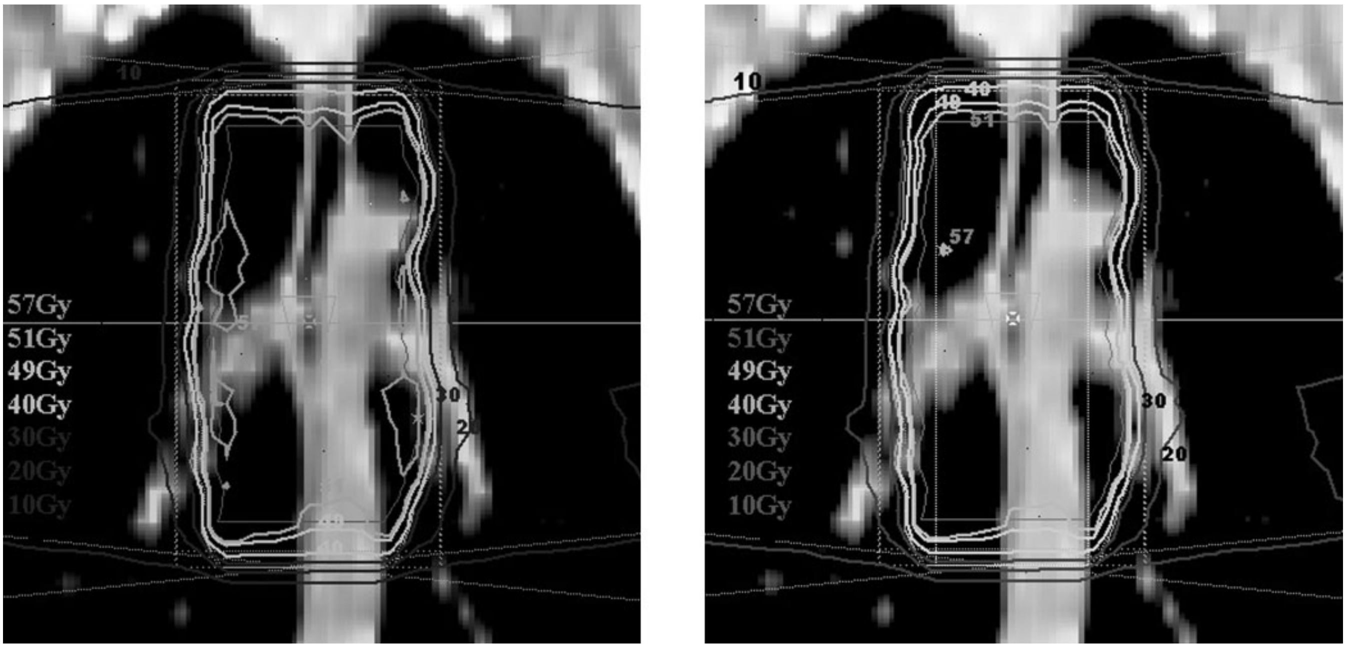
Thyroid

Figure 4 shows a transverse slice through the dose distribution for the 6 MV and Co-60 plans. In both cases the isodoses conform tightly around the concavity in the PTV, sparing the spinal cord. Minimum and maximum PTV doses for the 6 MV plan were 92.7% and 105.7% (median 100.7%), respectively, whereas for the Co-60 plan they were 90.0% and 105.7% (median 100.0%), respectively. V95% was 95.0% for the 6 MV plan and 96.2% for the Co-60 plan. The maximum dose to the spinal cord was 38.5 Gy for the 6 MV plan and 46.2 Gy for the Co-60 plan; the doses received by 1 ml of the spinal cord were 36.8 Gy and 38.6 Gy, respectively.

Table 2. Dose statistics for oesophagus plans

		6 MV	Co-60	Co-60 + segment
PTV	Minimum dose (%)	95.2	92.3	93.3
	Maximum dose (%)	106.7	108.7	106.5
	Median dose (%)	99.6	99.6	100.0
	V95% (%)	99.3	94.0	96.4
Spinal cord	Maximum dose (Gy)	40.3	41.9	42.0
Lungs	Volume >20 Gy (%)	13.6	16.2	17.0

PTV, planning target volume.



(a) (b)

Figure 1. Coronal distribution for Co-60 oesophagus plan (a) without and (b) with an anterior beam segment (shown dashed). Isodoses shown are 10 Gy, 20 Gy, 30 Gy (dark grey), 40 Gy, 49 Gy (light grey), 51 Gy and 57 Gy (mid-grey).

Discussion

As complex radiotherapy techniques become more widespread, there is a tendency for departments to move away from using cobalt units in favour of more sophisticated delivery techniques. However, the simplicity of cobalt units leads to lower maintenance costs and staffing needs as well as exceptional reliability. This paper therefore aimed to investigate the potential of such machines for conformal radiotherapy and IMRT. The treatment sites and plan types were chosen to cover a range of complexity, from simple rectangular fields through to conformal techniques and complex inverse-planned IMRT, including both superficial and deep-seated lesions. Only a single patient case was considered for each site, and hence the results cannot be considered as conclusive; however, they do demonstrate the possibility of designing complex radiotherapy treatments using cobalt.

Plans created for a small-breasted patient showed that cobalt offers a suitable alternative to 6 MV at this site. Although the original cobalt plan did not entirely encompass the PTV with the 95% isodose (minimum dose 94.5%), this was easily rectified by the addition of a wedge in the cranio-caudal direction. This latter cobalt plan showed slightly increased inhomogeneity compared with the 6 MV plan but was within standard International Commission on Radiation Units (ICRU) acceptance criteria. Lung doses were also slightly increased for the cobalt plan because of the larger penumbra for this modality but were still within tolerance criteria.

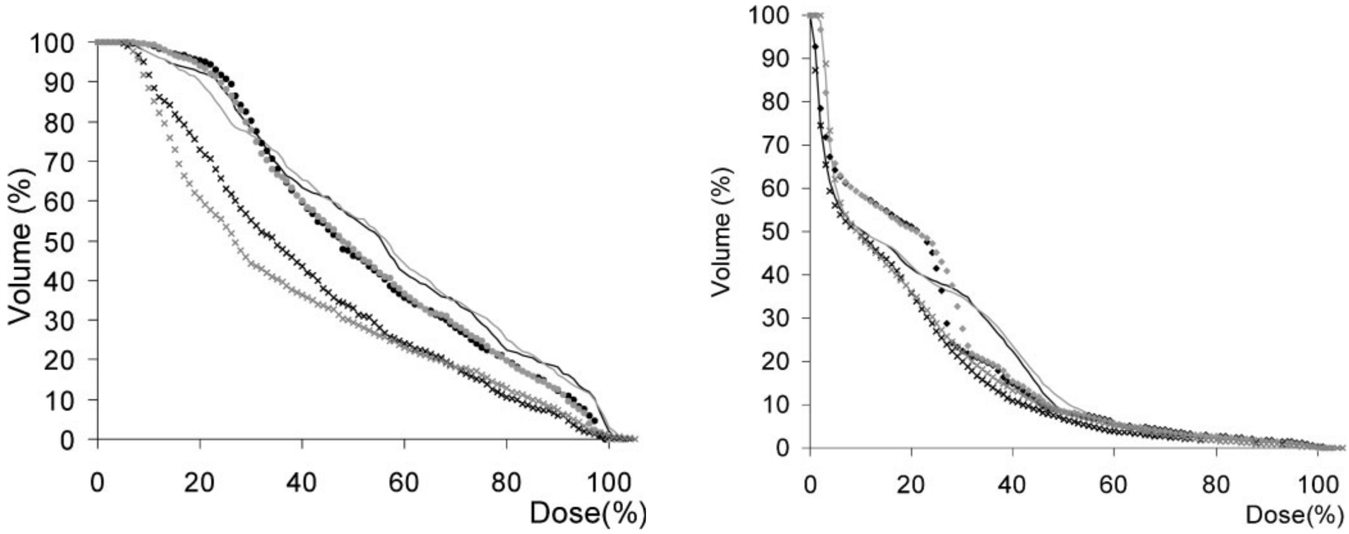
Two sites were considered to investigate the role of cobalt for conformal planning in the head: meningioma and parotid. In both cases, plans for the two modalities were very similar. The cobalt plans tended to show increased PTV inhomogeneity; for the meningioma case this was still well within acceptable limits and for the parotid the maximum dose only just exceeded the goal of 107% (107.2%) and was therefore considered acceptable. Increasing the number of fields in the meningioma case led to improved OAR sparing at higher dose levels; although the cobalt plans showed slightly increased brain irradiation at some dose levels, these differences were small compared with those caused by changing the number of fields. For the parotid, all OAR doses were comparable. These two treatment sites indicate that cobalt is a suitable modality for planning tumours in the head.

Conformal plans were also created for oesophagus and prostate tumours. For the oesophagus case, the initial cobalt plan showed poor PTV coverage and homogeneity. However, the addition of a rectangular segment to the anterior beam was able to significantly improve the dose distribution. Although the minimum PTV dose was still below the 95% level suggested by the ICRU [5], it was above 93% and more than 95% of the PTV volume was enclosed by the 95% isodose (V95%=96.4%); this

Table 3. Planning target volume (PTV) dose statistics for meningioma plans

	6 MV 4f CFRT	Co-60 4f CFRT	6 MV 6f CFRT	Co-60 6f CFRT	6 MV 6f IMRT	Co-60 6f IMRT
Minimum dose (%)	98.2	97.2	96.6	96.0	94.0	93.3
Maximum dose (%)	102.2	102.9	102.5	102.4	105.4	104.9

4f, four-field; 6f, six-field; CFRT, conformal radiotherapy; IMRT, intensity-modulated radiotherapy.



(a) (b)

Figure 2. Dose–volume histograms for (a) brainstem and (b) brain from meningioma plans: four-field conformal radiotherapy (CFRT) (solid), six-field CFRT (dotted) and six-field intensity-modulated radiotherapy (IMRT) (crosses) for Co-60 (grey) and 6 MV (black) plans.

would be considered acceptable at our institution. OAR doses were slightly higher for the cobalt plans than for 6 MV, but all were within acceptable limits. This indicates that Co-60 is a suitable modality for planning tumours in the thoracic region. The PTV coverage for the 6 MV plan was better than that for the cobalt plans; however, for this tumour site, the limitations of the pencil beam model used in this study will affect the calculated dose distribution, as neither the lack of scatter from adjacent lung tissue nor the build-up effect for beams passing through lungs will be properly accounted for. In reality, therefore, hotspots will be reduced, as will the coverage of the target in regions where the tumour is next to lung tissue. This latter effect will be more pronounced for 6 MV photons than for Co-60 as the build-up depth is greater, hence making the two modalities more comparable or possibly giving an advantage to the Co-60 plan [12]. A full investigation of this is outside the scope of this study but will be the subject of future work.

Plans using Co-60 were also able to satisfy tolerance criteria for the prostate case; although the PTV coverage was worse for the Co-60 plans than for the 10 MV plan, the minimum dose was above 95% in all cases. The maximum PTV dose was comparable for all plans and all OARs were within the plan acceptance criteria. The bladder doses were lower in the Co-60 plans because of the beam arrangement. Although the five-field Co-60 plan showed higher rectal doses in the 25–50 Gy region, the plans were all very similar for doses above 50 Gy; if doses in the 25–50 Gy region were considered to be important, the six-field Co-60 plan could be used, which gave similar results to those obtained with 10 MV. The need for an increase in the number of fields compared with the 10 MV plan, to maintain normal tissue doses, leads to the cobalt plans being less efficient than the corresponding linac plan. This is particularly true for the non-coplanar six-field plan, although the plan was designed with only two couch positions, thus minimizing the extra effort required. However, this case illustrates that it is possible to treat deep-seated malignancies in the pelvis using Co-60, which have long been cited as being generally unsuitable for this treatment modality.

IMRT planning with cobalt was investigated for parotid, meningioma and thyroid treatment sites. For the parotid case, use of Co-60 IMRT improved both PTV homogeneity and OAR sparing compared with the conformal plan, with the exception of the brainstem, which was still well within tolerance. As for the conformal plans, the differences between the two modalities were small. For the 6 MV IMRT plans, the PTV coverage was reduced compared with the conformal case, with a minimum dose of only 93.1%; however, 96.4% of the PTV was enclosed within the

Table 4. Dose statistics for parotid plans

		6 MV 2f CFRT	Co-60 2f CFRT	6 MV 4f IMRT	Co-60 4f IMRT
PTV	Minimum dose (%)	95.0	95.0	93.1	95.2
	Maximum dose (%)	105.9	107.2	105.8	105.2
	Median dose (%)	100.9	100.0	100.1	100.0
Cochlea	Mean dose (Gy)	38.8	38.8	29.8	30.8
Oral cavity	Mean dose (Gy)	26.3	25.3	19.6	19.0
Contralateral parotid	Mean dose (Gy)	1.7	2.7	1.4	2.2
Brainstem	Maximum dose (Gy)	30.9	28.9	36.8	39.3

2f, two-field; 4f, four-field; CFRT, conformal radiotherapy; IMRT, intensity-modulated radiotherapy, PVT, planning target volume.

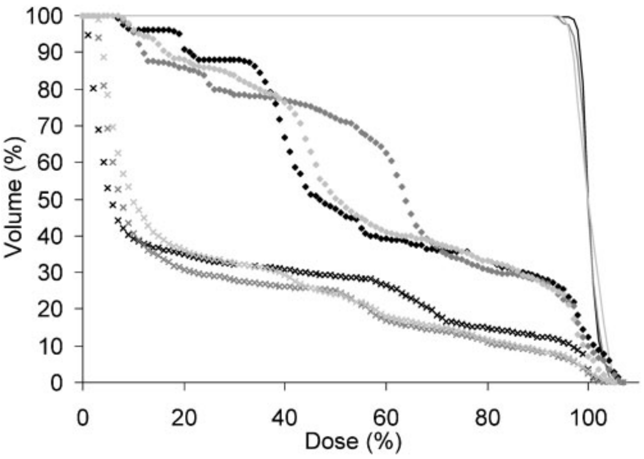


Figure 3. Dose–volume histograms from prostate plans. Planning target volume (PTV) (solid), rectum (dotted) and bladder (crosses) are shown for 10 MV (black), five-field coplanar Co-60 (mid-grey) and six-field non-coplanar Co-60 (light grey) plans.

95% isodose, which is above the criterion of 95% often used for IMRT planning. The meningioma IMRT plans were also comparable between the two modalities, with a significant improvement in OAR doses compared with the conformal plans. Both modalities showed a reduction in PTV coverage compared with the conformal cases, with minimum PTV doses below 95%; however, in both cases V95% was greater than 95% (98.6% for 6 MV, 97.8% for Co-60). The cobalt plan showed a small increase in the volume of brainstem treated to >40 Gy compared with the 6 MV plan, with a significant decrease at lower doses; for the brain, cobalt generally showed a small increase at all dose levels. As for the conformal plans, these differences between modalities were smaller than those between plan types.

For the thyroid case, both modalities were able to cover the PTV with the 90% isodose, with at least 95% of the volume covered by the 95% isodose, whilst sparing the spinal cord. Although the maximum cord dose for the cobalt plan (46.2 Gy) was slightly above the planned constraint of 46 Gy, this dose was only recorded for a very small volume of the cord; the dose received by a more clinically relevant volume (1 mL) was 38.6 Gy.

The Co-60 plans generated in this study used divergent, shaped blocks and/or compensators. Although these beam-shaping devices provide a ''gold standard'' of conformality, their use in X-ray radiotherapy has been discontinued in many departments because of concerns of overall efficiency, with the MLC providing a more practical alternative. Although it is possible for MLCs to be fitted to cobalt heads, this increase in complexity may compromise the much-cherished simplicity of these machines. Practical CFRT/IMRT delivery on cobalt units would therefore require a well-designed beam blocking/compensation system in order to be an efficient alternative to MLC-based linac treatments. Such a system has been designed by Yoda and Aoki [13], who quote a delivery time of approximately 2 min for a six-field compensated treatment on an accelerator, with approximately 1 min for gantry and collimator rotations, assuming a 2 Gy min^{-1} beam intensity and 2 Gy isocentre dose. Measurements made on a cobalt unit within our department [14], with a 2 Gy min^{-1} source intensity, have suggested IMRT beam delivery times of 20–75 s for a 2 Gy isocentre dose, which, although longer than the times quoted by Yoda and Aoki [13], compare well to linac-based IMRT treatments. A further requirement for precise, radical treatments is the ability to perform verification imaging, preferably electronically; this should be potentially realizable at this energy.

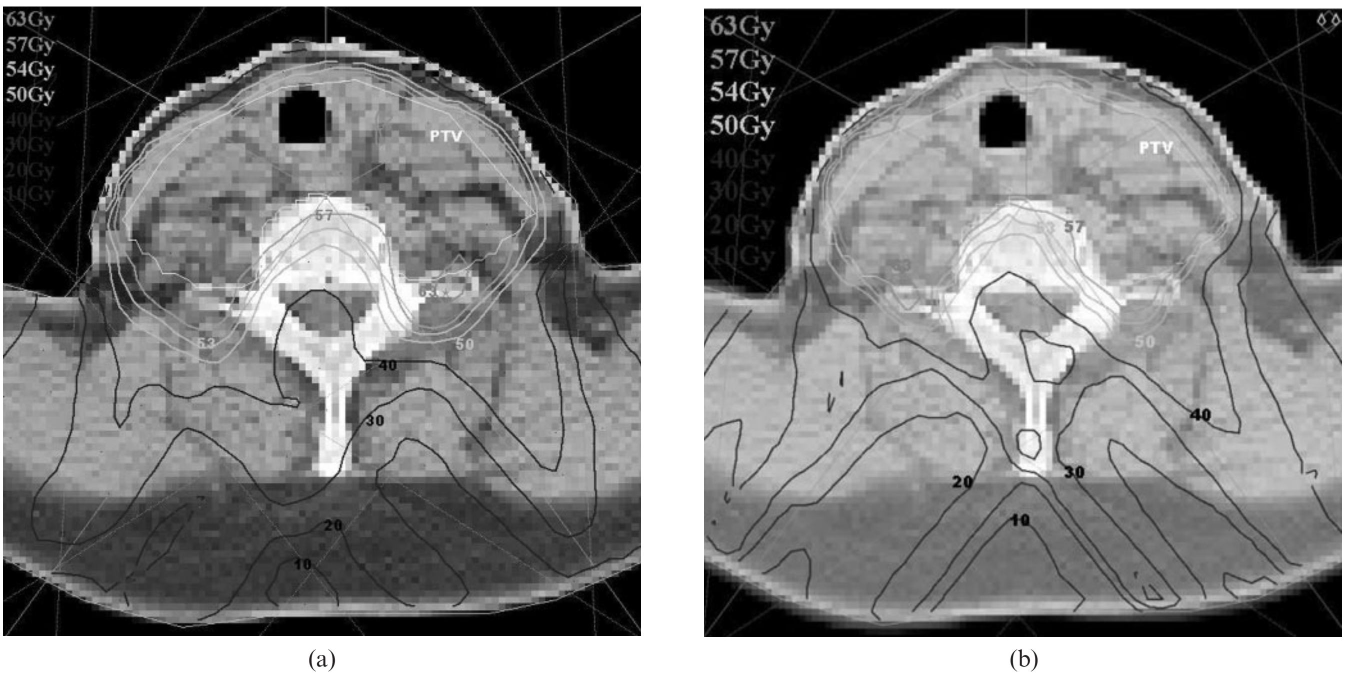


Figure 4. Transverse dose distributions for (a) 6 MV and (b) Co-60 intensity-modulated radiotherapy (IMRT) thyroid plans. Isodoses shown are 10 Gy, 20 Gy, 30 Gy, 40 Gy (dark grey), 50 Gy, 54 Gy (light grey), 57 Gy and 63 Gy (mid-grey).

Conclusions

Plans of varying complexity, including conformal and IMRT techniques, have been created for Co-60 using blocks and/or compensators for a range of treatment sites. In all cases, the cobalt plans were comparable to those created using 6/10 MV photons with an MLC; in most cases, this was achieved with the same beam arrangement although in some cases, such as the prostate, additional fields were required. These results suggest that it is possible to design high-quality radical radiotherapy treatments using cobalt units. To be able to offer an efficient alternative to MLC-based linac treatments, CFRT/IMRT delivery on cobalt units would require a well-designed beam blocking/compensation system and the ability to perform electronic verification imaging. If cobalt units were to have such features incorporated into them, they could offer considerable benefits to the radiotherapy community.

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