Journal of Radiotherapy in Practice

Journal of Radiotherapy in Practice (2017)
16, 391–402 © Cambridge University Press 2017
doi:10.1017/S1460396917000309

Original Article

A dosimetric comparison of craniospinal irradiation using TomoDirect radiotherapy, TomoHelical radiotherapy and 3D conventional radiotherapy

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(Received 1 February 2017; revised 5 April 2017; accepted 7 April 2017; first published online 22 June 2017)

Abstract

Aim: The purpose of this study was to dosimetrically compare TomoDirect, TomoHelical and linear accelerator-based 3D-conformal radiotherapy (Linac-3DCRT) for craniospinal irradiation (CSI) in the treatment of medulloblastoma.

Methods: Five CSI patients were replanned with Linac-3DCRT, TomoHelical, TomoDirect-3DCRT and TomoDirect-intensity-modulated radiotherapy (IMRT). Dose of 36 Gy in 20 fractions was prescribed to the planning target volume (PTV). Homogeneity index (HI), non-target integral dose (NTID), dose–volume histograms, organs-at-risk (OARs) D_{max}, D_{mean} and treatment times were compared.

Results: TomoHelical achieved the best PTV homogeneity compared with Linac-3DCRT, TomoDirect-3DCRT and TomoDirect-IMRT (HI of 3·6 versus 20·9, 8·7 and 9·4%, respectively). TomoDirect-IMRT achieved the lowest NTID compared with TomoDirect-3DCRT, TomoHelical and Linac-3DCRT (141 J versus 151 J, 181 J and 250 J), indicating least biological damage to normal tissues. TomoHelical plans achieved the lowest D_{max} in all organs except the breasts, and lowest D_{mean} for most OARs, except in laterally situated OARs, where TomoDirect triumphed. Beam-on time was longest for TomoHelical, followed by TomoDirect and Linac-3DCRT.

Findings: TomoDirect has the potential to lower NTID and shorten treatment times compared with TomoHelical. It reduces PTV inhomogeneity and better spares OARs compared with Linac-3DCRT. Therefore, TomoDirect may be a CSI treatment alternative to TomoHelical and in place of Linac-3DCRT.

Keywords: 3DCRT; craniospinal irradiation; TomoDirect; tomotherapy

INTRODUCTION

Medulloblastoma is a highly malignant tumour in the cerebellum, a part of the posterior fossa that coordinates all motor functions. It is the second

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most common central nervous system cancer in children, making up about 20% of all paediatric brain tumours. In adults (>15 years old), medulloblastoma is less common and accounts for <1% of adult brain tumours.[1,2] The current clinical practice involves surgery followed by postoperative radiotherapy to the cranial–spinal axis with adjuvant chemotherapy due to propensity to spread within the neuraxis.[3] Recent treatment strategies for medulloblastoma patients have been relatively successful with 5-year survival rates of 70–80%.[4,5] However, despite improved survival rates, patients experience long-term side-effects from the radiotherapy.[6] These toxicities include impaired neurocognitive development, growth retardation, endocrine dysfunction, cataract formation, hearing problems, cardiomyopathy, impaired fertility and secondary malignancies.[1]

Modern craniospinal irradiation (CSI) techniques have been developed with the aim of minimising long-term side-effects in children. Conventionally, two lateral cranial fields and one or two posterior spinal fields are arranged to treat the entire craniospinal axis.[7] Due to field-size constrictions, this type of linear accelerator-based 3D-conformal radiotherapy (Linac-3DCRT) requires the matching of junctions. The need for separate isocentres unfortunately reduces homogeneity at junction points and increases planning complexity.[8] Tomotherapy plans allow for the continuous treatment of long targets without the need for field matching. TomoHelical (Accuray Inc., Madison, WI, USA) radiotherapy, the most widely used form of tomotherapy, delivers dose from any of 360° and uses intensity-modulated radiotherapy (IMRT). The delivery of TomoHelical plans for CSI is well documented.[9–12] Compared with Linac-3DCRT, TomoHelical treatments for CSI in the supine position at the host institute as well as others have demonstrated increased patient comfort and dose conformity.[9,10] However, due to the nature of 360° TomoHelical beam arrangements, there are concerns about increased integral doses (ID) which potentially leads to increased secondary malignancies.[1,3,6] The 30–60-minute-long treatment duration is also a major concern for patient comfort and those who require sedation.

In contrast to TomoHelical radiotherapy, TomoDirect (Accuray Inc.) is a treatment option that enables the user to apply specific beam angles for treatment planning. There are two types of TomoDirect plans: TomoDirect-3DCRT and TomoDirect-IMRT. Forward planning in 3DCRT delivers dose to the target without regions-at-risk constraints while inverse planning in IMRT uses multi-leaf collimators (MLCs) to create highly conformal dose to targets.[13]

TomoDirect treatments for CSI have the potential to shorten treatment times and decrease ID. This new technology available from tomotherapy offers the potential to achieve lower dose to all non-target tissues without compromising the target dose. Despite the publication of two recent articles, there is a lack of evidence to support the use of TomoDirect for CSI treatments.[14,15] This paper aims to address this gap in knowledge by comparing TomoDirect radiotherapy with TomoHelical radiotherapy and Linac-3DCRT in a dosimetric study of CSI treatment.

METHODS

Five consecutive medulloblastoma patients previously treated with TomoHelical radiotherapy at the host hospital were replanned with 3DCRT, TomoHelical and TomoDirect. This included all three paediatric and two adult patients treated from 2008 to 2014. All five patients underwent computed tomography (GE Lightspeed™, Chicago, IL, USA) simulation in the supine position (Table 1). They were fitted with customised full body vacuum immobilisations to stabilise body positioning, as well as standardised head-rests and thermoplastic masks to immobilise the head and neck area.

Organs-at-risk (OARs) and planning target volumes (PTVs) were contoured using the Eclipse 10 (Varian, Palo Alto, CA, USA)

Table 1. *Patient demographics and CT parameters*

Patients	Sex	Age	PTV length (cm)	CT slice thickness (mm)
1	M	1	46·25	2·5
2	F	8	62·01	2·5
3	M	11	63	2·5
4	M	33	80·41	2
5	F	39	72·9	3

Abbreviation: CT, computer tomography; PTV, planning target volume.

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planning station. The target volumes were contoured by the oncologist to include the cranium and spinal axis. During planning, the PTV was split into PTVbrain (cranial contents) and PTVspine (inferiorly from C1) to further improve dosimetry. A list of OARs were contoured by trained contouring radiation therapists and adjusted by the primary researcher for consistency. These organs include brainstem, pituitary, optic nerves, optic chiasm, eyes, lenses, hearing apparatus (cochlea and middle ear), parotids, mandible, larynx, oesophagus, lungs, heart, breasts, liver, kidneys, bowels, testes, ovaries and uterus. The body was defined as the entire external contour down to the top third of the femur.

To permit comparisons, a prescription for high-risk medulloblastoma patients (36 Gy in 20 fractions) was applied for all plans.[15]

PLANNING

All TomoHelical plans were replanned for this study. A standardised planning protocol was applied to all patients. This protocol closely followed the guidelines set out by the host department. For medulloblastoma patients, nearly 15–20% of recurrences occur at the cribriform plate due to excessive shielding to protect ocular structures.[16,17] Therefore, in achieving adequate target coverage in the cribriform plate between the eyes, ocular structures unavoidably received unwanted dose from lateral opposing cranial fields. In this study, MLCs were used to shield the lenses and facial structures away from PTVbrain.

Linac-3DCRT

For conventional 3DCRT, a fixed-beam geometry and 6 MV X-rays were used. Two lateral opposing cranial fields were employed, half-beam blocked inferiorly to match the junction of a posterior spinal field. MLC positions were adjusted to block high-risk OARs. Prescription dose was normalised to the reference point located at the geometric centre of PTVbrain. Spinal field dose normalisation point was placed in the central axis, at depth of the spinal canal.[18,19] For patients with PTV lengths within 65 cm, one spinal field was used using a source-to-skin distance (SSD) of 100–110 cm. For patients with longer spinal lengths, two direct posterior spinal fields (SSD 100 cm) were dosimetrically matched at spine depth. All junctions were then shifted 1 cm each on a 3-day cycle to feather the dose.

Tomotherapy

Posterior and lateral blocks were added for TomoDirect to limit gantry angles of 90 and 270° to the brain and 180° to the spine. An overlap of 1·25 cm (half field width) between the posterior and lateral fields was introduced to allow for continuous dose distribution at the junction (Figure 1). For TomoDirect planning, a complete block was applied to restrict beam entry and exit through both lenses.

For all tomotherapy plans, *field width*, the axial thickness of the fan beam, was set to 2·51 cm and *pitch*, the couch travel distance for one complete gantry rotation relative to axial beam width was set to 0·287. A *fine* dose calculation grid was used, meaning that dose–volume calculation is based on a planning image that is not downsampled.

One generalised set of dose objectives was prepared as a starting point for TomoDirect-IMRT and TomoHelical plans. This template was created based on previously published data for OAR dose constraints.[1,20–23] After every 50 iterations, planning objectives were manually adjusted to tailor to the patient anatomy. *Modulation factor* is the maximum divided by average leaf-opening time. It estimates plan complexity. A modulation factor was first set to 2, increasing to 2·7 as needed to improve dose conformity at the expense of increased beam-on time.[13] All beam-on times were kept within 25 minutes as per departmental protocol.

Data analysis

Data collection was performed on the imaging software MIM 6.4.9 (MIM Software Inc., Cleveland, OH, USA). Plans were compared based on homogeneity index (HI), ID, overall treatment time and tissue sparing endpoints for all OARs including maximum dose (D_{max}), mean dose (D_{mean}), volumes of OARs receiving 5, 10, 20 and 30 Gy ($V_{5\,Gy}$, $V_{10\,Gy}$, $V_{20\,Gy}$, $V_{30\,Gy}$). Slice-by-slice

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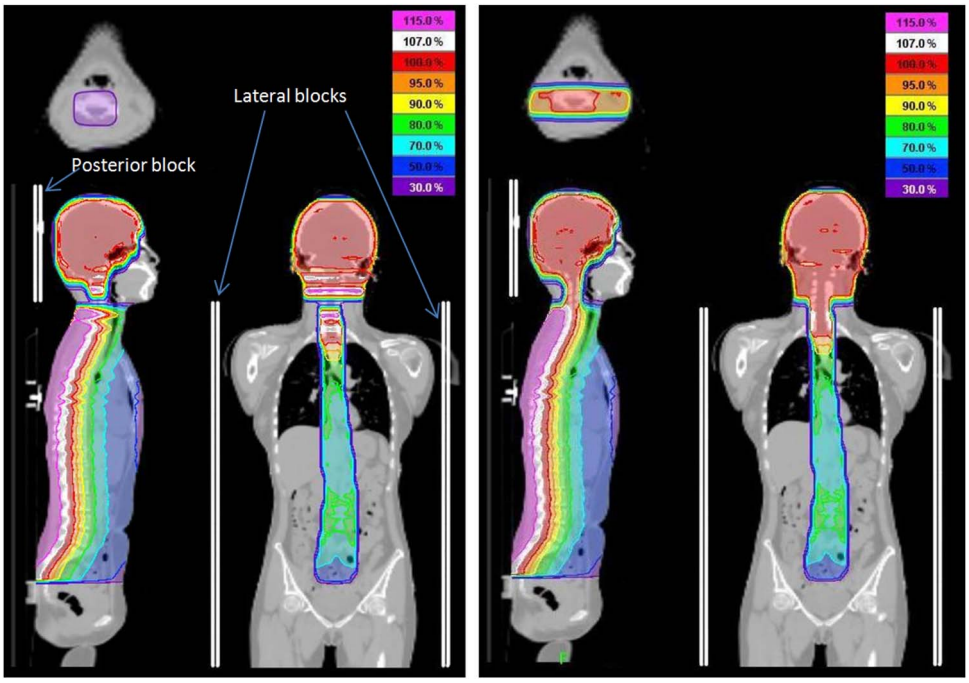

Figure 1. TomoDirect dose distribution with and without overlap.
Notes: Dose distribution for TomoDirect plan with no overlap of posterior and lateral fields (left image) exhibits gap in dose. The gap was eliminated by creating an overlap of 1·25 cm between posterior and lateral fields (right image).

isodose distributions and dose–volume histograms (DVHs) were compared for all plans.

The HI is calculated using

$$\mathrm{HI} = (D_{2\,\%} - D_{98\,\%})/D_{\mathrm{Rx}} \times 100\,\%$$

where $D_{2\%}$ and $D_{98\%}$ are the dose to 2 and 98% of the PTV, and D_{Rx} the prescription dose. A lower HI indicates better homogeneity.[24]

ID measures the amount of physical damage induced by irradiation. It incorporates all biological effects produced in an irradiated volume of tissue and is represented as total absorbed energy.[25,26] In this study, this was computed for the non-target body as follows:

$$\mathrm{ID} = D_{\mathrm{mean}} \times \rho_{\mathrm{mean}} \times V$$

where D_{mean} and V are the mean dose and volume of the non-target body, and ρ_{mean} is estimated to be the density of water.

Planning and treatment times for each method was obtained and compared. Beam-on time was calculated for Linac-3DCRT using a dose rate of 400 MU/minute.

RESULTS

Dose distributions for patients 1 and 5 are shown in Figures 2 and 3 to represent paediatric and adult patients, respectively, for Linac-3DCRT, TomoHelical, TomoDirect-3DCRT and TomoDirect-IMRT plans.

For Linac plans, dose at junction sites appear inhomogeneous despite feathering, with underdose and overdose posterior and anterior to the spine, respectively. Slice-by-slice comparisons of the isodose maps between TomoDirect-3DCRT and TomoDirect-IMRT plans displayed little visible differences in the cranium while the posterior beam is narrower in the lung regions.

Figure 4 shows the DVH for the PTV and lungs of patient 1. Sparing of the lungs was best achieved with TomoDirect planning, as is shown in the sample DVH for lungs.

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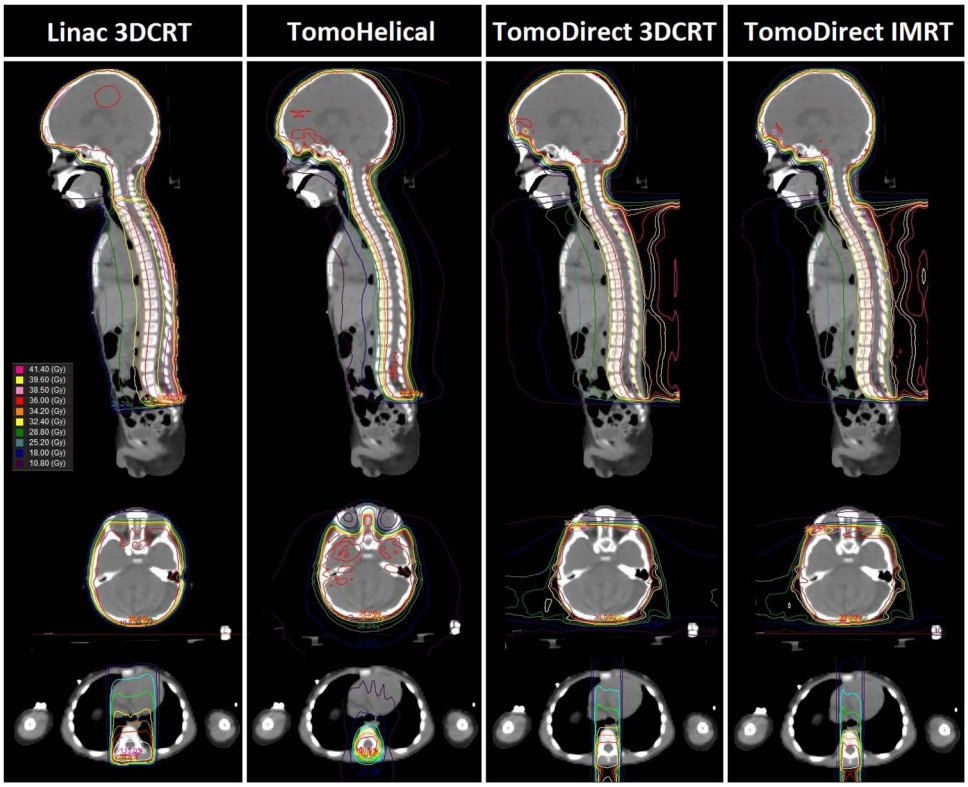

Figure 2. Sample dose distributions for one paediatric patient.
Notes: Isodose lines of 115, 110, 107, 100, 95, 90, 80, 70, 50 and 30% of the prescribed dose are displayed for linear accelerator-based 3D-conformal radiotherapy (Linac-3DCRT), TomoHelical, TomoDirect-3DCRT and TomoDirect-intensity-modulated radiotherapy (IMRT) plans.

Table 2 shows the summary of HI and non-target integral dose (NTID) for Linac-3DCRT, TomoHelical and TomoDirect plans. TomoHelical plans achieved the lowest mean HI and better comformity compared with Linac-3DCRT, TomoDirect-3DCRT and TomoDirect-IMRT. In contrast, TomoDirect-IMRT achieved the lowest NTID compared with TomoDirect-3DCRT, TomoHelical and Linac-3DCRT. The dose–volume information for OARs are shown in Table 3.

TomoHelical plans achieved the lowest D_{max} in all organs except the breasts. TomoHelical plans achieved the lowest D_{mean} for all OARs, except in the mandible, lungs, breasts, liver, kidneys, bowels and non-target body, where both TomoDirect methods triumphed (Figure 5). In Linac plans, the highest OAR D_{mean} were observed in all OARs except for the breasts.

OAR constraints were met in most cases. Exceptions include the eyes (D_{max} exceeded 20 Gy for all Linac and TomoDirect plans, and two TomoHelical plans), parotids (D_{mean} exceeded 25 Gy for four Linac, three TomoDirect-3DCRT and one TomoDirect-IMRT plan), lung (D_{mean} exceeded 10 Gy for four Linac plans) and heart (D_{mean} exceeded 3·5 Gy for all Linac and TomoDirect plans and one TomoHelical plan).

Table 4 summarises the planning and total treatment times for each treatment type.

DISCUSSION

In this study, four different methods for CSI treatments were evaluated: TomoDirect-3DCRT, TomoDirect-IMRT, TomoHelical radiotherapy and Linac-3DCRT. This study

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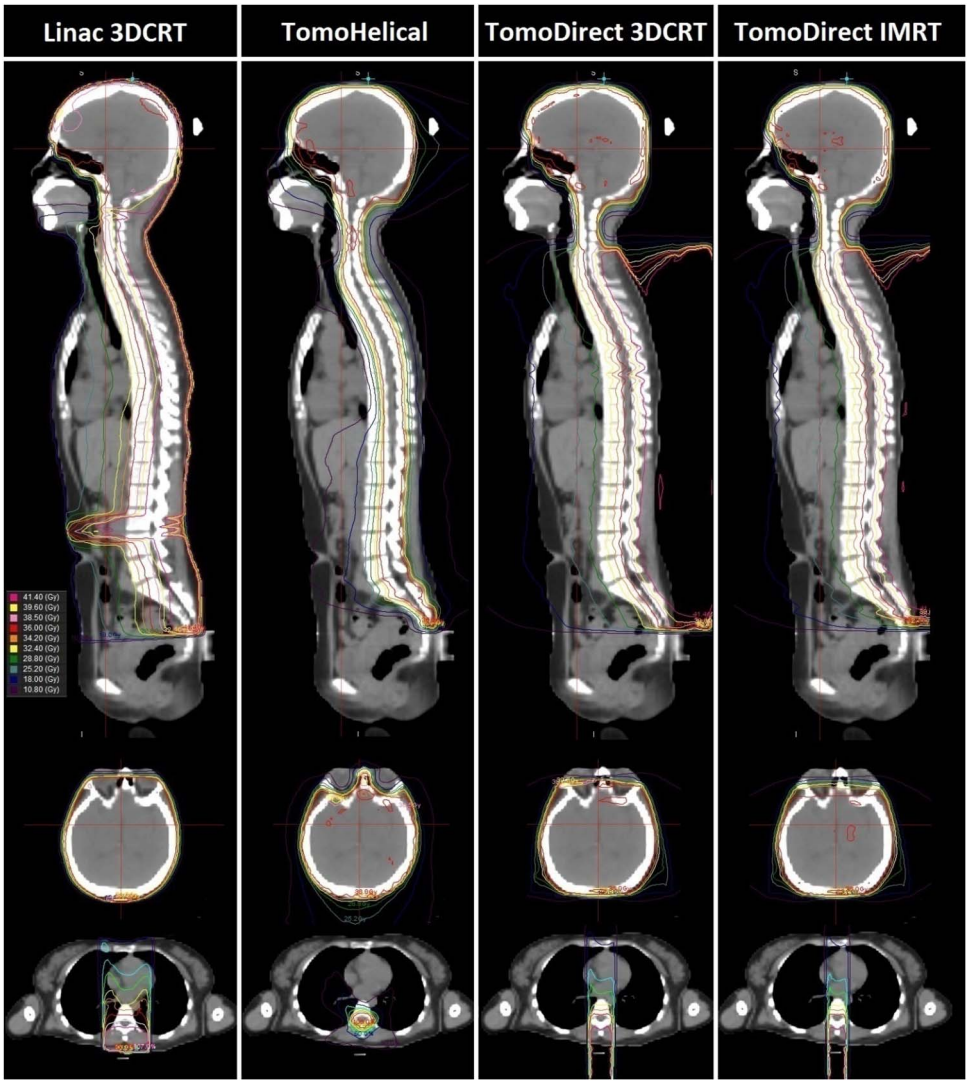

Figure 3. Sample dose distributions for one adult patient.
Notes: Isodose lines of 115, 110, 107, 100, 95, 90, 80, 70, 50 and 30% of the prescribed dose are displayed for linear accelerator-based 3D-conformal radiotherapy (Linac-3DCRT), TomoHelical, TomoDirect-3DCRT and TomoDirect-intensity-modulated radiotherapy (IMRT) plans.

aims to fill the gap in CSI treatment options to help guide future treatment decisions.

Dose homogeneity and ID

TomoHelical radiotherapy achieved higher dose homogeneity compared with Linac-3DCRT and TomoDirect methods (Table 2). These study results are consistent with existing literature. Langner et al.[15] reported the same pattern of PTV homogeneity: HI of 4, 17 and 18% for TomoHelical, TomoDirect-3DCRT and Linac-3DCRT, respectively. Similarly, Kim et al.[14] noted that dose homogeneity for PTV was higher for TomoHelical and TomoDirect-3DCRT plans (dose homogeneity index (DHI) given by the ratio of $D_{95\%}$ to $D_{5\%}$, of around 0·95) compared with Linac-3DCRT (DHI of 0·79).[14] The differences between endpoint values in this study and in others may be attributed to varying planning parameters and procedures, dose constraints and prescription dose used. For instance, Kim et al.[14] used two posterior oblique beams for TomoDirect plans. As this would incur exit dose to the lungs and double the treatment time in the spine region, multiple beam angles to the spine were not used in this study.

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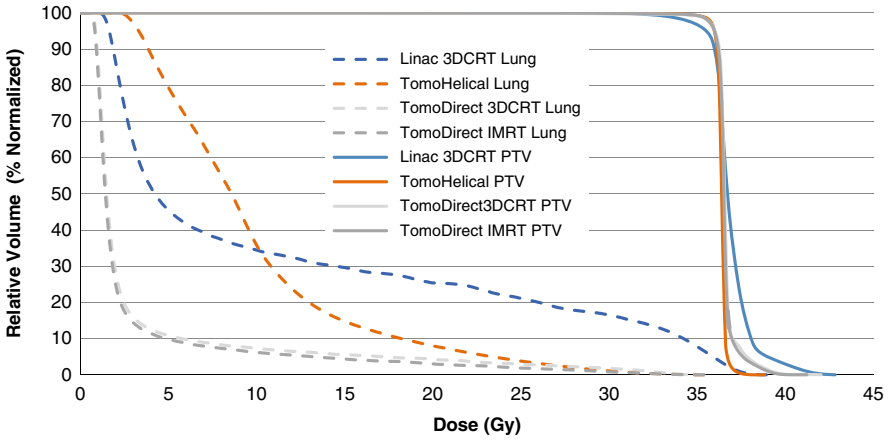

Figure 4. Planning target volume (PTV) dose–volume histogram (DVH) and total lung DVH for patient 1.
Abbreviations: Linac-3DCRT, linear accelerator-based 3D-conformal radiotherapy; IMRT, intensity-modulated radiotherapy.

Table 2. *Homogeneity index and non-target integral dose for all patients*

Patients	Homogeneity index (%)				Non-target integral dose (J)			
	3D	TH	TD3	TDI	3D	TH	TD3	TDI
CSI1	17·3	3·5	8·8	8·3	84·0	68·4	62·1	58·0
CSI2	18·3	2·7	9·7	10·0	175·4	107·8	90·9	83·5
CSI3	19·9	3·2	9·8	10·9	205·9	142·8	124·9	117·0
CSI4	26·9	3·5	8·0	9·6	441·7	320·8	254·2	231·9
CSI5	22·0	4·9	7·3	8·2	343·2	265·5	222·1	214·0

Notes: Data are shown for linear accelerator-based 3D-conformal radiotherapy (3D), TomoHelical (TH), TomoDirect-3D-conformal radiotherapy (TD3) and TomoDirect-intensity-modulated radiotherapy (TDI) plans.
Abbreviation: CSI, craniospinal irradiation.

One of the primary motives for investigating the use of TomoDirect radiotherapy was to reduce NTID compared with Linac-3DCRT and TomoHelical. This was observed for all five patients (Table 2). The low ID is a result of a smaller irradiated volume especially in the spine, where a direct posterior beam orientation avoids all non-target tissues lateral to PTVspine. The clinical implications of lowered NTID is the potential to reduce chances of radiation-induced secondary malignancies.[1,3,6]

Although ID for the TomoDirect CSI technique has never been explored in other studies, many have compared ID between Linac-3DCRT and TomoHelical radiotherapy. As attention first shifted from conventional radiotherapy to IMRT, studies evaluated the potential increase in secondary malignancies due to increased irradiated volumes. Correlation was drawn between ID and increased risk of secondary cancers.[1,9,26] Several authors found that IMRT and TomoHelical IMRT increases ID and therefore, risk of radiation-induced cancers, compared with conventional treatments.[23,27] This conclusion was challenged by various subsequent studies which showed that ID in conventional 3DCRT was comparable with IMRT techniques, including TomoHelical radiotherapy.[9,17,28]

In this study, TomoHelical plans resulted in lower NTID than Linac-3DCRT. This result varied between other studies. In a CSI study by Penagaricano et al.,[9] healthy tissue ID was found to be lower in TomoHelical than Linac-3DCRT in one patient and the opposite for two patients. In a study by Patel et al.,[17] NTID was lower for Linac-3DCRT than for TomoHelical in all of the five patients' plans. The varying results comparing Linac and TomoHelical are due to different Linac planning protocols. In the study by Patel et al.,[17] MLCs were used to shrink the lateral borders of the posterior spine field. This reduced the irradiated volume and subsequently, NTID. Unfortunately, as these studies contained five or less samples, results were not statistically significant.

Evaluating different tomotherapy treatment techniques

TomoDirect-3DCRT and TomoDirect-IMRT are similar in principle and mode of delivery and are expected to deliver similar endpoint results. For TomoDirect-3DCRT, the planning process

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Table 3. *Average volumes of organs-at-risk (OARs) receiving over 5, 10, 20 and 30 Gy*

OAR	$V_{5\,Gy}$				$V_{10\,Gy}$				$V_{20\,Gy}$				$V_{30\,Gy}$			
	3D	TH	TD3	TDI	3D	TH	TD3	TDI	3D	TH	TD3	TDI	3D	TH	TD3	TDI
Pituitary, optic chiasm, brainstem	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
Hearing apparatus	100	100	100	100	100	100	100	100	100	100	100	100	100	92	100	100
Optic nerves	100	100	100	100	100	100	100	100	100	100	98	98	99	59	95	68
Eyes	93	73	83	74	78	29	65	52	64	0	40	26	50	0	21	10
Mandible	83	88	37	29	69	47	24	18	32	7	10	6	6	1	6	3
Parotids	99	100	96	90	90	50	91	79	81	2	79	58	65	0	63	36
Oesophagus	100	94	98	96	100	61	96	93	100	27	93	86	87	3	66	59
Larynx	99	87	93	93	92	50	83	76	83	5	55	46	18	0	10	6
Lungs	47	79	10	9	36	30	6	6	29	5	4	3	19	0	1	1
Breasts	5	61	0	0	2	0	0	0	1	0	0	0	0	0	0	0
Heart	91	30	60	56	87	17	55	50	83	1	46	39	28	0	2	1
Liver	48	78	25	24	43	24	23	22	40	1	19	18	13	0	1	1
Kidneys	46	76	5	4	37	18	3	2	31	0	1	1	25	0	0	0
Testes	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Ovaries	86	22	48	24	82	1	40	13	78	0	26	4	70	0	1	0
Uterus	37	7	17	11	30	0	14	8	24	0	10	5	19	0	2	0
Bowels	59	84	37	35	53	39	33	31	48	4	28	26	22	0	3	3
Non-target body	35	50	22	21	32	26	20	19	29	11	17	16	19	6	10	9

Notes: volumes are shown for linear accelerator-based 3D-conformal radiotherapy (3D), TomoHelical (TH), TomoDirect-3D (TD3) and TomoDirect-intensity-modulated radiotherapy (TDI) plans. Average volumes for two female patients is shown for breasts, ovaries and uterus. Average volumes for three male patients is shown for testes. For other organs, average from five patients is shown.

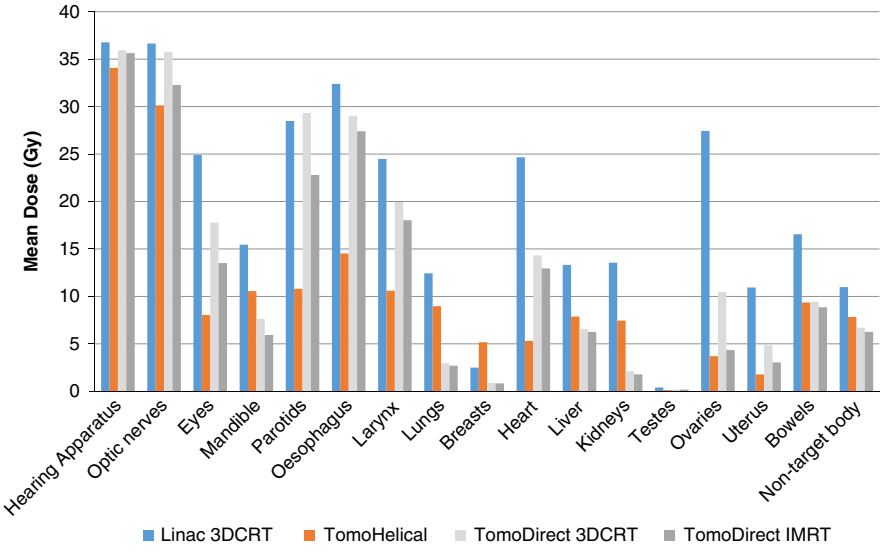

Figure 5. Average D_{mean} (Gy) for organs-at-risk.
Notes: Average D_{mean} for two female patients is shown for breasts, ovaries and uterus. Average D_{mean} for three male patients is shown for testes. For other organs, average from five patients is shown.
Abbreviations: Linac-3DCRT, linear accelerator-based 3D-conformal radiotherapy; IMRT, intensity-modulated radiotherapy.

took into account only the prescription to PTV, without allowing the user to apply constraints to regions-at-risk. Therefore, dose to the target is achieved at the expense of irradiating surrounding OARs. For TomoDirect-IMRT, dose constraints could be applied to regions-at-risk, enabling some dose modulation to lower the dose to OARs surrounding the PTV.[13]

For this study, little difference was observed between DVHs for the two sets of TomoDirect plans, with slightly lower OAR mean doses

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Table 4. Estimated planning and treatment times for each techniques

	Techniques			
	Linac-3DCRT	**TomoHelical**	**TomoDirect-3DCRT**	**TomoDirect-IMRT**
Planning duration (minutes)	60 ± 15	300 ± 90	40 ± 15	100 ± 60
Patient in/out (seconds)	300 ± 30	300 ± 30	300 ± 30	300 ± 30
Patient setup (seconds)	420 ± 60	300 ± 60	300 ± 60	300 ± 60
Image registration (seconds)	180 ± 30	600 ± 120	600 ± 120	600 ± 120
Move isocentre (seconds)	120 ± 30	0	0	0
Beam on (seconds)	78 ± 22	1,183 ± 197	731 ± 189	898 ± 235
Average treatment	1,098 ± 172	2,383 ± 407	1,931 ± 399	2,098 ± 445

Notes: planning durations were established by adding up stopwatch-timed procedures at each step of planning. Average time taken from the host department for linear accelerator-based 3D-conformal radiotherapy (Linac-3DCRT) and tomotherapy procedures are shown.
Abbreviation: IMRT, intensity-modulated radiotherapy.

observed for TomoDirect-IMRT plans. In particular, the parotids received a D_{mean} of over 25 Gy for three out of five TomoDirect-3DCRT plans which exceeds the dose constraint for parotids (75% reduced salivary flow).[20,21]

In the dosimetric analysis, it was demonstrated that TomoDirect-IMRT resulted in better NTID and important normal tissue sparing compared with TomoDirect-3DCRT. This is attributed to the use of inverse planning and the ability to increase dose modulation.

For better PTV homogeneity, TomoHelical radiotherapy is still the method of choice. One notable advantage of TomoHelical planning in the cranial region is the ability to achieve prescription dose to the region between the eyes, especially the cribriform plate, without compromising dose to ocular structures such as the eyes and optic nerves. Organs that are directly anterior to the spine, such as the oesophagus, larynx, heart, ovaries and uterus benefit from TomoHelical planning.

On the other hand, organs where the majority of the volume lies lateral to the single posterior field are thus better spared in TomoDirect compared with TomoHelical radiotherapy. Due to the larger margins and open posterior field arrangement of the traditional Linac-3DCRT technique, the benefit of organ sparing seen in TomoDirect was not observed except in the case of the breasts. This agrees with other studies where breast dose was lower in Linac-3DCRT compared with TomoHelical.[7,24,29]

Despite differences in OAR doses between plans, almost all tomotherapy plans achieved OAR dose constraints. However, only TomoHelical plans achieved D_{max} of eyes below 20 Gy and heart D_{mean} below 3·5 Gy.

Recommendations

This study demonstrated that both TomoHelical and TomoDirect plans offered better OAR sparing endpoints, homogeneity and ID than the traditional Linac-3DCRT technique. It is more difficult to single out a clear winner in the tomotherapy family.

For centres with only tomotherapy, the author recommends the use of TomoDirect technique as an alternative for CSI treatments due to its potentially lower NTID. Also, although TomoHelical treatments offer all around better OAR sparing and homogeneity it should be used with caution as the longer treatment time may lead to increased chances of patient movement due to discomfort. Hence the precise dose targeted to the PTV may not be the actual dose delivered.

The shorter TomoDirect-3DCRT treatment times may be chosen for patients requiring anaesthesia or for those patients who are claustrophobic. Moreover, TomoDirect radiotherapy should be considered for cases where sparing certain organs completely is desirable, especially laterally situated organs such as the breasts. The breasts should receive the lowest dose possible to reduce chances of a secondary malignancy. A peer-reviewed study showed that minimising

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the dose to the breast is inversely related to age and is therefore particularly essential in younger patients.[30] For better homogeneity, NTID and OAR sparing, TomoDirect-IMRT is recommended over TomoDirect-3DCRT.

Conversely, TomoDirect or Linac-3DCRT should not be used if the PTV is covered by the eyes in beam's eye view of the lateral cranial fields. This is because complete coverage of the cribriform plate becomes impossible without significant damage to ocular structures. The TomoHelical technique should be chosen instead.

Although Linac-3DCRT seemed the best in terms of resource distribution due to its short planning and treatment time, these benefits do not outweigh problems in dose homogeneity, NTID and organ sparing. Therefore, for clinics with only Linacs, it may be worth exploring other methods for CSI treatments, such as volumetric-modulated arc therapy (VMAT). VMAT offers a new promising treatment method with decreased ID while offering comparable normal tissue sparing to TomoHelical radiotherapy.[7,17,31] However, this technique does not address the field-size limitation of a Linac, still necessitating junction matching between the cranial and spinal fields, and between two spinal fields for longer PTVs.

LIMITATIONS AND FUTURE DIRECTIONS

There are several limitations in this study. First, biases and confounding variables such as age and gender differences may be present. Furthermore, dose to normal tissue is based on dosimetric information without considering potential clinical variances such as radiation leakage from the machine.

Moreover, due to the limited sample size ($n = 5$), statistical significance could not be achieved. Patterns observed may be due to chance. This is a common problem with CSI studies, as medulloblastoma is a rare disease. In the future, the author hopes to collect more samples for further statistical analyses.

Limitations in estimating planning and treatment times must be noted. All planning times are subject to variances in computer speeds. Similarly, treatment setup and imaging times vary for each patient and each fraction. They should only be used as a reference.

Finally, limitations in the use of theoretical parameters such as HI, conformation number and ID to compare plans apply. There is limited published data regarding the possible correlations between clinical outcome and these indices proposed in the literature. Further research of population-based studies and prospective studies are needed to correlate dosimetric results and ID to late effects and incidences of secondary malignancy.

CONCLUSIONS

This study showed that although TomoDirect plans lacked the PTV dose homogeneity present in TomoHelical plans, they perform better in those aspects than traditional Linac-3DCRT plans. The TomoDirect technique may also reduce PTV inhomogeneity compared with Linac-3DCRT. TomoDirect treatment time is shorter than that of TomoHelical treatments and may be considered for patients requiring anaesthetics. In all, TomoDirect may be an option for cases where the patient needs to be treated supine, require shorter treatment times or better sparing of the laterally situated OAR.

More importantly, TomoDirect plans resulted in the lowest NTID, a factor linked with radiation-induced secondary malignancies. Interestingly, NTID for TomoHelical radiotherapy is also lower than Linac-3DCRT. Conclusions regarding ID should be drawn with caution as the results from comparisons between Linac-3DCRT and TomoHelical radiotherapy differ between studies, suggesting that findings are department specific. Thus it is recommended that each radiotherapy centre conduct its own planning study to obtain results based on their in-house protocols, software, hardware and expertise. In the future, extensive research is needed to evaluate the clinical implications of these findings in the reduction of treatment toxicities and secondary malignancies.

https://doi.org/10.1017/S1460396917000309 Published online by Cambridge University Press

Acknowledgements

None.

Financial support

This research received no specific grant from any funding agency, commercial or non-for-profit sectors.

Conflicts of Interest

None.

References

1. Brodin N P, Munck Af Rosenschold P, Aznar M C et al. Radiobiological risk estimates of adverse events and secondary cancer for proton and photon radiation therapy of pediatric medulloblastoma. Acta Oncol 2011; 50 (6): 806–816.
2. GLOBOCAN. GLOBOCAN 1: cancer incidence and mortality worldwide. J Clin Pathol 2000; 53 (2): 164.
3. Lopez Guerra J L, Marrone I, Jaen J et al. Outcome and toxicity using helical tomotherapy for craniospinal irradiation in pediatric medulloblastoma. Clin Transl Oncol 2014; 16 (1): 96–101.
4. Packer R J, Gajjar A, Vezina G et al. Phase III study of craniospinal radiation therapy followed by adjuvant chemotherapy for newly diagnosed average-risk medulloblastoma. J Clin Oncol 2006; 24 (25): 4202–4208.
5. Ostrom Q T, Gittleman H, Liao P et al. CBTRUS statistical report: primary brain and central nervous system tumors diagnosed in the United States in 2007–2011. Neuro Oncol 2014; 16 (suppl 4): iv1–iv63.
6. Fossati P, Ricardi U, Orecchia R. Pediatric medulloblastoma: toxicity of current treatment and potential role of protontherapy. Cancer Treat Rev 2009; 35 (1): 79–96.
7. Myers P A, Mavroidis P, Papanikolaou N, Stathakis S. Comparing conformal, arc radiotherapy and helical tomotherapy in craniospinal irradiation planning. J Appl Clin Med Phys 2014; 15 (5): 4724.
8. Barrett A. Practical Radiotherapy Planning, 4th edition. London: Hodder Arnold, 2009; viii, 468 pp., 20–21, 214–215.
9. Penagaricano J, Moros E, Corry P, Saylors R, Ratanatharathorn V. Pediatric craniospinal axis irradiation with helical tomotherapy: patient outcome and lack of acute pulmonary toxicity. Int J Radiat Oncol Biol Phys 2009; 75 (4): 1155–1161.
10. Huang F, Parker W, Freeman C R. Feasibility and early outcomes of supine-position craniospinal irradiation. Pediatr Blood Cancer 2010; 54 (2): 322–325.
11. Parker W, Brodeur M, Roberge D, Freeman C. Standard and nonstandard craniospinal radiotherapy using helical TomoTherapy. Int J Radiat Oncol Biol Phys 2010; 77 (3): 926–931.
12. Sugie C, Shibamoto Y, Ayakawa S et al. Craniospinal irradiation using helical tomotherapy: evaluation of acute toxicity and dose distribution. Technol Cancer Res Treat 2011; 10 (2): 187–195.
13. TomoTherapy Treatment System. Tomo Planning Guide 105191A TomoHD Version 1.0.x. Madison, WI: TomoTherapy Incorporated, 2010.
14. Kim J, Jeong K, Chung Y et al. Feasibility of TomoDirect 3D-conformal radiotherapy for craniospinal irradiation. Int J Radiat Oncol 2010; 78 (3): S828.
15. Langner U W, Molloy J A, Gleason J F Jr, Feddock J M. A feasibility study using TomoDirect for craniospinal irradiation. J Appl Clin Med Phys 2013; 14 (5): 104–114.
16. Patil V M, Oinam A S, Chakraborty S, Ghoshal S, Sharma S C. Shielding in whole brain irradiation in the multileaf collimator era: dosimetric evaluation of coverage using SFOP guidelines against in-house guidelines. J Cancer Res Ther 2010; 6 (2): 152–158.
17. Patel S, Drodge S, Jacques A, Warkentin H, Powell K, Chafe S. A comparative planning analysis and integral dose of volumetric modulated arc therapy, helical tomotherapy, and three-dimensional conformal craniospinal irradiation for pediatric medulloblastoma. J Med Imaging Radiat Sci 2015; 46: 134–140.
18. Nakamura N, Shikama N, Wada H et al. Variability in the point to which single direct field irradiation is prescribed for spinal bone metastases: a survey of practice patterns in Japan. J Radiat Res 2013; 54 (6): 1065–1068.
19. Gupta T, Sarin R. Palliative radiation therapy for painful vertebral metastases: a practice survey. Cancer 2004; 101 (12): 2892–2896.
20. Marks L B, Yorke E D, Jackson A et al. Use of normal tissue complication probability models in the clinic. Int J Radiat Oncol Biol Phys 2010; 76 (3 suppl): S10–S19.
21. Roesink J M, Moerland M A, Battermann J J, Hordijk G J, Terhaard C H. Quantitative dose-volume response analysis of changes in parotid gland function after radiotherapy in the head-and-neck region. Int J Radiat Oncol Biol Phys 2001; 51 (4): 938–946.
22. Société Française de Radiothérapie Oncologique (SFRO). Guide des procédures de radiothérapie externe 2007, 2007. http://www.has-sante.fr/portail/upload/docs/application/pdf/2008-08/guide_de_rth_des_tumeurs_v7_complet.pdf. Accessed on 20th April 2015.
23. Verellen D, Vanhavere F. Risk assessment of radiation-induced malignancies based on whole-body equivalent dose estimates for IMRT treatment in the head and neck region. Radiother Oncol 1999; 53 (3): 199–203.
24. Yoon M, Shin D H, Kim J et al. Craniospinal irradiation techniques: a dosimetric comparison of proton

beams with standard and advanced photon radiotherapy. Int J Radiat Oncol Biol Phys 2011; 81 (3): 637–646.

25. Mayneord W V. The measurement of radiation for medical purposes. Proceedings of the Physical Society, 1942; 54: 405–421.
26. Nguyen F, Rubino C, Guerin S et al. Risk of a second malignant neoplasm after cancer in childhood treated with radiotherapy: correlation with the integral dose restricted to the irradiated fields. Int J Radiat Oncol Biol Phys 2008; 70 (3): 908–915.
27. Hall E J, Wuu C S. Radiation-induced second cancers: the impact of 3D-CRT and IMRT. Int J Radiat Oncol Biol Phys 2003; 56 (1): 83–88.
28. Barra S, Gusinu M, Cavagnetto F et al. Comparison of treatment plans between 3D-CRT and helical tomotherapy based on integral dose delivered to pediatric patients receiving craniospinal irradiation. Int J Radiat Oncol Biol Phys 2010; 78 (3): S594.
29. Sharma D S, Gupta T, Jalali R, Master Z, Phurailatpam R D, Sarin R. High-precision radiotherapy for craniospinal irradiation: evaluation of three-dimensional conformal radiotherapy, intensity-modulated radiation therapy and helical Tomo-Therapy. Br J Radiol 2009; 82 (984): 1000–1009.
30. Stovall M, Smith S A, Langholz B M et al. Dose to the contralateral breast from radiotherapy and risk of second primary breast cancer in the WECARE study. Int J Radiat Oncol Biol Phys 2008; 72 (4): 1021–1030.
31. Srivastava R, Saini G, Sharma P K et al. A technique to reduce low dose region for craniospinal irradiation (CSI) with RapidArc and its dosimetric comparison with 3D conformal technique (3DCRT). J Cancer Res Ther 2015; 11 (2): 488–491.