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Evaluation of intracranial stereotactic treatment plans: a comparison study of CyberKnife and TrueBeam systems

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Original Article

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CyberKnife; gradient index (GI); homogeneity index(HI); new conformity index (nCI); selectivity index (SI); SRS; SRT; TrueBeam

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Abstract

Background: Stereotactic radiotherapy (SRT) for patients with intracranial tumours are delivered using a dedicated platform or a conventional linear accelerator with a flattening filter-free beam.

Materials and methods: This study compares treatment plans with intracranial tumours. A total of 29 patients were treated on CyberKnife and planned using the Accuray Precision. The same structure sets ws then exported to Varian Eclipse, and plans were made using a 6 MV FFF beam. Both plans were compared for parameters of target coverage, homogeneity index (HI), new conformity index (nCI), gradient index, selectivity index (SI), volumetric and OAR doses.

Results: The treatment plans made for CyberKnife exhibit better results in terms of nCI (1·168 ± 0·08 versus 1·173 ± 0·077), SI (0·885 ± 0·05 versus 0·877 ± 0·05) and GI (3·64 ± 0·5 versus 4·45 ± 1·25), while HI values are better for TrueBeam. For OAR doses, in 65·5% and 72% of treatment plans, brainstem and optic pathways received lower doses on CyberKnife, respectively. In terms of dose spillage, Truebeam plans are better for very low doses ($V_{5\%}$), while for $V_{10\%}$, $V_{20\%}$ and $V_{50\%}$ CyberKnife plans are better.

Conclusion: CyberKnife is a better modality for the delivery of SRS/SRT to intracranial tumours except for dose homogeneity where TrueBeam offered better results.

Introduction

The efficacy and usefulness of stereotactic radiosurgery and stereotactic radiation therapy (SRS/SRT) over conventional radiotherapy have been well-established by many investigators.[1–3] Modern radiotherapy techniques are based on precise target localisation and implementation of multiple coplanar or non-coplanar beams to deliver a highly precise and conformal radiation dose to the tumour while administering the minimal dose to normal tissues. Consequently, the dose per fraction to target the tumour may be increased to a very high level as compared with the conventional fractionation, exempting the need to give time for normal tissue healing. This paves the way to SRS/SRT.[4,5]

The debate on the selection of a suitable platform for the delivery of SRS treatment has been there since the advent of the technique. Currently, dedicated SRS platforms CyberKnife and Gamma Knife are commercially available, while linear accelerators with flattening filter-free (FFF) beams also offer optimal results.[6] Both platforms have their advantages and disadvantages for treatment delivery. Their comparisons for different sites have been reported in the literature with both phantom and retrospective patient data.[7–13] A few of the research articles presented a comparison of intracranial treatment plans using different modalities. The present study is focused on the comparison of intracranial treatment plans made to be delivered on CyberKnife and TrueBeam.

Materials and Methods

In this study, CyberKnife, M6 Model (Accuray, Sunnyvale, CA, USA) and TrueBeam (Varian Medical Systems, CA, USA) have been used as SRS treatment modalities. The treatment planning was performed on the Accuray Precision TPS (version 3·3·1) using the Ray Tracing dose calculation algorithm for CyberKnife and on the Varian Eclipse TPS using the Acuros XB algorithm for TrueBeam. The dose rates of CyberKnife and TrueBeam are 950 MU/min and 1000 MU/min, respectively. A 6 MV FFF beam was used for treatment plans of both modalities.

Twenty-nine patients with intracranial tumours of miscellaneous sizes and types were treated on CyberKnife during the 8-month interval of this study. The types of tumour included in this study were meningioma, AVM, glioma, pituitary adenoma, schwannoma and brain mets.

The target volume for each plan comprised of a gross tumour volume (GTV) and a planning tumour volume (PTV) where PTV was obtained by adding a 1 mm symmetric margin around GTV. The volume of the PTV ranged between 0·99 and 79·2 cc with an average of 16·53 cc. The organs at risk (OAR) contoured by the oncologists included mostly the normal brain (whole brain minus GTV), optic pathway (sum of all optic structures including the optic chiasm, optic nerves, eyes and lenses) and the brainstem.

For CyberKnife, most of the patients were planned using three or fewer collimators, whereas the number of non-coplanar beams ranged from 88 to 257. All the plans were verified for patient-specific quality assurance (PSQA) by measuring point doses using Sun Nuclear SNC 125c (active volume: 0·125 cc) and Exradin A14SL (active volume: 0·016cc) ion chambers. A commercially available stereo phantom (StereoPHAN) was used for point dose measurements.

For TrueBeam, the treatment plans were prepared with arc therapy using two full arcs of the volumetric arc therapy technique. The PSQA plans were created from the SRS/SRT plans and delivered on an electronic portal imaging device using portal dosimetry. All plans complied with 3%/3 mm criteria with a 95% confidence interval.

In both cases, the outcome for planning was set to be the coverage of PTV and GTV. The optimisation was repeated until minimum doses for OARs were achieved while keeping the target coverage optimised.

The treatment plans prepared for CyberKnife and TrueBeam were evaluated by a combined team comprising physicists and oncologists using the following treatment planning outcomes and indices.

Target coverage

Target coverage is defined as the volume receiving 100% of the prescribed dose.[14] Target coverage for both PTV and GTV was compared.

$$Target\ coverage = \frac{PTV\_V_{PD}}{PTV\_V}$$

Selectivity index (SI)

SI is defined as the quotient of the PTV volume and the body receiving the prescribed dose.

$$SI = \frac{PTV\_V_{PD}}{Body\_V_{PD}}$$

were PTV_V_{PD} and Body_V_{PD} are volumes of target and body, respectively, within the prescribed dose isodose line. The SI indicates how much of the normal tissue surrounding the target is being irradiated by the prescribed dose. The value 1 of the SI indicates the ideal situation of no irradiation of normal tissue beyond the target volume with the prescribed dose. Its value should be higher than 0·9 while greater than 0·75 for SRS/SRT is also acceptable.[15]

New conformity index (nCI)

The conformity index (CI) is defined as the quotient of volume within the prescription isodose curve with the volume of PTV. These volumes may not overlap each other which leads to a deficit in the calculation of CI value. CI equal to 1 indicates that the volumes of the prescription isodose line and the PTV are equal but cannot identify the non-overlapping region resulting in missed coverage and spillage of prescribed isodose.[14,16,17] This issue was addressed by defining the new conformity index (nCI) which indicates the degree of conformality with which the target is being conformed by the prescribed isodose curve. It is a tool to assess the conformity of delivered doses.[18] nCI equals to 1 indicates 100% PTV coverage with no spillage of isodose to the surrounding normal tissues. The inverse of nCI is called the Paddick conformity index (PCI).[15,19]

$$PCI = PTV\ coverage \times SI$$

$$nCI = \frac{1}{PCI}$$

Homogeneity index (HI)

Homogeneity index is defined as the quotient of the maximum and minimum dose received by the PTV.[14,20] HI equals to 1 signifies no hot spots or cold spots within or outside the target volume.

$$HI = \frac{PTV\_D_{max}}{PTV\_D_{min}}$$

Gradient index (GI)

GI is defined as the quotient of volumes of the body receiving 100–50% of the prescribed dose. The GI signifies the rate of decrease of dose outside the target volume. For SRS/SRT, its optimal value is less than or equal to 3, but it should not exceed 5.[15]

$$GI = \frac{Body\_V_{PD}}{Body\_V_{50\%\ of\ PD}}$$

where Body_V_{PD} is the volume of the body receiving the prescribed dose and Body_$V_{50\%\ of\ PD}$ is the volume of the body receiving 50% of the prescribed dose.[19]

The comparison of CyberKnife and TrueBeam plans was made as the quotient of CyberKnife value and TrueBeam value. A value greater than unity signifies the higher value of the parameter for the TrueBeam plan and vice versa.

For comparison, the ratio of indices values for CyberKnife to TrueBeam (CK-TB) was calculated.

$$\frac{CyberKnife\ (CK)}{TrueBeam\ (TB)} = \frac{Index\ value\ for\ CyberKnife}{Index\ value\ for\ TrueBeam}$$

Volumetric doses

Lower dose spillage was compared by evaluation of doses received by the body with 5, 10, 20, and 50% of the prescribed doses, denoted as $V_{5\%}$, $V_{10\%}$, $V_{20\%}$ and $V_{50\%}$, respectively.

OAR dose constraints

Dose constraints for intracranial treatment plans including Dmax, D0·03cc and D10% of the brainstem, optic pathway (Boolean of all optic structures), spinal cord planning risk volume (PRV) (including the medulla) and V12Gy, V18Gy and V5Gy of the normal brain were evaluated and compared. PRVs for OARs were drawn by adding a 1 mm margin to the respective OARs.[21,22]

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Table 1. Acceptability criteria for target volumes and OARs in case of intracranial SRS/SRT[21]

	One fraction	Three fractions	Five fractions
GTV coverage ($V_{100\%}$)*	100%	100%	100%
PTV coverage ($V_{100\%}$)	> 95%	> 95%	> 95%
OARs		Acceptability criteria of dose constraints	
Brainstem ($D_{0\cdot035cc}$)	< 10 Gy (Optimal) < 15 Gy (Mandatory)	< 18 Gy (Optimal) < 23·1 Gy (Mandatory)	< 23 Gy (Optimal) < 31 Gy (Mandatory)
Optic pathway ($D_{0\cdot035cc}$)	< 8 Gy (Optimal) < 10 Gy (Mandatory)	< 10 Gy (Optimal) < 15 Gy (Mandatory)	< 22·5 Gy (Optimal) < 25 Gy (Mandatory)
Normal brain	V_{12Gy} < 10 cc	< 50 cc	–

OARs, organs at risk; SRS/SRT, stereotactic radiosurgery and stereotactic radiation therapy; GTV, gross tumour volume; PTV, planning tumour volume.
*GTV coverage was achieved 100 in 99% of the cases, while it was greater than 99.5 in 100% of cases.

Treatment planning goals for targets and dose constraints for OARs that were considered in this study are given in Table 1.

Results and Discussion

A total of 29 SRS/SRT plans with 1, 3 and 5 fractions were evaluated. Out of these 28 patients, 8 were treated with single fraction, 9 patients were treated with 3 fractions, and 12 patients were treated with 5 fractions. All the plans were evaluated, and a comprehensive comparison was made, based on treatment planning parameters and evaluation indices. The results of these comparisons are given in Table 2 and discussed below.

Dosimetric parameters and evaluation indices

The mean value of the indices along with their range and standard deviation from all the treatment plans are stated. The CyberKnife plans recorded better values of GTV coverage, SI, GI and nCI in comparison to TrueBeam plans. On the contrary, the HI is relatively better achieved in a treatment plan for TrueBeam. The evaluated results for CyberKnife and TrueBeam are given in Table 2.

The ratio of the dosimetric parameters and evaluation indices values from the treatment plans for CyberKnife and TrueBeam are plotted against the patient number as shown in Figure 1. The graphs show that CyberKnife is superior to TrueBeam as nCI and GI are better for CyberKnife in 15 and 23 out of 29 treatment plans, respectively, while HI for TrueBeam is better in 27 treatment plans out of 29.

Dose spillage

Although GI provides the measure of dose spillage beyond the PTV boundaries, it signifies the dose drop of 50% isodose line.[19] GI does not consider low doses which are absorbed in the surrounding normal tissues. For the assessment of low doses, values of $V_{5\%}$, $V_{10\%}$, $V_{20\%}$ and $V_{50\%}$ as a percentage of total body volume are evaluated. The results of the comparison are given in Table 3.

Figure 2 shows a comparison of $V_{5\%}$, $V_{10\%}$, $V_{20\%}$ and $V_{50\%}$ doses as CK–TB values. For $V_{5\%}$, more treatment plans with greater than 0 value signify the higher value for CyberKnife treatment plans. For $V_{10\%}$, $V_{20\%}$ and $V_{50\%}$, more points are below the zero line which shows that the values of these parameters are less in the CyberKnife treatment plans than in the TrueBeam.

Doses of OARs

The doses received by OAR are linked to their proximity to the PTV. In some cases, these OARs about the GTV and PTV are making it difficult to achieve the desired tumour coverage. The $D_{0\cdot035cc}$ doses for brainstem and optic pathways were evaluated and compared as shown in Table 4.

The doses received by the brainstem and optic pathway are linked to their proximity towards the target volume. In some of the treatment plans, these OARs are being abutted by the tumour, making it difficult to achieve the desired tumour coverage while sparing the normal tissues. The tolerance doses $D_{0\cdot035cc}$ of the brainstem and optic pathways were evaluated in treatment plans prepared for CyberKnife and TrueBeam.

Figure 3 illustrates the status of individual patient doses for both OARs as the difference between CyberKnife and TrueBeam treatment plans. A negative value exhibits less dose received by the OAR from the CyberKnife treatment plan while a positive value shows a higher dose received from the CyberKnife treatment plan. To summarise the results, in 65·5 and 72·5% of patients, the brainstem and optic pathway received lesser doses in the CyberKnife treatment plans, respectively.

For normal brain percent doses, V_{5Gy}, V_{12Gy} and V_{18Gy} were evaluated and compared for CyberKnife and TrueBeam.

Figure 4 shows the comparison of doses received by the volume of normal brain in CyberKnife treatment plans versus TrueBeam. A negative value exhibits a better treatment plan with CyberKnife. Figure 4 shows that for the majority of patients (22 out of 29), the volume of the brain receiving 5 Gy dose is lower for CyberKnife plans than TrueBeam. A similar trend has been observed for V_{12Gy} where 18 out of 10 treatment plans showed negative values. For V_{18Gy}, the comparison of the values is insignificant. The absolute difference in values of volumetric doses for the normal brain is higher for V_{5Gy} (mean 2·87 ± 1·77 Gy) than the difference for V_{12Gy} (mean 1·18 with an exception of 16·7 Gy) and V_{18Gy} (mean 0·34 ± 0·38 Gy).

Several research articles, previously published, support these results. These studies either include retrospective patient data or are done on a phantom.

Makoto Ito et al.[20] compared treatment plans for TrueBeam and CyberKnife made on dummy targets on a phantom. The targets include cube and spherical shapes of different sizes. A total of 16 plans for each modality were made. They reported higher means target doses, less homogeneity and similar conformity in CyberKnife plans as compared with the TrueBeam plans.

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Table 2. Comparison of evaluation indices in treatment plans of CyberKnife versus TrueBeam

Treatment planning outcomes	CyberKnife	TrueBeam
PTV coverage	97·5 ± 1·15 (91·1–99·8)	97·5 ± 1·15 (91·1–99·8)
GTV coverage	99·72 ± 0·93 (95–100)	99·3 ± 1·48 (92·4–100)
SI	0·885 ± 0·05 (0·73–0·95)	0·877 ± 0·05 (0·76–0·96)
nCI	1·168 ± 0·08 (1·06–1·40)	1·173 ± 0·077 (1·07–1·35)
HI	1·32 ± 0·07(1·15–1·44)	1·117 ± 0·06 (1·04–1·35)
GI	3·64 ± 0·5 (2·49–4·47)	4·45 ± 1·25 (2·77–8·06)

PTV, planning tumour volume; GTV, gross tumour volume; SI, selectivity index; nCI, new conformity index; HI, homogeneity index; GI, gradient index.

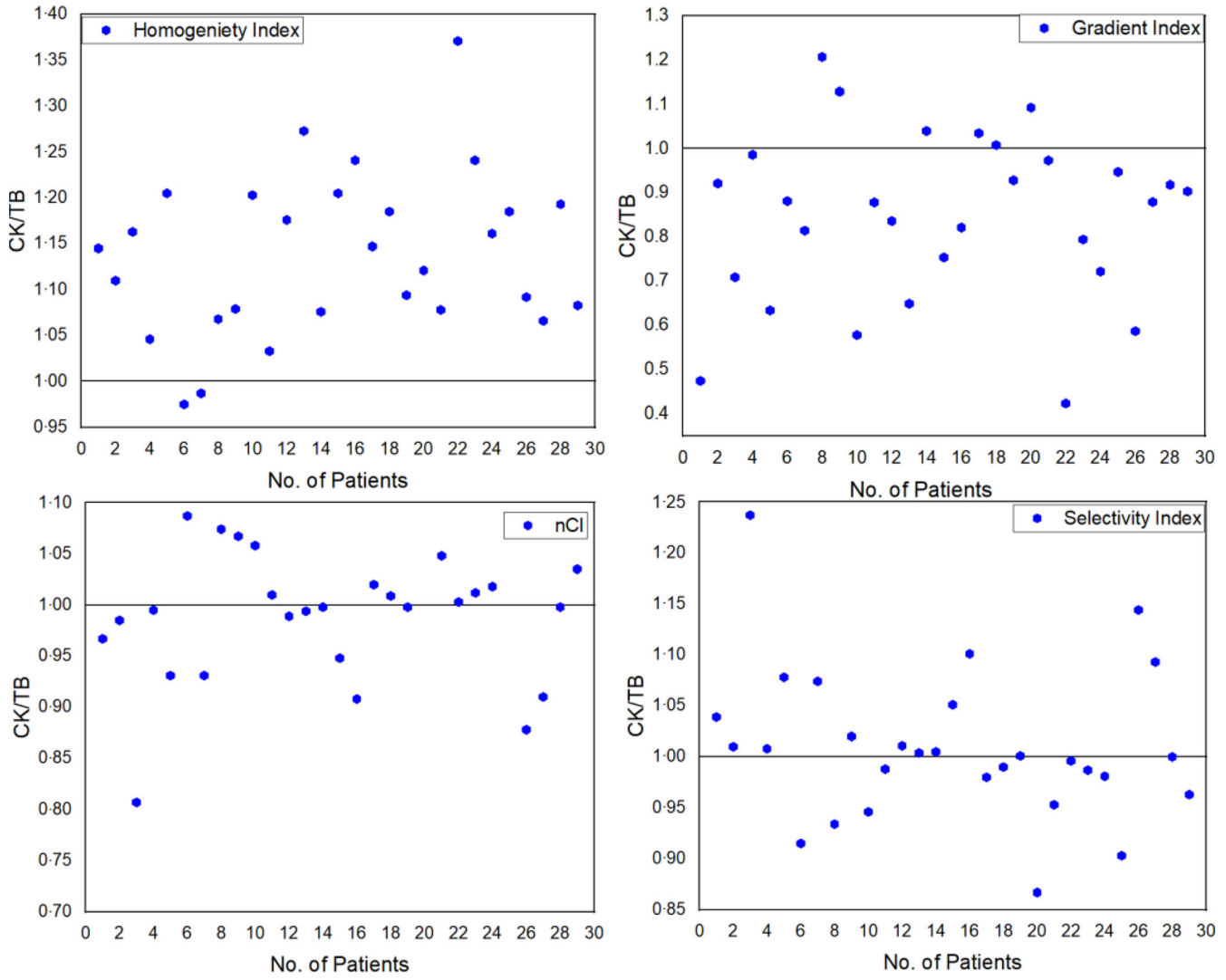

Figure 1. The graphs showing planning endpoints for both CyberKnife and TrueBeam plans. For each parameter, a point having a value above 1 signifies higher values for that parameter for the CyberKnife plan and vice versa.

Gevaert et al.[23] compared the treatment plans of patients treated on Gamma Knife with the plans made on Novalis (Brain lab) and CyberKnife. They compared conformity, homogeneity and gradient indices of the plans made on these three machines. Their sample size was a total of 15 patients (5 acoustic neuromas and 10 AVM). Although they reported that Gamma Knife plans are superior to the other two, CyberKnife showed better values in all three indices as compared with the conventional linear accelerator (LINAC)-based plans.

Dutta et al.[24] compared seven patient plans retrospectively treated on CyberKnife diagnosed with acoustic neuromas. Their results also support our study with similar conclusions. They reported comparable values of CI in both plans but better OAR sparing in CyberKnife plans as compared with the plans made on

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Table 3. Dose spillage in treatment plans of CyberKnife versus TrueBeam

	$V_{5\%}$	$V_{10\%}$	$V_{20\%}$	$V_{50\%}$
CyberKnife	–	18, 3·5%, (0·1–16·5%)	24, 1·6%, (0·2–3·4%)	16, 0·25%, (0–1·7%)
TrueBeam	23, 9%, (0·7–34%)	–	–	–

where X, Y%, (Z_1–Z_2%), X = number of patients for which the index has a negative value, Y% = mean of difference between CyberKnife and TrueBeam results, and Z_1–Z_2% = range of difference.

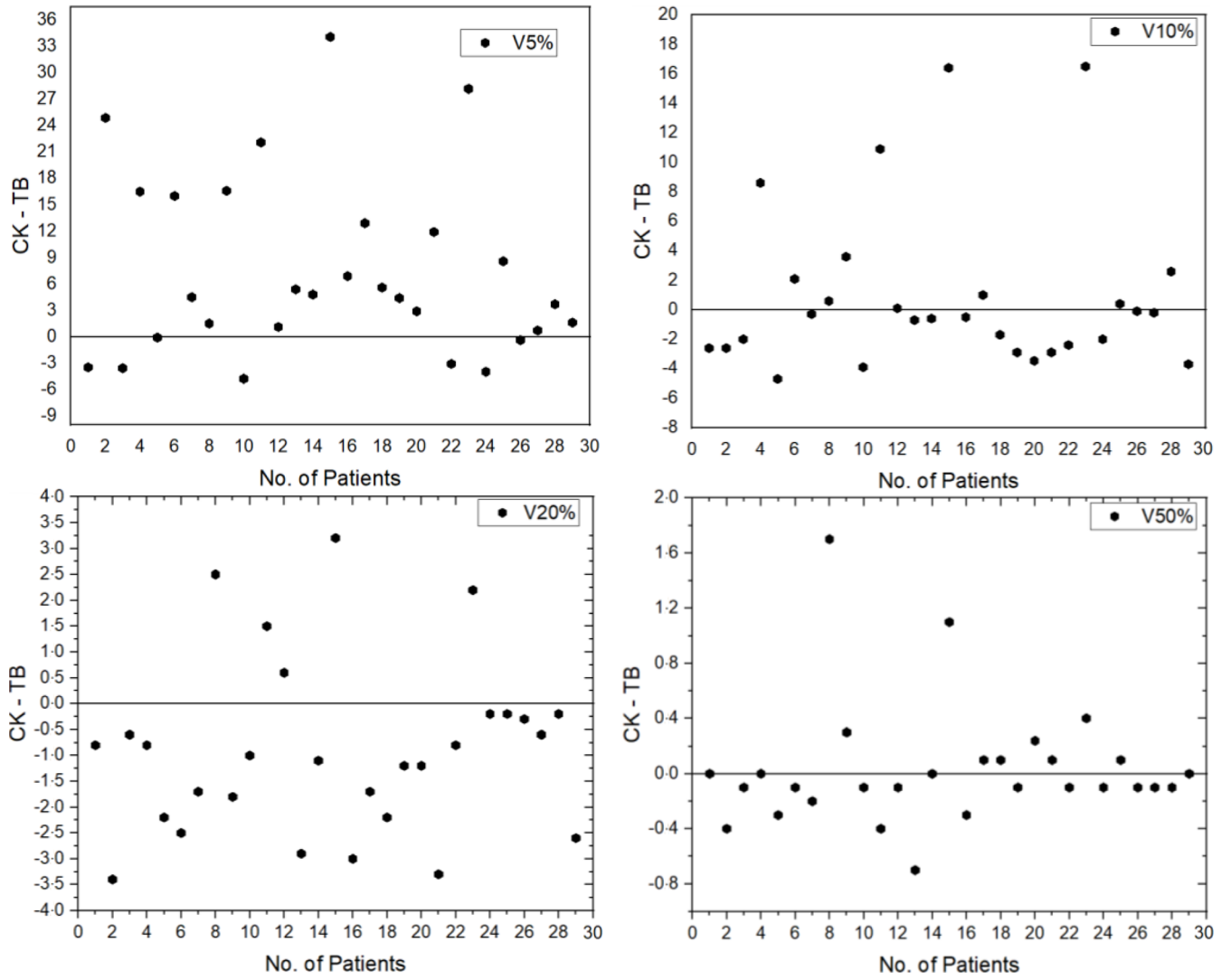

Figure 2. Low doses received by the patient's body from CyberKnife and TrueBeam plans as CK–TB values for the parameter. A negative value signifies the lower volume irradiated in CyberKnife plans.

Brain lab. Their results are different from ours in the aspect of low-dose spread. Their results showed that lesser volumes are being irradiated with low doses in Brain lab plans as compared with CyberKnife.

David Kaul et al.[25] also did a retrospective study of patients diagnosed with meningioma. They compared plans of ten patients made on CyberKnife and LINAC-based systems (Novalis). They concluded that CyberKnife plans are superior in terms of conformity and homogeneity.

Most of the studies are confined to either single or two tumour types, with smaller volumes and only to a single fraction. The analysis of dose spillage into the normal tissue is also lacking in previous studies. Our study encompassed almost all types of brain tumours being treated for radiosurgery with different sizes including large tumours. It also includes plans comparison both with SRS and SRT techniques. The results are all supported by previous studies except few parameters.

Conclusion

The treatment plans made on CyberKnife showed better values of conformity and gradient indices, while the plans made on

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Table 4. Doses of OARs in treatment plans of CyberKnife versus TrueBeam

	Brainstem	Optic pathway
CyberKnife	19, 2·52 ± 3·52 Gy, (0·02–15 Gy)	21, 1·65 ± 2·56 Gy, (0·01–13·6 Gy)
TrueBeam		

where X, Y%, (Z_1–Z_2%), X = number of patients for which the dose to the OAR is lower, Y = mean of difference between CyberKnife and TrueBeam results with uncertainty, and Z_1–Z_2% = minimum to maximum doses.
OAR, organs at risk.

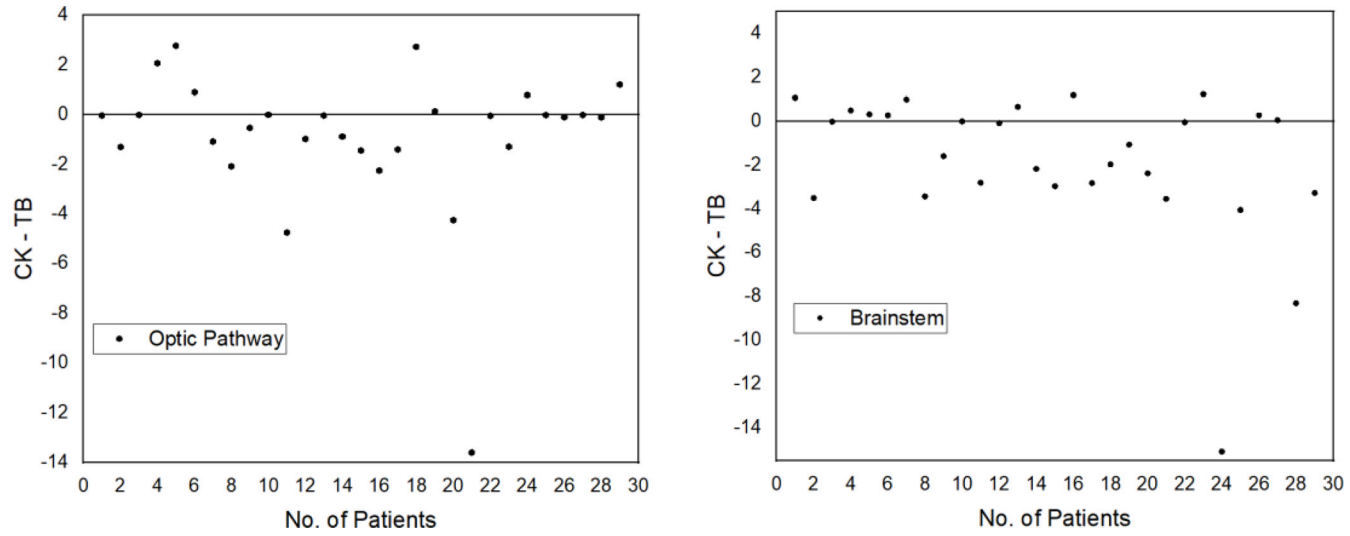

Figure 3. Doses received by the brainstem and optic pathway in treatment plans for CyberKnife and TrueBeam plans. A positive value signifies a higher dose from TrueBeam plans and vice versa.

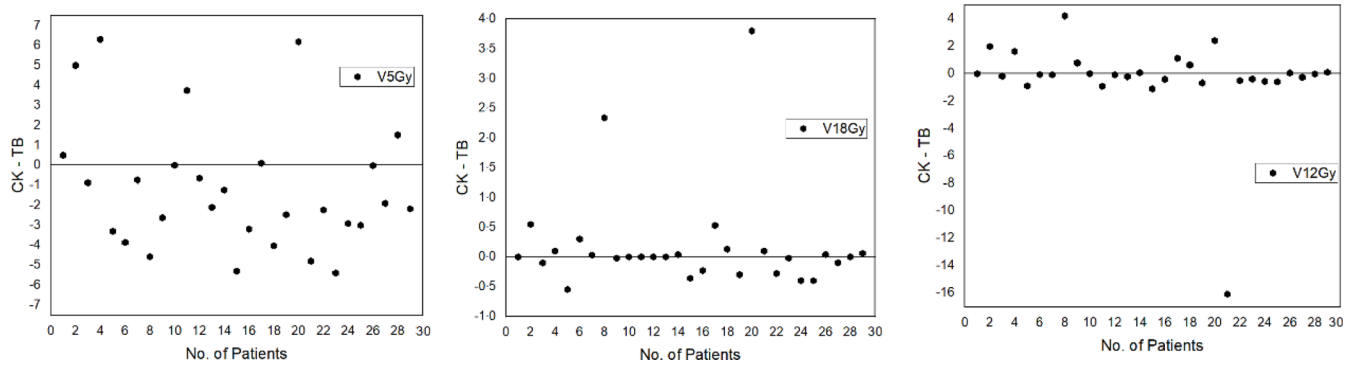

Figure 4. Doses received by normal brain with CyberKnife and TrueBeam treatment plans. A negative number indicates that a smaller volume of the normal brain has received the respective dose in the case of the CyberKnife treatment plan.

TrueBeam are more homogenous. The CyberKnife presented better results in sparing brainstem and optic structures as compared with the TrueBeam plans with similar target coverage. The normal brain was also more spared in the CyberKnife plans than TrueBeam. Low-dose spread is also a very important factor to consider while planning radiation therapy. For very low doses (5% of the prescribed dose), the TrueBeam showed better results. The volume of the body irradiated with a low dose is smaller for TrueBeam than for CyberKnife. But for higher doses, that is, 10, 20 and 50% of the prescribed doses, CyberKnife has shown an evident advantage over TrueBeam. From the results, it is concluded that CyberKnife is superior to TrueBeam for the delivery of SRS/SRT treatment to patients with intracranial tumours.

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