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Dose deviations induced by fractional image guidance system errors in intensity-modulated radiotherapy for brain tumor treatment

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ABSTRACT

Background: Intensity-modulated radiotherapy (IMRT) techniques have a steep dose distribution, leading to large dosimetric errors caused by incorrect daily patient setup. Image-guided radiotherapy (IGRT) is an essential technique to verify accurate patient setup. The accuracy of verifying a patient's position depends on many factors including the image guidance system and image registration software.

Objectives: This study investigated the dosimetric and geometric differences between the original plan and simulated plans with setup errors associated with kilovoltage cone-beam computed tomography (kV-CBCT), kV, kV planar image, and electronic portal imaging detector (EPID) for brain tumor treatment using IMRT.

Materials and methods: A PIXY Anthropomorphic Training/Teaching Phantom was used in this study. IMRT treatment plans with five co-planar fields from a 6 MV Elekta Versa HD linear accelerator were generated using the RayStation computer treatment planning system. Three image guidance systems, including kV-CBCT, kV planar imager, and EPID were used to perform image registration. To evaluate the efficiency of each image guidance system, a simulated setup error by couch was shifted 0, ±2, and ±4 mm in the lateral, longitudinal, and vertical planes. Errors in the image registration from the actual couch shift were collected. Measured errors were used to generate the treatment plans of 25 fractions using the IMRT technique by random shifts of the isocenter of each fraction while maintaining other planning parameters of the original plan. The dose deviation in planning target volume (PTV) and geometric deviation compared to original plan were recalculated and analyzed.

Results: Accuracy of image registration in all image guidance systems indicated that the registration errors were less than 1.7, 2.0, and 1.0 mm for the kV-CBCT, kV planar, and EPID, respectively. The average PTV dosimetric deviation induced by the setup error ranged from -2 to 2 mm per fraction; this study showed dosimetric deviation at $D_{98\%}$ approximately -6%, $D_{95\%}$ approximately -4% and $D_{2\%}$ below -1%, while the average of isodose distribution shift of -5% inside the PTV of the isocenter region were -1.58±0.67, -1.28±0.52 and -1.30±0.80 mm in the cerebella, parasagittal, and convex areas, respectively. An isodose shift of -10% was <1 mm in all PTV locations.

Conclusion: The efficiency of image guidance resulted in small errors within ±2 mm using kV-CBCT, kV planar, and EPID. The setup error influenced daily dose distribution, while the PTV recorded underdose of about 4% in the brain IMRT technique.

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Introduction

The highly conformal radiation treatment technique allows for high doses to be given to the target volume while sparing the surrounding tissue. Intensity-modulated radiotherapy (IMRT) techniques are widely used in radiotherapy because they can deliver a highly conformal dose distribution to the target volume while sparing the normal tissue.[1] However, the steep dose distribution of the IMRT technique can lead to large dosimetric errors caused by incorrect patient positioning. Therefore, the accuracy of patient positioning is the main factor for radiotherapy treatment success. Any shift from the intra-inter fraction can result in dose variation in the target volume and organs at risk (OAR) between planned and delivered doses. Positioning verification by image-guided radiotherapy (IGRT) is used to improve the position accuracy. Modern image guidance techniques offer more precise patient positioning with different image modalities such as kilovoltage cone-beam computed tomography (kV-CBCT), kV x-ray planar imaging, and electronic portal imaging detector (EPID) systems. However, these modalities offer different pre-treatment position accuracy, which can impact system error and estimation of CTV-PTV margins.[2-6] The delivered dose of the kV planar image is lower and image quality is better than an MV image but its isocenter is not in the same direction as the linear accelerator (Linac). CBCT provides high resolution 3D patient anatomy which helps to achieve high position verification accuracy[7] and a lower dose than two MV planar images (AP-lateral). Devereux *et al*.[8] suggested kV imaging as the method of choice for head and neck IGRT but the setup errors of kV-CBCT are smaller than for the kV planar image, and the CTV-PTV margin could be reduced.[9] Ideally, the patient's position should be controlled and corrected for every fraction but fractional imaging comprises additional doses for the patient.

Metastatic brain tumors are commonly found in the northern region of Thailand.[10] For brain metastatic patient treatment, long-term survival and neurocognitive improvements were found to be correlated with lesion control. Treatment dose compromise could partially preserve the neurocognitive memory functions.[11-12] Therefore, the treatment of patients with metastatic brain tumors using IMRT presents challenges to improve potential long-term survival. Clinical studies have shown that IMRT techniques reduce complications compared to whole-brain radiotherapy (WB-RT) or 3D conformal radiotherapy. Brain treatment requires a rigid immobilization technique, and daily inter-fractional setup errors may cause an underdose in the target volume and overdose in normal tissues near the target. Matching of the planning CT and in-room images is limited by the modality and algorithms of image registration.

This study investigated the dosimetric and geometric differences between the original plan and the simulated plans with setup errors using kV-CBCT, , kV planar image, and EPID for brain tumor treatment using IMRT techniques.

Materials and methods

CT simulation and planning

The experiment was performed at Lampang Cancer Hospital using a Philips Brilliance Big Bore CT simulator (Philips Medical System, Cleveland, OH) to scan a supine PIXY Anthropomorphic Training/Teaching Head Phantom with a short thermoplastic mask placed on a B head rest with a 2-mm slice thickness. CT image data were then transferred to the RayStation computer treatment planning system version 11B (RaySearch Laboratories, Stockholm, Sweden) for target delineation and dose distribution calculation in the brain. The radiation oncologist drew the simulated target volume and organs at risk (OARs) contours from the CT images slice-by-slice on each axial slice plane, with slice thickness of 5 mm. The spherical target volume included three locations at the cerebella and parasagittal regions of the brain and a convex shape near the skull vertex, with an approximate size of 2.5 cm in diameter. The planning target volume (PTV) was created by symmetrically expanding the target volume or clinical target volume (CTV) with a 5-mm margin in all directions. The prescribed dose was 5,000 cGy in 25 conventional fractions and normalized dose to $D_{95\%}$ of PTV. IMRT treatment plans with five co-planar fields from a 6 MV Elekta Versa HD linear accelerator (Elekta, Stockholm, Sweden) were generated using the RayStation treatment planning system. The Elekta Versa HD linear accelerator has 160 tungsten Agility multi-leaf collimators (MLC) with 9 cm thickness and 0.5 cm width and a leaf speed of 3.5 cm/s. The carriage can travel at up to 3 cm/s, thus giving a maximum MLC speed of 6.5 cm/s.

Evaluation of image guidance system accuracy

Image guidance systems such as kV-CBCT, kV planar imager, and EPID can be attached to the Elekta linear accelerator for position verification according to the machine's protocol. The kV-CBCT imaging and kV planar image were performed using an x-ray volumetric imaging (XVI) system mounted on a linear accelerator. The kV-CBCT imaging technique operates at 100 kV, 10 mA, with the angular range of 200° and the angular separation of 0.54°. The kV planar imaging technique uses 100 kV and 0.5 mAs. The MV imaging technique with the EPID used 2 MUs of 6 MV x-rays. Simulation of the intentional setup error by moving the couch in each plane was performed at 0, ±2, and ±4 mm in the lateral (X), longitudinal (Y), and vertical (Z) planes, including combinations of ±2 mm and ±4 mm in all planes, and was used to verify the accuracy of the image registration software for each image guidance system. The planning CT images and in-room images of each image guidance system were automatically registered in XVI software based on the Feldkamp-Davis-Kress algorithm, using bone matching and soft tissue-gray value matching followed by manual correction by the same technician. The results of phantom setup errors from the actual translation are shown in Table 1. The accuracy of the image guidance system presented extremes in setup errors different to the actual translation below 1.7 mm, 2.0 mm, and 1.0 mm for the kV-CBCT, kV planar, and EPID images, respectively.

Simulation of dosimetric deviation induced by the errors of the image guidance systems

This study simulated a plan with a setup error as the isocenter of each fraction shifted based on the image guidance system errors in the previous process of evaluation of the image guidance system accuracy. The simulated plans with the setup error were created for all 25 fractions (200

cGy/fraction) using the isocenters of the simulated plans which were randomly shifted from -2 to 2 mm in three dimensions from the original treatment isocenter on the translation plane for all 25 simulated fractions. The other parameters of planning remained unchanged and the dose distribution for each fraction was recalculated. Dosimetric deviations in terms of the PTV as $D_{98\%}$, $D_{95\%}$, and $D_{2\%}$ and the geometric deviation between the original plan and simulated plans with the setup errors were evaluated in RayStation. The geometric deviation of isodose distribution shift from the PTV surface was evaluated slide by slide in the axial plane in three regions as: (1) at the isocenter 10 slices were evaluated by ±5 slides from the isocenter; (2) the last 5 slides from the inferior end of the PTV, and (3) the last 5 slides from the superior end of the PTV. The geometric deviation was averaged for all investigated planes.

Table 1 Setup errors along the lateral, longitudinal and vertical planes of each image guidance system in the PIXY head phantom.

Translation (mm)	Registration error in mm (Lateral/Longitudinal/Vertical)				
	kV-CBCT	kV planar		MV planar	
		AP-Rt. lateral	AP-Lt. lateral	AP-Rt. lateral	AP-Lt. lateral
2.0, 0.0, 0.0	0.3/0.0/0.1	0.6/0.0/0.0	1.0/0.0/0.0	0.0/0.0/0.0	-0.2/0.0/0.0
4.0, 0.0, 0.0	0.2/0.0/0.1	0.3/0.6/0.0	0.0/0.0/0.0	-0.8/0.4/0.0	-0.8/0.0/0.0
-2.0, 0.0, 0.0	0.4/0.1/0.1	-0.2/0.2/0.0	-0.2/0.0/-0.8	-0.4/-0.2/0.0	0.0/-0.4/0.0
-4.0, 0.0, 0.0	0.2/0.1/0.1	-0.3/0.0/0.0	-0.4/0.2/1.0	-0.6/-0.4/0.0	-0.6/-0.4/0.0
0.0, 2.0, 0.0	0.0/0.6/0.1	-0.4/0.2/-0.6	-0.4/0.0/1.0	-0.2/-0.2/0.0	0.0/-0.3/0.0
0.0, 4.0, 0.0	0.1/0.4/0.1	0.0/-0.1/-0.8	0.0/-0.4/0.8	0.0/-0.4/0.0	0.0/-0.1/-0.4
0.0, -2.0, 0.0	0.0/0.1/0.1	0.0/-0.2/-0.2	-0.2/-0.2/1.0	0.0/0.0/0.0	-0.4/-0.2/-0.2
0.0, -4.0, 0.0	0.1/0.7/0.1	-0.6/-0.3/-0.2	-0.4/-0.3/0.8	-0.2/-0.3/-0.3	-0.2/-0.1/-0.2
0.0, 0.0, 2.0	-0.2/-0.1/1.4	-0.4/0.0/-1.0	-0.4/-0.2/-1.0	0.0/-0.4/0.8	0.2/-0.4/-0.8
0.0, 0.0, 4.0	-0.1/0.0/0.9	-0.8/0.2/0.8	-0.8/0.4/-1.0	0.0/-0.2/-0.6	0.0/-0.4/-0.3
0.0, 0.0, -2.0	-0.2/0.0/1.5	-0.8/0.2/0.8	-0.8/0.4/-1.1	-0.2/0.0/-0.2	0.0/0.0/-0.2
0.0, 0.0, -4.0	0.0/-0.1/1.5	-0.8/0.0/0.9	-0.8/0.0/-0.9	-0.6/-0.2/-0.9	-0.6/-0.2/-0.9
2.0, 2.0, 2.0	0.4/0.5/1.5	0.2/0.2/-0.4	0.4/0.4/-0.8	0.4/0.2/-0.6	0.6/-0.4/-0.2
4.0, 4.0, 4.0	0.7/0.6/1.6	-0.3/0.3/-0.4	0.5/0.5/-1.0	-0.8/-0.1/-0.4	0.4/-0.3/-0.6
-2.0, -2.0, -2.0	0.4/0.4/1.4	-0.6/0.0/-0.8	2.0/0.2/-1.4	0.0/0.0/-0.8	0.0/-0.4/ -0.4
-4.0, -4.0, -4.0	0.6/0.4/1.7	-0.4/0.3/0.9	-0.4/0.1/-0.9	-1.0/-0.1/-0.1	-1.0/-0.9/0.3

Results

The setup errors were found to be less than 2 mm for all image guidance systems. As a result, the dose deviations between the original plan and simulated plans with setup errors are shown in Table 2. Dose 95% coverage of the PTV was reduced by approximately 4%, while the setup error had a greater effect on $D_{98\%}$ (about 6%) than on $D_{2\%}$ (less effect than 1%). Ranges of $D_{95\%}$ variation were 187-198 cGy/fraction, 188-198 cGy/fraction and 185-198 cGy/fraction, and the ranges of $D_{98\%}$ variation were 176-194 cGy/fraction, 178-196 cGy/fraction and 174-195 cGy/fraction in the cerebella, parasagittal, and convex areas, respectively. Figure 1 shows examples of dose deviation between the original plan and the simulated plans with setup errors of a 2 mm shift in the lateral, longitudinal, and vertical directions simultaneously. The hot and cold colors on the heat maps indicate the overdose and underdose relative to the original dose plan as no isocenter shift, respectively.

The geometric deviations of the isodose distribution of the PTV at the cerebella, parasagittal, and convex shape are shown in Tables 3, 4, and 5, respectively. The average of isodose distribution shifts of -5% inside the PTV surface of the isocenter region were -1.58±0.67 (ranged from -0.17 to -3.65 mm), -1.28±0.52 (ranged from -0.33 to -2.47 mm) and -1.30±0.80 (ranged from -0.20 to -4.24 mm) in the cerebella, parasagittal, and convex areas, respectively. The average of isodose distribution shift of -10% inside the PTV surface of the isocenter region was less than 1 mm, except for the parasagittal area which saw no dose deviation (range within -2 mm). For the inferior end and superior end, the isodose distribution shift of -5% and -10% inside the PTV surface were on average less than 5 mm in all PTV locations. The isodose distribution shift of 5% and 10% were found on the outside of the PTV, but small when found on the inside of the PTV. The difference of means of the isodose distribution shift of -5% between the different three locations (cerebella, parasagittal, and convex areas) of the PTV was not significant (p>0.05) using one-way ANOVA with SPSS version 17 (FB7E105EFD8A514130CC).

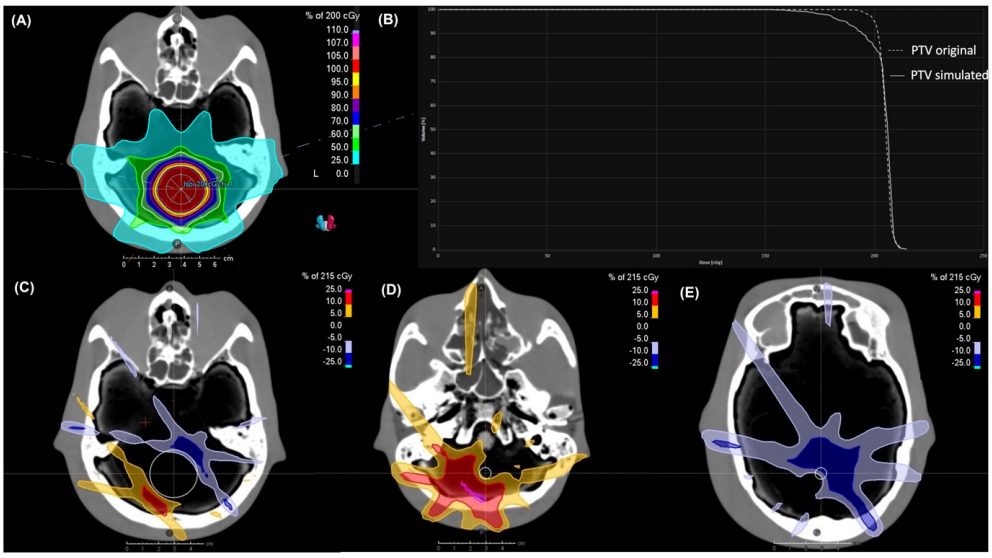

Figure 1. *Examples of dose deviations between the original plan and simulated plans with setup errors by a 2 mm, 2 mm, and 2 mm shift on the X, Y, and Z planes in PTV at the cerebella. A: dose distribution of original plan at the isocenter, B: DVH of PTV, C: dose deviation at the isocenter, D: dose deviation at the inferior end from the isocenter, and E: dose deviation at the superior end from the isocenter. A positive percentage difference is an overdose (red color zone) and a negative percentage difference is an underdose (blue color zone) compared to the original plan.*

Table 2 Comparison of dosimetric parameters between the original plan and simulated plans with setup errors. Prescription dose in 25 fraction is 5000 cGy, therefore the dose per fraction is 200 cGy per fraction.

Dosimetric parameter	Original plan		Dose of simulated plans with setup errors.				Different of accumulation dose (%)
	Dose for all 25 fractions (cGy)	Dose per fraction (cGy)	Avg/fraction (cGy)	Min (cGy)	Max (cGy)	Accumulation Dose (cGy)	
PTV at cerebella (spherical)							
$D_{98\%}$	4923	197	185±5.01	176	194	4621	-6.13
$D_{95\%}$	5000	200	192±3.35	187	198	4796	-4.08
$D_{2\%}$	5271	211	210±0.93	209	212	5256	-0.28
PTV at para-sagittal (spherical)							
$D_{98\%}$	4927	197	187±4.65	178	196	4669	-5.24
$D_{95\%}$	5000	200	193±3.04	188	198	4823	-3.54
$D_{2\%}$	5256	210	210±0.65	208	211	5238	-0.34
PTV at vertex (convex)							
$D_{98\%}$	4943	198	186±5.18	174	195	4657	-5.79
$D_{95\%}$	5000	200	193±3.74	185	198	4824	-3.52
$D_{2\%}$	5219	209	209±0.84	207	210	5218	-0.02

Table 3 Geometric deviation of isodose distribution of the PTV at cerebella.

Region	Distance (mm)	-5% difference of isodose distribution (Origi - Simulated)		-10% difference of isodose distribution (Origi-Simulated)		5% difference of isodose distribution (Origi-Simulated)		10% difference of isodose distribution (Origi-Simulated)	
		Inside PTV	Outside PTV	Inside PTV	Outside PTV	Inside PTV	Outside PTV	Inside PTV	Outside PTV
Inferior end	Range for all 25 fractions	-7.14 to -0.63	0.46 to 7.34	-4.15 to -0.46	0.36 to 6.63	-1.43 to -0.36	0.28 to 8.23	No dev.	1.52 to 10.61
	Avg	-4.05±1.95	2.33±1.98	-2.01±1.02	2.68±1.67	-0.89±0.39	2.47±2.13		4.29±1.77
Isocenter	Range for all 25 fractions	-3.65 to -0.17	0.13 to 2.89	-1.42 to -0.28	0.18 to 8.10	No dev.	0.13 to 2.99	No dev.	1.62 to 3.95
	Avg	-1.58 ±0.67	0.96±0.57	-0.63±0.29	1.25±0.99	No dev.	1.18±1.19		2.61±1.04
Superior end	Range for all 25 fractions	-7.59 to -0.72	0.28 to 7.55	-4.71 to -0.63	0.40 to 6.84	-9.54 to -0.36	0.36 to 8.50	No dev.	1.59 to 9.24
	Avg	-4.06±2.21	2.74±2.09	-2.93±1.16	3.21±1.73	-1.01±1.55	1.80±1.81		3.77±1.92

Note: Origi: original plan, No dev.: no deviation from original plan.

Table 4 Geometric deviation of isodose distribution of the PTV at parasagittal.

Region	Distance (mm)	-5% difference of isodose distribution (Origi-Simulated)		-10% difference of isodose distribution (Origi-Simulated)		5% difference of isodose distribution (Origi-Simulated)		10% difference of isodose distribution (Origi-Simulated)	
		Inside PTV	Outside PTV	Inside PTV	Outside PTV	Inside PTV	Outside PTV	Inside PTV	Outside PTV
Inferior end	Range for all 25 fractions	-7.12 to -0.40	0.25 to 6.85	-3.62 to -0.32	1.01 to 6.71	No dev.	0.24 to 11.43	No dev.	2.67 to 8.60
	Avg	-3.85±2.00	3.56±2.47	-1.94±1.22	3.30±1.93		2.48±2.40		5.01±1.96
Isocenter	Range for all 25 fractions	-2.47 to -0.33	0.35 to 5.58	No dev.	0.35 to 6.80	No dev.	0.94 to 4.79	No dev.	2.74 to 7.09
	Avg	-1.28±0.52	2.26±1.04		2.22±1.27		2.08±0.94		4.59±0.77
Superior end	Range for all 25 fractions	-8.02 to -0.80	0.60 to 9.50	-4.64 to -1.27	0.46 to 8.00	-2.12 to -0.25	0.25 to 9.32	No dev.	1.50 to 8.50
	Avg	-4.52±2.43	3.92±2.30	-2.85±0.92	3.77±1.82	-0.99±0.52	2.47±2.21		3.84±1.63

Note: Origi: original plan, No dev.: no deviation from original plan.

Table 5 Geometric deviation of isodose distribution of the PTV at convex shape.

Region	Distance (mm)	-5% difference of isodose distribution (Origi-Simulated)		-10% difference of isodose distribution (Origi-Simulated)		5% difference of isodose distribution (Origi-Simulated)		10% difference of isodose distribution (Origi-Simulated)	
		Inside PTV	Outside PTV	Inside PTV	Outside PTV	Inside PTV	Outside PTV	Inside PTV	Outside PTV
Inferior end	Range for all 25 fractions	-8.51 to -1.29	0.32 to 7.41	-4.56 to -0.52	0.32 to 8.52	-2.29 to -0.32	0.32 to 8.06	No dev.	2.86 to 11.22
	Avg	-4.94±2.04	3.00±1.98	-3.07±1.41	3.47±2.57	-1.08±0.88	2.63±1.80		5.87±1.95
Isocenter	Range for all 25 fractions	-4.24 to -0.20	0.20 to 5.32	-1.92 to -0.20	0.32 to 5.33	No dev.	0.61 to 5.66	No dev.	2.34 to 7.31
	Avg	-1.30±0.80	1.57±1.14	-0.85±0.55	1.18±1.26		1.98±0.82		4.51±1.04
Superior end	Range for all 25 fractions	-6.08 to -0.40	0.32 to 6.52	-3.09 to -0.57	0.91 to 6.62	-1.54 to -0.64	0.52 to 4.77	No dev.	1.04 to 8.44
	Avg	-2.63±1.49	2.52±1.79	-1.54±0.75	2.85±1.30	-1.09±0.30	1.96±1.18		3.67±1.39

Note: Origi: original plan, No dev.: no deviation from original plan.

Discussion

IGRT has been introduced as a treatment procedure to decrease patient positioning setup errors. The actual treatment position can be accurately confirmed through image guidance systems such as kV-CBCT, kV planar imager, and EPID. The efficiency of all image guidance systems to detect setup errors was below 2 mm, with simulation setup errors of 0, ±2, and ±4 mm in all planes. As a result, the newly simulated plans were created by the random shift of the isocenter from -2 to 2 mm from the original treatment isocenter on three translation plane dimensions for all 25 fractions. The three image guidance systems (kV-CBCT, kV planar image, and EPID) had different image data and image quality for image registration. The kV-CBCT had higher accuracy correction in the lateral and longitudinal planes compared with the vertical plane, especially when the vertical planes were shifted. The phantom's weight may affect the translation of the actual position in the vertical plane. The same isocenter of the Linac and EPID devices detected good geometrical uncertainty with a smaller error than the onboard imager (OBI), while the lowest MV image resolution still achieved high accuracy of image registration. Therefore, frequent QC checks and strict adherence to the QA program are necessary when using OBI. However, the kV image beam had a lower additional dose compared with the treatment beam (MV), leading to the use of the kV beam image for verification of the patient setup.[13] The image registration algorithm has the potential to improve the patient verification in radiotherapy.[14] This result shows that recently developed image registration software achieves accurate and precise image fusion between the reference image and in-room image for brain treatment. The image guidance systems can detect deviations of less than 1 mm in 96.25%, 100%, and 80% of cases for the X, Y, and Z planes, respectively. Guckenberger *et al*.[15] concluded that the translational setup errors using the CB-CT scanner and an EPID device differed by <1 mm in 70.7% and <2 mm in 93.2% of all cases. This

study showed the EPID device differed by <1 mm in 97.5% and <2 mm in 100% of cases.

Setup errors influenced the dose distribution between the reference position and the actual treatment position. This usually has the effect of underdosing the target volume and overdosing the OAR. The results showed that the average dosimetric deviation of the PTV due to setup errors ranging from -2 to 2 mm per fraction were approximately -6% for $D_{98\%}$, -4% for $D_{95\%}$, and less than -1% for $D_{2\%}$. Errors in fractional delivery dose led to a large underdose in the $D_{98\%}$ correlation, as found by Utena *et al*.,[16] while dose deviation was caused by a high isodose line shift from the PTV. Siebers *et al*.[17] have shown that the dose changes in gross target volume of head-and-neck squamous cell carcinomas treated with simultaneous integrated boost (SIB)-IMRT techniques were about 3-5% and the $D_{98\%}$ is the parameter that is most sensitive to patient position uncertainties. The PTV margin used in Lampang Cancer Hospital for head and neck planning has following RTOG protocol 0225.[18] From the geometric deviation of isodose distribution of -5% inside the PTV surface of the isocenter region, inducing the cold spot in PTV can reduce the PTV margin to less than 5 mm for brain treatment using the IMRT technique. The magnitudes of geometric deviation were 3.65 mm, 2.47 mm, and 4.24 mm in the cerebella, parasagittal, and convex areas, respectively. Therefore, we recommend CTV to PTV margins of 3.70 mm for spherical target volume but convex shapes should still have CTV to PTV margins of 5 mm. Cubillos *et al*.[19] concluded that CTV to PTV margins had a range of 3.30-3.70 mm in the brain region. However, the ICRU[20] recommends estimating the magnitude of uncertainties in every radiotherapy unit to apply appropriate CTV to PTV margins for individual institutes. The anatomy of the brain as the cranial bone is easy to match for all image guidance systems but the limits of image registration software and mechanisms of imaging have errors of at least ±2 mm. These factors can affect dose coverage by approximately 4%.

The number of beams also affects PTV dose coverage. IMRT brain treatment usually uses a high number of beams.[21] Five beams were used in this study because this number simulates brain metastasis and the hospital had huge patient loads and a limited number of Linac machines. Five beam IMRT was adopted as this gave faster treatment. This study has several limitations. We used a solid phantom since actual patients are non-rigid and vary in physique, which affects the accuracy of image registration. In clinical practice, the dose distribution in TPS is not related to actual dose distribution in patients. Further research using actual patients is required to confirm dose variation from setup errors.

Conclusion

Accuracies of phantom setup error from actual translation using image registration software in kV-CBCT, kV planar, and EPID images were within a tolerance limit of ±2 mm for all image guidance systems. Setup errors influenced dose deviation between the original plan and simulated plans with setup errors in all the PTV locations of approximately -6% for $D_{98\%}$, -4% for $D_{95\%}$, and less than -1% for $D_{2\%}$. The average of isodose distribution shifts of -5% inside the PTV surface of the isocenter area were -1.58±0.67 (3.65 mm in magnitude), -1.28±0.52 (2.47 mm in magnitude), and -1.30±0.80 (4.24 mm in magnitude) in the cerebella, parasagittal, and convex areas, respectively, and the isodose distribution shift of -10% inside the PTV surface was less than 1 mm in all PTV locations.

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