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ORIGINAL RESEARCH

Dosimetric evaluation of the gantry sag effect in clinical SRS plans

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Objectives: The gantry sag introduces a largely reproducible variation of the radiation field center around the radiation isocenter. The purpose of this work is to assess the change of the dose distribution caused by the gantry sag in clinical stereotactic plans.

Methods: Brain stereotactic radio surgery treatment plans were evaluated and grouped according to radiation therapy planning technique. Group 1 was planned with volumetric arc therapy technique using coplanar arcs while Group 2—non-coplanar arcs. To simulate the gantry sag effect in the treatment planning system, the original plan segments were divided into four groups according to corresponding gantry angles: upper, lower, left and right quadrants. Then, isocenter of the upper quadrant was shifted towards "Gun", isocenter of the lower quadrant was shifted towards "Target" and isocenter of the left and right quadrants was left at its original positions. The magnitude of the shift was 0.5, 1 and 1.5 mm in each direction, corresponding to 1, 2 and 3 mm of gantry isocenter diameter. To estimate the changes in dose distribution between the original and modified plans, the following dose–volume metrics were tracked: planning target volume (PTV) coverage ($V_{99;PTV}$), hotspot dose in PTV ($D_{PTV;0.015cc}$), coldspot doses in PTV ($D_{PTV;(V-0.015cc)}$), conformity and gradient indexes, maximum point doses in organs at risk (OAR, $D_{OAR;0.015cc}$) and outside PTV ($D_{outsidePTV;0,015cc}$). For the second group of patients volume of brain receiving 12 Gy (V_{12Gy}) was analyzed.

Results: The mean relative change of all metrics was within −2%/+2.5% range for both techniques for isocenter diameter up to 2 mm. Isocenter diameter of 3 mm causes significant changes in $V_{99;PTV}$, conformity and gradient indexes for coplanar, and additionally in $D_{PTV;(V-0.015cc)}$ for non-coplanar plans. The largest increase of maximum point dose in OAR was 1.1, 2.1 and 3.2% for ±0.5, ±1 and ±1.5 mm shift, respectively.

Conclusion: The results demonstrate dosimetric effect of gantry sag depending on its value. By itself, the gantry sag effect does not produce clinically perceptible dose changes neither for PTV nor for OARs for shift ranges up to ±1 mm, both for coplanar and non-coplanar delivery techniques. For the larger gantry sag magnitude dosimetric changes can become significant, especially for non-coplanar plans. It indicates that 2 mm diameter tolerance of gantry isocenter postulated in TG-142 is reasonable, as variations in excess of this value start to affect the overall dosimetric and spatial uncertainty.

Advances in knowledge: Dosimetric evaluation of the gantry sag effect in clinical stereotactic radio surgery plans is presented for the first time.

Stereotactic radiation [stereotactic radio surgery/stereotactic body radio therapy (SRS/SBRT)] relies on the accuracy of delivery of large doses with rapid dose falloff outside of the target volume. To reduce the chance of normal tissue toxicity resulting from a very high radiation dose, the target volumes are limited in size and planning treatment volume (PTV) margin is often 0–2 mm. The combination of small target, high target dose and a steep dose gradient, permits a very small tolerance for errors. Therefore, applying SRS/SBRT necessitates rigorous quality assurance (QA). In recent years, advances in radiation therapy (RT) including imaging, localization and immobilization, facilitated the wide use of linear accelerator for SRS/SBRT. Treating small volume with extremely small PTVs allows for no unaccounted delivery uncertainties.

Gravity force acting on the linear accelerator gantry produces moment of force. During gantry rotation, this moment causes deviation from the ideal circle trajectory that can be observed, *e.g.* by a gantry angle-dependent shift of a front pointer attached to the radiation head of the linac. The gantry sag, combined with other mechanical

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imperfections of the linac, induces a variation of the radiation field center (RFC) around the radiation isocenter. This effect is a well-known issue in radiotherapy and has been described in details by Du et al.[1]

A classical method to measure the RFC variation is the star-shot technique.[2] Recently, another method based on the Winston–Lutz test[3] performed with the help of the electronic portal imaging device (EPID) was introduced.[4] The advantage of this approach over the star-shot technique is a possibility to measure three-dimensional RFC variation that contains the longitudinal (Gun-Target) component from many gantry angles. This longitudinal component determines the magnitude of the gantry sag. There are several publications dedicated to quantifying the gantry sag and RFC variation with different techniques and equipment.[5–9] Interpretation of measurements can be based on publications of the American Association of Physicists in Medicine (AAPM) Reports of Task Group No. 142 (TG-142) that provide guidelines for the QA of medical accelerators.[10] In this document, the AAPM declares a tolerance of gantry rotation isocenter of 2 mm diameter and requires an action if the parameter exceeds the tabulated value. Both Varian (Varian Medical Systems, Inc., Palo Alto, CA) and Elekta (Elekta AB, Stockholm, Sweden) linac manufacturers offer two levels of isocenter accuracy: standard tolerance of 2 mm and enhanced accuracy for SBRT/SRS applications. The main incentive for reduction of gantry sag is a pre-assurance that this effect is especially detrimental in linac-based radiosurgery. Du et al[9] suggested that in stereotactic type of treatments where the other uncertainties are minimized, gantry sag may become significant and should be taken in account. However, to the best of authors' knowledge, there are no reports investigating the effect of gantry sag on dose distribution in clinical plans.

The purpose of this work is to assess the change of the dose distribution caused by the gantry sag of different magnitudes in clinical stereotactic plans with coplanar and non-coplanar dose delivery techniques.

METHODS AND MATERIALS

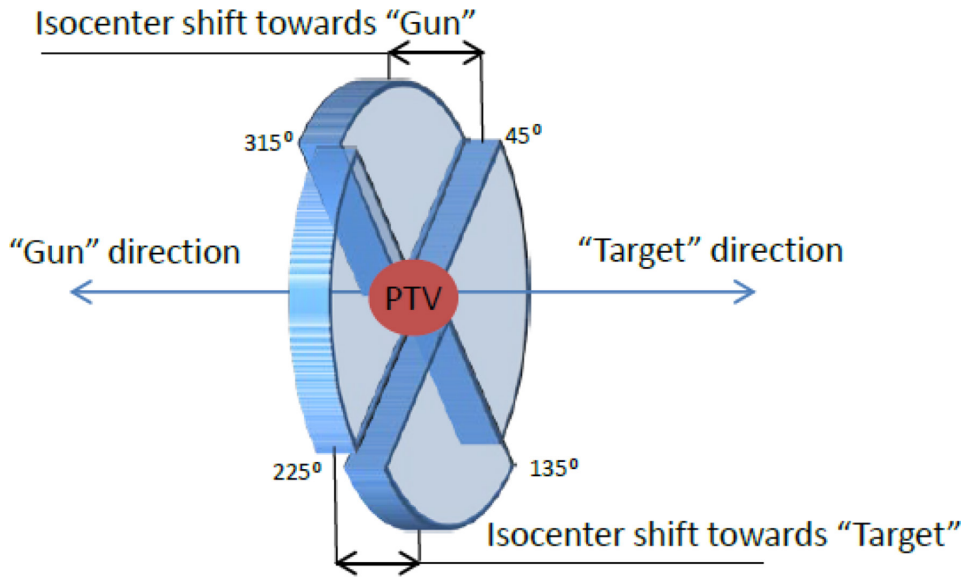
Brain SRS treatment plans of 20 patients were evaluated and grouped according to RT planning technique. Group 1 consisted of 10 patients planned with the volumetric arc therapy technique using one full coplanar arc. Group 2 included 10 patients planned using four volumetric arc therapy arcs: one full coplanar arc and three non-coplanar half arcs with table angles of 45°, 90° and 315°. Prescription schedules for patients in the Group 1 were: 6 Gy * 3 = 18 Gy, 9 Gy * 3 = 27 Gy, or 13 Gy * 1 = 13 Gy; while the non-coplanar technique (Group 2) was chosen for delivery of single fraction of higher doses: 15 Gy * 1 = 15 Gy, 18 Gy * 1 = 18 Gy or 24 Gy * 1 = 24 Gy. The prescription schedule was chosen by a physician based on the clinical considerations, while the non-coplanar technique was used for a treatment with a high (more than 13 Gy) single dose in order to minimize dose gradient index and dose to the normal brain tissue. The cases were intentionally selected so that PTV volumes were less than 2.5 cc. During treatment planning, the criteria of target coverage included ensuring that 99% of PTV volume received more than 95% of the prescription dose ($D_{99;PTV}$>0.95Rx), while the maximum dose inside the PTV was in the range of 125–160% of prescription dose (1.25Rx <$D_{max(0.1cc);PTV}$<1.6Rx). Paddick conformity index (CI) was defined as CI=$(V^{PTV}{}_{Rx})^2/(V_{PTV}*V_{Rx})$, where $V^{PTV}{}_{Rx}$ is the volume of PTV covered by a prescription isodose, V_{PTV} is the volume of PTV, and V_{Rx} is the total volume covered by a prescription isodose. Gradient index defined as a ratio of the volume irradiated by a half of prescription dose and the volume irradiated by a full prescription dose (GI=V_{50Rx}/V_{100Rx}) was kept as low as reasonably achievable. Organs at risk (OARs) limitations were based on the AAPM report TG101 and QUANTEC for brain tissue.[11,12]

The linear accelerator used in this study was the Elekta Versa HD equipped with the high definition Agility multi leaf collimator (MLC, leaf width of 5 mm) and 6 MV FFF photon beam. Treatment plans were created in the Monaco treatment planning system (TPS) (Elekta AB, Stockholm, Sweden) v. 5.11 with the Monte Carlo calculation algorithm. To minimize the errors associated with dose calculation uncertainties and dose–volume histogram (DVH) calculation accuracy, the following options were set in the TPS: 1% of dose uncertainty per control point, 1 × 1 × 1 mm^3 dose spatial grid, 1 mm of DVH resolution and 0.01 Gy for the DVH bin width.

The simulation of the gantry sag in the TPS consisted of the following steps and assumptions. First, all segments from the original plan were divided into four groups according to the corresponding gantry angles: upper, lower, left and right quadrants (Figure 1). Then, the isocenter of the upper quadrant was shifted towards "Gun", isocenter of the lower quadrant was shifted towards "Target", and isocenter of the left and right quadrants was left at its original positions. Apart from the isocenter shift, all other segment parameters (number of MU, shape, gantry angle etc.) were left unchanged. Lastly, dose distribution for the modified plan with the shifted isocenters was recalculated on the original CT set. The magnitude of the shift was ±0.5, ±1 and ±1.5 mm, corresponding to 1, 2 and 3 mm of gantry isocenter diameter.

To estimate the changes in dose distribution between the original and modified plans, the following dose–volume metrics were tracked: hotspot dose in PTV ($D_{PTV;0.015cc}$), coldspot dose in PTV ($D_{PTV;(V-0.015cc)}$), PTV coverage (the volume of PTV receiving 99% of the prescription dose $V_{99;PTV}$), CI and GI indexes. In this study, organs located at a distance of 0–5 mm from PTV were assigned as OAR. The change of a maximum point dose in OAR ($D_{OAR;0.015cc}$) and in volume outside PTV ($D_{outsidePTV;0,015cc}$) were also tracked. The hotspots and coldspots correspond to near-maximum and near-minimum doses for volume of 0.015 cc. The choice of reporting values and volumes is based on ICRU 91 Report: "Prescribing, Recording, and Reporting of Stereotactic Treatments with Small Photon Beams".[13] For patients in the second group (single fraction treatments), the parameter V_{12Gy} of brain tissue was also analyzed. In order to estimate the relative change in the dose–volume metrics for the modified plan, all metrics were normalized to the corresponding value of the original plan. Statistical paired *t*-test was performed in order

Figure 1. Detailed illustration of the model simulating gantry sag effect.



to study significance of the observed changes in dose–volume metrics between the original and modified plans.

RESULTS

Tables 1 and 2 summarize the patients and the targets information including diagnosis, margins from GTV to PTV and distance from OAR to PTV. The mean relative changes of $D_{PTV;(V-0.015cc)}$, $D_{PTV;0.015cc}$, $V_{99;PTV}$, $D_{outsidePTV;0,015cc}$, CI and GI for the Group 1 are presented in Figure 2A. The changes of the same parameters and V_{12Gy} for the Group 2 (non-coplanar technique) are shown in Figure 2B. Along with mean relative changes, the significant results of a paired *t*-test between original and modified plans are shown in Figure 2. The changes of point doses in OARs are presented in Figure 3.

DISCUSSION

All moving parts of linear accelerator that take a part in a dose delivery contribute to overall geometrical uncertainty. However, modern engineering solutions allow to minimize isocenter walkout caused by collimator and table rotation. An accurate and periodical MLC calibration decrease the role of MLC misalignments. On the other hand, gantry sag is a mechanical problem which cannot be completely avoided. There are several tons of radiation-generating and shielding materials that work as a lever

Table 1. Details of the Group 1 of patients, coplanar plans

Case	Diagnosis	Location	GTV to PTV margin, mm	PTV volume, cc	PTV shape	Prescription schedule, Gy	OARs	Distance from OAR to PTV, mm
1	Acoustic shwannoma	Cerebellum	1	1.14	Spherical	1 × 13	Cochlea	0.8
2	Meningioma	Temporal	1	2.11	Elliptical	3 × 6	Optic nerve, chiasm	Adjacent, 5
3	Acoustic shwannoma	Temporal	1	1.00	Irregular	3 × 6	Cochlea, brain stem	Adjacent, 1.2
4	Meningioma	Frontal	2	2.42	Elliptical	1 × 13	Optic nerve	1.5
5	Meningioma	Temporal	2	2.19	Irregular	1 × 13	Cochlea, brain stem	0.5, adjacent
6	Meningioma	Temporal	1	2.43	Spherical	1 × 13	Brain stem	2.5
7	NSCLC	Occipital	2	1.88	Spherical	3 × 9	Brain stem	More than 5 mm
8	Acoustic shwannoma	Temporal	1	1.98	Irregular	1 × 13	Cochlea, brain stem	Adjacent, adjacent
9	Meningioma	Temporal	1	1.47	Irregular	1 × 13	Cochlea, brain stem	1.8, 2
10	NSCLC	Temporal	2	2.37	Spherical	3 × 9	Brain stem	More than 5 mm

GTV, gross tumor volume; NSCLC, non-small-cell lung carcinoma; OAR, organ at risk; PTV, planning target volume.

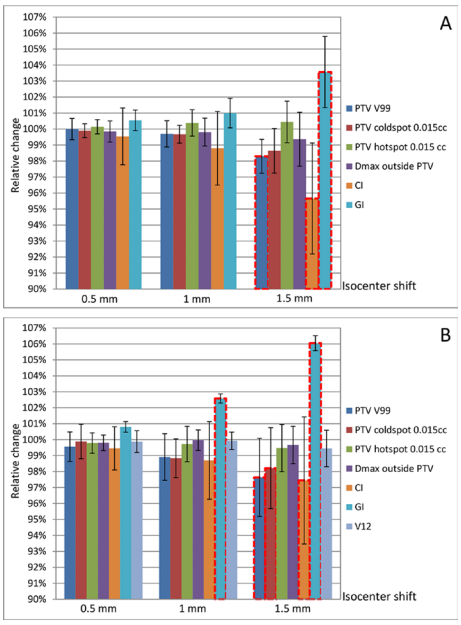
Table 2. Details of the Group 2 of patients, non-coplanar plans

Case	Diagnosis	Location	GTV to PTV margin, mm	PTV volume, cc	PTV shape	Prescription schedule, Gy	OARs	Distance from OAR to PTV, mm
1nc	NSCLC	Frontal	2	1.79	Spherical	1 × 15	Brain tissue	More than 5 mm
2nc	NSCLC	Cerebellum	2	2.30	Spherical	1 × 20	Brain tissue	More than 5 mm
3nc	Ovarian carcinoma	Occipital	2	1.36	Spherical	1 × 20	Brain tissue	More than 5 mm
4nc	Breast carcinoma	Frontal	2	1.53	Elliptical	1 × 18	Brain tissue	More than 5 mm
5nc	NSCLC	Parietal	1	1.49	Spherical	1 × 18	Brain tissue	More than 5 mm
6nc	NSCLC	Temporal	2	2.02	Elliptical	1 × 24	Brain tissue	More than 5 mm
7nc	NSCLC	Parietal	2	1.46	Spherical	1 × 20	Brain tissue	More than 5 mm
8nc	Breast carcinoma	Frontal	2	1.62	Spherical	1 × 18	Brain tissue	More than 5 mm
9nc	Breast carcinoma	Occipital	2	0.99	Spherical	1 × 18	Brain tissue	More than 5 mm
10nc	Meningioma	Frontal	2	1.79	Irregular	1 × 15	Brain tissue	More than 5 mm

GTV, gross tumor volume; NSCLC, non-small-cell lung carcinoma; OARs, organs at risk; PTV, planning target volume.

arm on the rotating structure and cause it to bend or sag. This is most important in the setting of SRS/SBRT, where there is a steep dose gradient, PTV margin is limited and the target volume is small, thus deviation of a few mm can result in non-therapeutic doses to the target volume. The gantry sag magnitude is not known exactly until the linac is installed. Moreover, this value can change during the years of operation.[7,8] In our study, the range of shifts from ±0.5 to ±1.5 mm covers all reported data of the measurements of the RFC varying in "Gun-Target" direction for different linac manufactures.[1,7–9,14–16]

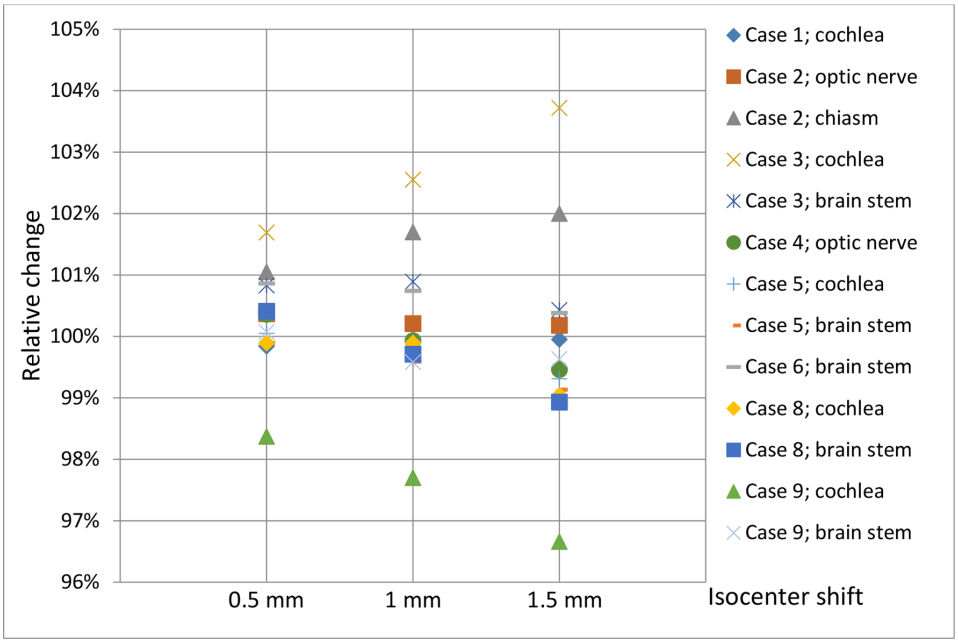
Figure 2. Mean relative changes of dosimetric parameters for the plans in Group1 and Group 2. Bars show ±1 standard deviation. Columns with red dotted borders present parameters that significantly ($p < 0.05$) differ from those of the original plan. A—Group1, coplanar plans; B—Group2, non-coplanar.



As shown in Figure 1, the mean relative change of all metrics was within −2%/+2.5% range for both techniques for gantry isocenter diameter up to 2 mm, and within −4.5%/+6% range for isocenter diameter of 3 mm. For both groups, all dosimetric parameters decreased or remained about unity while the shift increased, except for the GI. The behavior of the GI demonstrates how the gantry sag effects on different isodose levels: while V_{100Rx} increases very slightly, V_{50Rx} (and other low doses) increases faster that results in increasing of GI. This behavior is more expressed for the plans in Group 2 when table rotation was applied. In Figure 1, columns with red dotted borders present parameters that significantly ($p < 0.05$) differ from those of the original plan. Gantry sag with isocenter diameter of 3 mm causes significant changes in $V_{99;PTV}$, CI and GI for coplanar and, additionally in $D_{PTV;(V-0.015cc)}$, for non-coplanar plans. For the relative changes, the influence of the effect is noticeably more expressed in the non-coplanar group where the change is statistically significant for GI even for 2 mm isocenter diameter. One should note that the significance of dosimetric changes, especially in metrics such as GI and CI, does not necessarily mean clinical unacceptability of the plans.

The relative change in maximal point dose outside PTV $D_{outsidePTV;0,015cc}$ was about unity for all shifts and techniques. There is a general consensus that detriment of the gantry sag produces extra high dose spillage over PTV volume and consequently possible OARs overdose. In fact, the dose distribution is changed in another way. Since the isocenter undergoes two opposite shifts, the resulting dose distribution is blurred and maximal dose outside PTV does not change dramatically, tending to decrease. The maximum point dose in OARs changes similarly to that of the maximal dose outside PTV and in some cases slightly

Figure 3. Changes of point dose D0.015 cc in OARs for the Group 1. OARs, organs at risk.



increased compared with original plan. The worst scenario we observed in the current study was the increase in maximum dose for cochlea in Case 3 (Figure 3): 1.1, 2.1 and 3.2% for ±0.5, ±1 and ±1.5 mm shift, respectively.

In order to better describe the changes in dose distribution, dose difference (original minus modified plan) maps were built and are shown in Figure 4 for a single case from each group for 3 mm isocenter diameter. Colorwash map represents the dose difference in percent of the prescription dose. As has been mentioned above, only slight dose changes about 5% from the prescription dose occur due to the gantry sag. Warm colors on the PTV edges in the Gun-Target direction represent regions with lower dose in the modified plan compared with the original plan. The decrease in dose in these regions is due to a dose blurring caused by the gantry sag. This dose blurring is a direct consequence of the fact that during gantry rotation the isocenter undergoes shift in two opposite directions relative to its average position. This might be in contrary to the general perception that gantry sag causes the whole dose distribution shift and therefore might result in the increased dose near the PTV edges. For the non-coplanar plan, dose blurring occurs in four directions and not only in the Gun-Target direction as in the case of the coplanar plan. Larger dose blurring in non-coplanar plans is reflected in larger increase of GI due to gantry sag, compared to increase of GI for coplanar plans (Figure 2).

Each modified plan was assessed separately in order to decide its suitability for the treatment. Based on the clinical evaluation, all modified plans with ±0.5 and ±1 mm shifts remained acceptable

Figure 4. The dose difference between original and modified plan (original minus modified) for 1.5 mm shift. Blue contour is a PTV. Colorwash map represents dose difference in percents of the prescription dose. A, coplanar plan with prescription dose of 27 Gy; B, non-coplanar plan with prescription dose of 20 Gy. PTV, planning target volume.

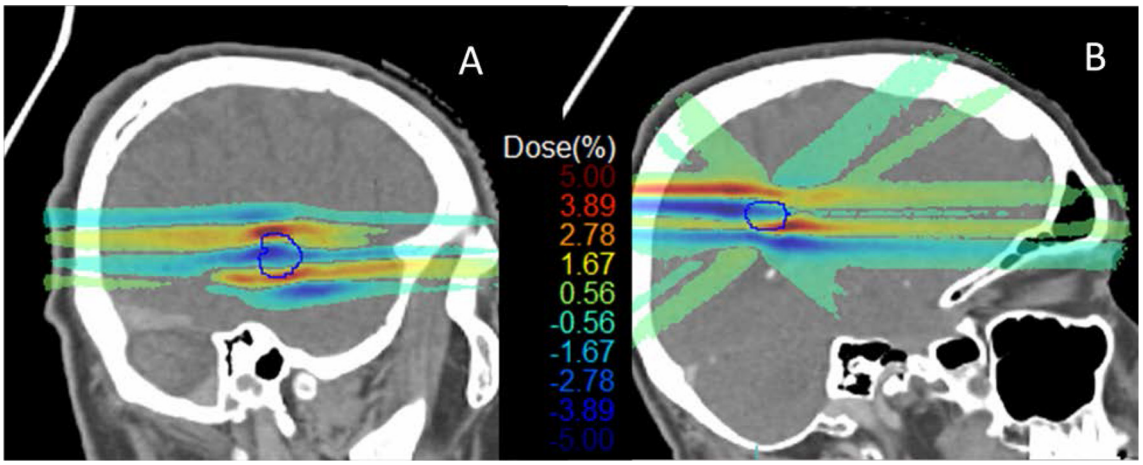
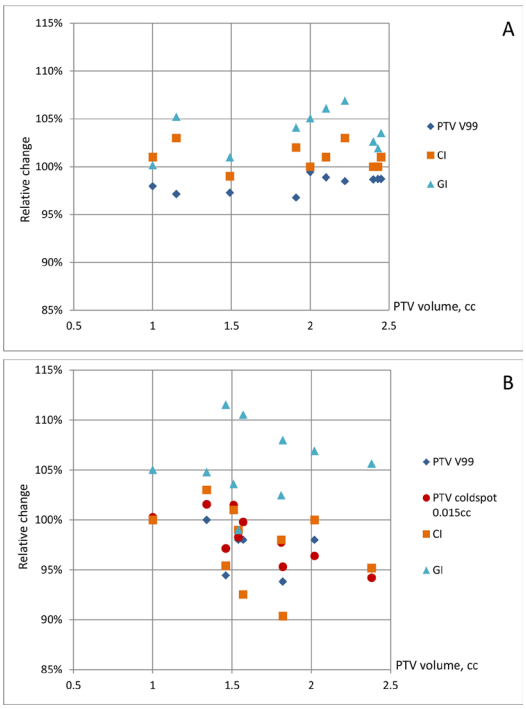


Figure 5. Dependence of dosimetric metrics on PTV volume for Group 1 (A) and Group 2 (B) for 1.5 mm shift. Metrics shown on this plot significantly differ (p <0.05) from those of the original plan. PTV, planning target volume



for the treatment. For ±1.5 mm shift, a majority of plans (from both groups of patients) became unsuitable due to PTV undercoverage (when the planning rule $D_{99;PTV} > 0.95Rx$ is broken), OAR overdose, too low CI or too high GI. The clinical acceptance of such plans raises questions. Since that is not practical to evaluate gantry sag effect for each particular case, linacs with gantry isocenter diameter of more than 2 mm seems are not suitable for SRS.

The clinical cases selected for this work were characterized by small PTV volumes so that the gantry sag would produce the largest dosimetric effect. The dependence of dosimetric metrics on PTV volume for 1.5 mm shift are shown in Figure 5. Metrics shown in this figure significantly differ (p < 0,05) from those of the original plan. Most probably, due to small variation of the PTV volumes in the selected cases, distinct dependency was not observed.

We expect that the obtained results do not depend on the TPS or the linac model. Some numerical differences in the calculated metrics may be caused by different definitions of GI, CI, prescription isodose or—more generally—by differences in planning technique. However, it should not affect the main observation that the effect of the isocenter shift in two opposite directions should lead to the dose blurring and to non-increase of maximal dose outside PTV. Moreover, since the gantry sag is a pure mechanical problem and its nature should not depend on the linac model and its specification, our conclusions should remain true when MLC with narrower leaves or stereotactic cones are used.

In the present study, a few simplifications were accepted. Isocenters of upper and lower quadrants were shifted along gantry axis, although in practice gantry sag causes rotation in the in-plane. For SSD of 100 cm and a shift of 1.5 mm, the angle of rotation is less than 0.09° and can be neglected. Another assumption is dependence of the gantry sag on the gantry angle. In our model, this dependence is described by the step-functions in the in-plane direction that approximately fit the smooth curve obtained from the measurements.[9] These measurements demonstrate that the maximum values of the gantry sag are achieved at 0° and 180°, and also show the actual absence of the gantry sag in the cross-plane direction. As noted above, the profile of the gantry sag is linac-dependent, but we expect that our approach describes well a general situation and gives an overestimation of the gantry sag effect. In the case of specific conditions, when dose contributions from the anterior and posterior directions are extremely high, the gantry sag influence can increase. However, there were no such observations in our practice.

CONCLUSION

The results demonstrate dosimetric effect of gantry sag depending on its value. By itself, the gantry sag effect does not produce clinically perceptible dose changes neither for PTV nor for OARs for shift ranges up to ±1 mm, both for coplanar and non-coplanar delivery techniques. For the larger gantry sag magnitude dosimetric changes become significant, especially for non-coplanar plans. It indicates that 2 mm diameter tolerance of gantry isocenter postulated in TG-142 is reasonable as variations in excess of this value start to affect the overall dosimetric and spatial uncertainty. Our center does not take any additional actions to take the gantry sag into account during stereotactic treatment planning or target delineation.

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