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Original Research Article

# Precision of image-guided spinal stereotactic ablative radiotherapy and impact of positioning variables

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ABSTRACT

*Background and purpose:* Spinal stereotactic ablative body radiotherapy (SABR) requires high precision. We evaluate the intrafraction motion during cone-beam computed tomography (CBCT) guided SABR with different immobilization techniques.
*Material and methods:* Fifty-seven consecutive patients were treated for 62 spinal lesions with SABR with positioning corrected in six degrees of freedom. A surface monitoring system was used for patient set up and to ensure patient immobilization in 65% of patients. Intrafractional motion was defined as the difference between the last CBCT before the start of treatment and the first CT afterwards.
*Results:* For all 194 fractions, the mean intrafractional motion was 0.1 cm (0–1.1 cm) in vertical direction, 0.1 cm (0–1.1 cm) in longitudinal direction and 0.1 cm (0–0.5 cm) in lateral direction. A mean pitch of 0.6° (0–4.3°), a roll of 0.5° (0–3.4°) and a rotational motion of 0.4° (0–3.9°) was observed. 95.5% of the translational errors and 95.4% of the rotational errors were within safety range. There was a significantly higher rotational motion for patients with arms along the body ($p = 0.01$) and without the use of the body mask ($p = 0.05$). For cervical locations a higher rotational motion was seen, although not significant ($p = 0.1$). The acquisition of an extra CBCT was correlated with a higher rotational (pitch) motion ($p = 0 < 0.01$).
*Conclusion:* Very high precision in CBCT guided and surface-guided spinal SABR was observed in this cohort. The lowest intrafraction motion was seen in patients treated with arms above their head and a body mask. The use of IGRT with surface monitoring is an added value for patient monitoring leading to treatment interruption if necessary.

## 1. Introduction

Approximately one third of all cancer patients develop bone metastases in the course of their disease [1], of which 70% originate within the spine [2]. Radiotherapy (RT) plays an essential role in the multidisciplinary management of vertebral metastases.

Conventional external beam radiation therapy to the entire involved spinal level has been the standard of care for several decades and has excellent palliative effect. However doses are too low to ensure long term local control because the spinal cord tolerance is typically the dose-limiting factor in conventional RT. Dose-intensified stereotactic ablative body radiation therapy (SABR) uses highly conformal treatment planning and image-guidance to enable precise and accurate delivery of high radiation doses (in a single or a few fractions). Typically, these doses have steep dose gradients to spare the adjacent organs at risk (OAR). Prospective trials have already demonstrated SABR to be an effective tool for treating metastatic spinal disease [3–9].

Although very promising, the major challenge in the delivery of SABR for spinal metastases remains the close proximity of the spinal cord. Therefore, it is essential to ensure as precisely as possible that the intended dose is rightly delivered. Accurate setup and immobilization are required to minimize the intrafraction motion. Technical evolutions in modern radiotherapy such as the development of image-guided radiotherapy (IGRT) and the possibility of couch corrections in all six degrees-of-freedom offer the possibility to achieve this [10,11]. In addition, surface-guided monitoring systems (SGRT) have been recently introduced in clinical practice with the advantage of monitoring patient set up before and during treatment, leading to treatment interruption

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**Table 1**
Patient and treatment characteristics.

| (patients: N = 57; treatment sessions: N = 194) | | |
|---|---|---|
| Use of surface monitoring system | | |
| Yes | 37/57 | 65% |
| No | 20/57 | 35% |
| Treatment location | | |
| Cervical | 3/57 | 5% |
| Thoracic | 28/57 | 49% |
| Lumbosacral | 26/57 | 46% |
| Use of body mask | | |
| Yes | 16/57 | 28% |
| No | 41/57 | 72% |
| Use of head mask | | |
| Yes | 20/57 | 35% |
| No | 37/57 | 65% |
| Arm position | | |
| Above the head | 43/57 | 75% |
| Along the body | 14/57 | 25% |
| Extra CBCT acquisition | | |
| Yes | 47/194 | 24% |
| No | 147/194 | 76% |

when motion is detected. However, the added value in spinal SABR and the influence of different immobilization and positioning material remains unknown.

The aim of this study was to determine the accuracy of the SGRT system for spinal SABR treatments and the precision of different immobilization and positioning parameters.

## 2. Material and methods

### 2.1. Patients:

Between March 2015 and June 2019, 57 consecutive patients with localized spinal metastases (C1 to sacrum) were treated with stereotactic ablative radiotherapy (SABR) at the Iridium Netwerk, Antwerp, Belgium. The protocol of this retrospective study was approved by the institutional review board or research ethics committee of our institute.

Fifty-seven spinal lesions with a total of 194 fractions were consecutively registered. Patient and treatment characteristics were described in Table 1. SABR was delivered mostly in 3 fractions of 8–10 Gy (n = 48) or 5 fractions of 8 Gy (n = 9). Target lesions were divided to the cervical spine (n = 3), thoracic spine (n = 28), and lumbar-sacral (n = 26) locations. Patients were immobilized in a thermoplastic body mask in 28% of patient (n = 16), with use of head mask only in 7% of patients (n = 4) or without mask and arms elevated above the head in 75% of patients (n = 75%). An optical surface monitoring system was used for patient set up and to ensure patient immobilization during treatment in 65% of patients (from 2017 onwards). The system interrupted the treatment in 24% of cases, leading to the acquisition of an extra Cone Beam CT (CBCT) and online position correction followed by treatment continuation.

### 2.2. Treatment planning

Treatment details were described previously more extensive [9]. Briefly, all patients underwent treatment-planning computed tomography (CT) using 1 mm CT slice thickness in treatment position: patients were immobilized in a comfortable and stable supine position to irradiate the metastatic lesion(s) using different support and/or immobilization devices (e.g. knee and feet support, head or body mask) to increase patient comfort and to ensure set-up reproducibility.

A high-definition magnetic resonance image (MRI) of the treatment region was obtained and fused with the CT simulation scan for delineation of gross target volume (GTV) and clinical target volume (CTV). The high-dose planning target volume (PTV) was generated with an isotropic expansion of the CTV. Initially, this margin was 3 mm, since 2017 this was reduced to 2 mm after analysis of the set-up accuracy during treatment.

The spinal cord or cauda equina, plexus, esophagus, heart, great vessels, lungs, kidneys, and bowel were delineated as organs at risk. The spinal cord and cauda equina were expanded by a 2–3-mm margin to obtain the corresponding planning at-risk volumes.

Treatment planning was initially performed using a Varian Clinac IX, and more recently, since 2017, using a Varian Truebeam STX. Volumetric modulated arc therapy (VMAT) plans were generated for 6 or 6X flattening filter-free MV photons using ≥4 arcs with full or partial gantry rotation. The collimator angle was optimized to achieve optimal sparing of the spinal cord and coverage of the PTV. Inverse planning was used for IMRT-VMAT optimization. Final dose calculation was performed with a collapsed cone algorithm (RayStation v7.0, RaySearch Laboratories, Sweden) since 2017 with a grid size of 1.0 mm. Immobilization material was taken into account. Quality management included daily (output and coincidence of imaging and treatment isocenter verification), weekly (CBCT and SGRT calibration) and quarterly (end-to-end testing with an SABR dedicated phantom) quality assurance. Patient-specific pre-treatment QA and in vivo dosimetry was performed for every patient using the PerFRACTION platform (SunNuclear coorp., Florida, USA). The constraints of the report of the AAPM task group 101 [12] were used for treatment planning.

### 2.3. Treatment delivery

All patients were treated with LINAC-based rotational SABR using CBCT image-guidance and online correction of set-up errors in six degrees of freedom. An optical surface monitoring system (AlignRT, VisionRT, UK) was used since 2017 for patient positioning and to ensure set-up accuracy during treatment. For positioning, a region of interest (ROI) was defined including the isocenter with target volume and adequate topographic information. For monitoring during treatment, the ROI was reduced, but still including the isocenter and both lateral parts of the body necessary for detecting motion. For parts of the body that are subject to respiratory movement, a gated capture was used to compensate for movement of the monitored surface. In case of periodic, respiratory-based, out of tolerance during treatment seen on the 6D information screen, the ROI was adjusted accordingly.

Prior to each fraction, a CBCT was acquired and translational as well as rotational setup errors were corrected online, followed by a second CBCT to check the correction. In patients with treatment interruption triggered by the surface monitoring, a new CBCT was acquired. For evaluation purposes, a final CBCT was obtained at the end of each fraction. Intrafractional motion was defined as the difference between the last CBCT before the start of treatment and the first CT afterwards (Supplementary material; Suppl. Fig S1). A 3D-vector was created for the average three-dimensional intrafraction positional deviation for rotational and translational motion.

### 2.4. 2.4.Statistical analysis

The influence of following variables was analysed: arm position, head mask, body mask, location, and extra CBCT due to IGRT-warranted interruption (observed in 24% of fractions). To evaluate the influence of various factors on rotational and translational movement, a two-way mixed ANOVA model was set up using the R-package rstatix. Repeated measures were modelled as within-group variables and factors of interest were included as between-group variables. P-values inferior to 5% were considered significant. Post-hoc testing for significant results was performed using the Wilcoxon signed rank test and differences were visualized using boxplots (R-package ggpubr). In addition, descriptive statistics were calculated using base R functions.

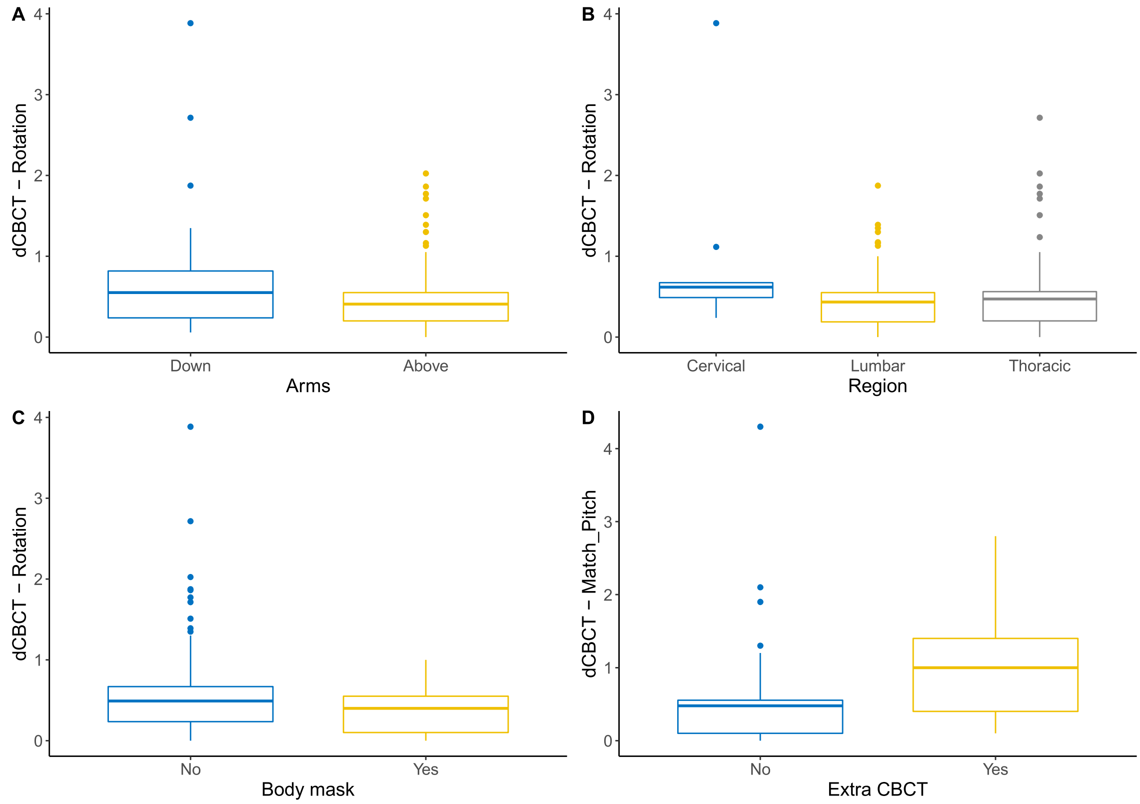


**Fig. 1.** Influence of arm position (A), location (B), body mask (C) and extra CBCT (D) for rotational motion (°).

## 3. Results

For all 194 fractions, the mean intrafractional motion was 0.1 cm (range 0–1.1 cm) in vertical direction, 0.1 cm (range 0–1.1 cm) in longitudinal direction and 0.1 cm (range 0–0.5 cm) in lateral direction in absolute values. Concerning rotational intrafractional motion, a mean pitch of 0.6° (range 0–4.3°), a roll of 0.5° (range 0–3.4°) and a rotational motion of 0.4° (range 0–3.9°) was observed. The mean translational motion 3D vector was 0.1 cm (range 0–0.9 cm) and the rotational motion 3D vector was 0.5° (range 0–3.9°).

Since 2 or 3-mm planning target (PTV) as well as planning organ at risk volume margins and a 2° correction threshold were used, 95.5% of the translational errors and 95.4% of the rotational errors were within an acceptable range.

There was a significantly higher rotational motion (3D rotational vector) for patients with arms along the body compared to arms elevated ($p = 0.01$) (Fig. 1) and without the use of the body mask ($p = 0.05$). Also, for cervical locations a higher rotational motion was observed compared to thoracic or lumbosacral lesions, although not significant ($p = 0.1$). The use of a head mask had no significant influence on intrafractional motion. Finally, the acquisition of an extra CBCT was correlated with a higher rotational (pitch) motion ($p = 0 < 0.01$).

## 4. Discussion

In this study, the precision of spinal SABR was analyzed using IGRT with online correction in six degrees of freedom and SGRT with an optical surface monitoring system. Our institutional analysis for a large cohort of consecutively treated spinal SABR patients showed a limited and reassuring translational and rotational intrafractional motion. These data are in good agreement with those reported in the literature for patients treated with spinal SABR and allow small PTV/PRV margins of 2 mm, making it easier to achieve both target and OAR planning aims.

IGRT is considered nowadays an essential tool to safely deliver high dose radiation. Yamoah et al observed an intrafraction motion regardless of immobilization technique to be 1.28 ± 0.57 mm in 12 patients with spinal metastasis treated with 25 spinal stereotactic radiotherapy fractions [13]. Another analysis of Dahele et al in 2016 indicated also that SABR to spinal lesions could be carried out with good translational and rotational stability [14]: 90% and 94.4% of displacements were +/-1 and +/-1.5 mm, respectively. Rotational displacements, which may be especially important for longer target volumes, were small: 97.6% and 98.8% were +/-1 and +/-1.5°, respectively. Finally, in a larger cohort of 102 spinal SABR treatments, the authors retrospectively assessed intrafractional translations of 3–7 mm, highlighting the need for image guidance to verify the position of the target [15]. Also Wang et al. reported that a 2-mm error in translational patient positioning could result in >5% loss of tumor coverage and >25% maximal dose increase to OAR [16].

To obtain more information about the optimal immobilization and positioning devices, the influence of different variables on intrafractional motion was analyzed. The lowest intrafraction motion was seen in patients treated with arms above their head and in patients treated using a body mask. Patients immobilized in the body mask were treated before the implementation of an optical surface monitoring system in our institute in 2017. Li et al also demonstrated the lowest intrafractional motion using a body vacuum fixation device [14]. These results indicate clearly that immobilization of the patient's body (cervico-abdominal) is reliable, although compromising patient comfort.

Since 2017, surface-based monitoring technology has been introduced in our clinical practice, with the advantage of verifying and monitoring the patient setup in 3D in real-time during treatment. Still very small intrafractional motion was detected with the large advantage of patient comfort decreasing the use of thermoplastic masks and continuous tracking during treatment. Our analysis clearly shows the added value for SGRT during treatment leading to treatment interruption if necessary. In 24% of fractions, there was a treatment interruption and the acquisition of an extra CBCT was correlated with a higher rotational (pitch) motion ($p = 0 < 0.01$). In literature, the number of studies available which report SGRT in SBRT is extremely limited. A recent review only found 4 publications with clinical data in relation for patient set up and intra-fraction motion monitoring [17]. Sarudis et al [18] examined 137 fractions delivered to 25 patients using surface guidance. The intrafractional motion using CBCT was ≤2 mm for 132/137 fractions in the vertical and lateral directions, and 134/137 fractions in the longitudinal direction.

Other recently published data show very limited intrafractional motion for spinal SABR in patient without immobilization devices. No SGRT but a fiducial free tracking robotic system was used [19]. Also in our cohort, very limited immobilization devices were used since use of the surface-guidance, with very high precision, enhancing patient comfort.

Special attention is necessary for cervical spine locations to reduce (rotational) intrafraction motion. This was also observed in a study by Yamoah et al [13]. A possible explanation can be the underestimation of motion detection by the surface monitoring because of the overlying thermoplastic mask. Therefore, in our institution we moved towards a chin only mask to have the possibility of increased surface guided monitoring of the patient's shoulders and neck.

Based on our analysis, very high precision in CBCT guided and surface-monitored spinal SABR was observed in this cohort. The lowest intrafraction motion was seen in patients treated with arms above their head and a body mask. Special attention is necessary for cervical spine locations to reduce (rotational) intrafraction motion. The use of SGRT is an added value for patient monitoring during treatment leading to treatment interruption if necessary and to decreased use of immobilization devices enhancing patient comfort.

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.phro.2022.04.006.

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