Received:
10 March 2016

Revised:
20 September 2016

Accepted:
3 October 2016

<https://doi.org/10.1259/bjr.20160227>

Cite this article as:

Moore K, Paterson C, Hicks J, Harrow S, McJury M. Stereotactic ablative body radiotherapy for non-small-cell lung cancer: setup reproducibility with novel arms-down immobilization. *Br J Radiol* 2016; **89**: 20160227.

FULL PAPER

Stereotactic ablative body radiotherapy for non-small-cell lung cancer: setup reproducibility with novel arms-down immobilization

¹KAREN MOORE, MSc, ²CLAIRE PATERSON, FRCR, ²JONATHAN HICKS, FRCR, ²STEPHEN HARROW, PhD, FRCR and ³MARK MCJURY, PhD

¹Department of Radiotherapy, Beatson West of Scotland Cancer Centre, Glasgow, UK

²Department of Clinical Oncology, Beatson West of Scotland Cancer Centre, Glasgow, UK

³Radiotherapy Physics Section, Department of Clinical Physics and Bio-engineering, Beatson West of Scotland Cancer Centre, Glasgow, UK

Address correspondence to: Karen Moore

E-mail: Karen.moore@ggc.scot.nhs.uk

Objective: A clinical evaluation of the intrafraction and interfraction setup accuracy of a novel thermoplastic mould immobilization device and patient position in early-stage lung cancer being treated with stereotactic radiotherapy at the Beatson West of Scotland Cancer Centre, Glasgow, UK.

Methods: 35 patients were immobilized in a novel, arms-down position, with a four-point Klarity™ (Klarity Medical Products, Ohio, US) clear thermoplastic mould fixed to a SinMed (CIVCO Medical solutions, Iowa, US) head and neck board. A knee support was also used for patient comfort and support. Pre- and post-treatment kilovoltage cone beam CT (CBCT) images were fused with the planning CT scan to determine intra- and interfraction motion. A total of 175 CBCT scans were analysed in the longitudinal, vertical and lateral directions.

Results: The mean intrafraction errors were 0.05 ± 0.77 mm (lateral), 0.44 ± 1.2 mm (superior-inferior) and -1.44 ± 1.35 mm (anteroposterior), respectively. Mean composite three-dimensional displacement vector was 2.14 ± 1.2 mm. Interfraction errors were -0.66 ± 2.35 mm (lateral), -0.13 ± 3.11 mm (superior-inferior) and 0.00 ± 2.94 mm (anteroposterior), with three-dimensional vector 4.08 ± 2.73 mm.

Conclusion: Setup accuracy for lung image-guided stereotactic ablative radiotherapy using a unique immobilization device, where patients have arms by their sides, has been shown to be safe and favourably comparable to other published setup data where more complex and cumbersome devices were utilised. There was no arm toxicity reported and low arm doses.

Advances in knowledge: We report on the accuracy of a novel patient immobilization device.

INTRODUCTION

Stereotactic ablative radiotherapy (SABR) has been shown to be an effective option in the treatment of early-stage lung cancer for more than a decade, with outcomes comparable to surgery in non-randomized studies.^{1,2} SABR uses high dose per fraction with the use of either multiple beam, intensity-modulated radiotherapy or volumetric modulated arc therapy (VMAT) to deliver high-precision target localization with steep dose gradients. Coupled with respiratory management techniques and image guidance, radiotherapy can be delivered with smaller planning target volumes allowing increased normal tissue sparing. Confidence that the patient is immobilized sufficiently both throughout each fraction and for each subsequent fraction is also required when delivering such high doses to such a precise target. Previous studies have reported on several fixation devices and their efficacy. These include vacuum systems,^{3–11} soft mattresses,¹² thermoplastic shells¹³ or chest

boards,^{3–5,14} whereas some describe more complex devices such as the stereotactic body lock frame^{6,15–18} or cradle systems^{11,18–20}—sometimes in combination and always in an arms-above-the-head position. Often these devices are used in conjunction with abdominal compression^{4–6,9,15,18} to minimize patient involuntary motion and reduce respiration motion during planning and treatment, whereas other centres have utilized and reported on breath-hold techniques.⁸ These studies have all reported that inter- and intrafraction setup errors were minimized.

Extracranial SABR was introduced in this centre in 2010.²¹ After much consideration of which immobilization device to use, it was decided to take a different approach from those previously documented. For both inter- and intrafraction setup error to be minimized, it is recognized that patient comfort is as important as any immobilization or respiratory management device used to deliver accurate

SABR. This centre is the largest cancer centre in the UK delivering 110,000 fractions per year on 11 linear accelerators, therefore when implementing a new technique, we must be extremely mindful of the on-treatment time required. The department has no dedicated research linear accelerator on which to implement new techniques. Some commercially available immobilization devices for SABR were assessed by the team, who concluded they were cumbersome to use, and potentially time-consuming, as it has been reported that the setup could take up to 50 min.²² A multidisciplinary team was established to develop an innovative in-house immobilization device. The head and neck thermoplastic five-point fixation mould, currently utilized in the department was modified to become a four-point neck and upper thorax immobilization device (Figure 1). This requires patients to be in an arms-down position which has not been reported before in the literature when treating patients with lung cancer. This positioning was considered to contribute to patient comfort, potentially leading to the least patient movement and the highest setup precision. It would be particularly beneficial for frail patients who represent a significant proportion of patients treated with SABR. In our centre, VMAT has been successfully implemented for head and neck cancer, with patients being set up and treatment delivered in a 10-min treatment slot, and it was intended to utilize this modality for SABR in lung cancer. VMAT was seen to be an efficient way to deliver high dose per fraction quickly; however, consideration would have to be made regarding the dose to the arm which would have been previously avoided in an arms-up technique. The multidisciplinary team took the decision that the introduction of such a high dose per fraction technique, delivered to a small lesion with 5-mm planning margins, in close proximity to organs at risk would require importance to be placed on stable immobilization, reproducibility and patient comfort. These elements were critical, whereas the dose delivered to the arm, particularly in this elderly and frail patient group, would not be clinically significant. This dose would be minimized utilizing VMAT where there is a steep dose gradient outside the planning target volume (PTV).

Figure 1. The in-house fabricated four-point immobilization device for stereotactic ablative radiotherapy lung treatments.

The aim of this study was to evaluate the setup accuracy of this novel patient positioning and immobilization device.

METHODS AND MATERIALS

Kilovoltage (kV) cone beam CT (CBCT) allows three-dimensional (3D) visualization of patient anatomy for bony and soft-tissue position verification. With this technology, pre-treatment position can be verified with high accuracy. In addition, the operator can ensure that the positions of the organs at risk (OARs) are also considered. Bone and soft-tissue position can then be verified post-treatment by capturing a second CBCT which allows analysis of intrafraction movement of the patient and the tumour.

Data were collected prospectively to assess the intra- and interfraction motion. This was performed by comparing image-based patient setup shifts in three dimensions (superior/inferior, anterior/posterior and right/left). Data were compared with setup errors reported from other departments using other immobilization devices. Toxicity data were also collected prospectively for musculoskeletal and connective tissue disorders in accordance with the Common Terminology Criteria for Adverse Events v.4 (CTCEA)²³ to monitor any introduction of toxicity to the arms with this novel arm position.

We analysed 35 ($n = 35$) sequential patients with T1/T2 N0 M0 lung cancer treated with SABR using VMAT on a Varian Clinac® 600 linear accelerator (Varian Medical Systems, Palo Alto, CA). For patient demographics, please see Table 1.

All patients were planned using RapidArc in the Eclipse™ treatment planning system (Varian Medical Systems) using two full arcs to deliver 5500 cGy over five fractions on alternate days (total of 11 days, no treatment over weekends).

Table 1. Patient demographics

Sex	Number (%)
Male	10 (28.6)
Female	25 (71.8)
Age (years)	Number (%)
45–55	1 (2.8)
56–65	4 (11.4)
66–75	11 (31.4)
76–85	13 (37.2)
86–95	6 (17.2)
Tumour position	Number (%)
Left upper lobe	18 (51.4)
Left lower lobe	13 (37.4)
Right upper lobe	9 (27.5)
Right lower lobe	3 (8.6)

Table 2. Intrafraction errors for the patient group

Orientation	Group mean error, M (mm)	Group systematic error, Σ (mm)	Group random error, σ (mm)
Anteroposterior	-1.44	1.35	1.66
Superior-inferior	0.44	1.20	1.59
Lateral	0.05	0.77	1.31
3D vector	2.14	1.21	1.44

3D, three-dimensional.

All patients had an individual four-point thermoplastic mould made in a supine, arms-down position. For each patient, a headrest was selected (from a standard set of three) which offered the best comfort and stability. Arms were placed as close to the patient's body as possible to ensure no air gaps between the arm and body. It was found that palms facing the ceiling and tucked under the patients, bottom achieved this comfortably. The thermoplastic mould covered the patients' chin, neck, shoulders and as much of the thorax as possible. In most cases, this included the nipples. A knee rest was used to add to patient comfort and stability. The patient lay directly on the treatment couch top with no abdominal compression, additional immobilization or mattress/foam. This mould room appointment took 30 min per patient.

For treatment planning, all patients underwent a four-dimensional CT (4DCT), acquired on a GE Lightspeed® RT16 Simulator LS CT scanner (GE Medical Systems, Crawley, UK) while wearing the individualized immobilization device. Our departmental SABR pathway sets a timeline of 22 days from planning scan to the start of treatment. All scans were captured during free breathing, and no patient was coached other than to be asked to breathe normally. Helical scans were captured using 120-kV 475-mA, 2.5-mm slice thickness on 65-cm dual field of view. A 4DCT was performed for each patient, with the cine time equal to the patient's average breathing cycle plus 0.25 s. Using Advantage Windows® 4.3 software (GE Medical), Data were then sorted into 10 phases, an average intensity projection (AveIP) and a maximum intensity projection (MIP) were generated before being imported into Eclipse. For all patients, the gross internal tumour volume (GITV) was delineated on the AveIP after considering all 10 phases of the breathing cycle. A 5-mm margin was added to the GITV to create the PTV. For each patients' target delineation, volumes were reviewed by a second clinician with SABR experience. RapidArc planning was performed on the AveIP image data set, using dose constraints for the PTV and OARs based on the Rosel protocol.²⁴

Treatment position was verified by fusing the planning scan AveIP with a CBCT scan pre- and post-treatment. 3D image registration was performed using the standard rigid body algorithm in Aria® (Varian Medical Systems). CBCT data were acquired with 2.5-mm slices, over a full 360° rotation. Bony registration was performed, using the vertebrae at the level of the PTV. Any discrepancy between AveIP and CBCT represents

patient positioning error (PPE). Shifts based on these bony match errors were recorded but not applied to the patient. The treatment couch was returned to the pre-matched position. A soft-tissue match was then performed using the PTV as the region of interest to aid manual registration. Any discrepancy between AveIP and CBCT for this match represents a tumour position error (TPE). These soft-tissue match shifts were recorded and applied to the patient. Using the moving window on the image review platform, the entire scan set was compared with the planning scan to look for arm position discrepancy or other anatomical mismatch.

A post-treatment CBCT was taken immediately after completion of the two treatment arcs. Both bony and soft-tissue matches were performed following the same process as pre-treatment matches and the shifts were recorded.

Statistical analyses

Analysis of data and generation of errors were performed following the van Herk²⁵ methodology. In summary, the population group mean, M , is defined as the average of patient errors. The systematic error, Σ , is calculated as the standard deviation of the patient mean errors and the random error, σ , as the root mean square of the patient standard deviations.

Figure 2. Intrafraction errors displayed as frequency data. 3D, three-dimensional.

Table 3. Interfraction errors for the patient group

Orientation	Group mean error, M (mm)	Group systematic error, Σ (mm)	Group random error, σ (mm)
Anteroposterior	0.00	2.94	1.74
Superior–inferior	−0.13	3.11	2.18
Lateral	−0.66	2.35	1.94
3D vector	4.08	2.73	1.79

3D, three-dimensional.

Intrafraction errors

To assess the setup errors associated with patient intrafraction movement, we reviewed the data corresponding to the residual post-treatment TPEs. These were recorded for each orthogonal axis and a combined 3D vector generated.

Interfraction errors

For each patient, the pre-treatment CBCT scans were registered with planning CT using a bony match, and the errors recorded in all three orthogonal axes. A 3D vector was generated from the axial errors providing the PPE.

Comparing pre- and post-treatment PPEs shows the inherent stability of patient setup, independent of tumour motion. For each patient, the difference seen in the longitudinal, vertical and lateral couch parameters required to make a match between the pre- and post-PPE data was also calculated, with patient and group analysis carried out as above.

The baseline shift corresponds to the difference between TPE and PPE; these were also calculated based on data for orthogonal axes and 3D vectors.

Arm toxicity

With patient setup in the arms-down position, a proportion of the VMAT treatment beam will pass through the arms (no avoidance sectors were used when generating the VMAT plans). Monitoring was performed by reviewing acute effects with patients prior to the start of treatment, after each fraction, and as part of post-treatment reviews for 2 years.

To enable quantitative dose assessment, arm structures were delineated by a specialist radiographer. The anatomical limits of the ipsilateral arm were defined as the superior and inferior extent of the D_{2cm} structure. The mean and maximum doses were calculated for the ipsilateral arm. Note also that the dose to the opposite arm was minimized (<250 cGy) in all cases as a consequence of using a contralateral lung dose constraint during plan optimization (volume of tissue receiving 5 Gy (V_5) < 1% of the prescription dose).

RESULTS

A total of 175 pairs of CBCT scans were analysed for 35 patients. The patient characteristics and tumour position for these patients are shown in Table 1.

Intrafraction setup errors

Table 2 shows the intrafraction (errors between pre- and post-soft-tissue-matched CBCT scan) errors. Errors in each orthogonal axis are shown and a resultant 3D vector.

The error range (along all two-dimensional axes) was found to be −10.6 to 4.8 mm. For the 3D vector, the range was −11.3 to 0.2 mm. For the 3D vector, the proportion of errors >5 mm was 17.1%.

Figure 2 shows the frequency data, where the peak for intrafraction 3D vector errors is approximately 2 mm. Interfraction errors are shown in Table 3 and plotted as frequency data in Figure 3.

Interfraction errors

An assessment of the robustness of the immobilization can be performed by reviewing the difference between the pre- and post-treatment bony-matched CBCT scans. Table 4 below shows these errors, with a 3D vector group mean error of <0.1 mm. Comparing the bony match pre- and post-CBCT errors, we find a range in group means of −0.06 to −0.4 mm and a 3D vector group mean of <0.1 mm. Figure 4 demonstrates the error frequency data for the difference in millimetres between the pre-treatment and post-treatment bony match as being 1 mm or less in the majority of matches.

The TPEs, PPEs and baseline shifts can be seen in Table 5. The mean TPEs are of the order of 1 mm for measurements on orthogonal axes. The PPEs show more variation in errors

Figure 3. Interfraction errors for axial and three-dimensional (3D) vector data plotted as frequency information.

Table 4. Differences between pre- and post-treatment bony match errors

Orientation	Group mean error, M (mm)	Group systematic error, Σ (mm)	Group random error, σ (mm)
Anteroposterior	-0.40	0.64	1.0
Superior-inferior	-0.18	0.76	1.0
Lateral	-0.06	0.86	1.54
3D vector	-0.07	0.73	1.22

3D, three-dimensional.

between axes, with the largest value occurring along the superior-inferior axis. For baseline shifts, the means range from 0.29 to 1.26 mm for the orthogonal axes, again with the superior-inferior axis showing the largest error. The mean 3D vector baseline shift is <1 mm (0.67 mm). For the 3D vector data, TPE and PPE have a similar magnitude, and baseline shifts are minimal (0.67 mm).

Arm toxicity and dose

A member of the SABR team reviewed each patient before each fraction of radiotherapy was delivered and then at 2 weeks, 3 months, 6 months, 1 year, 1.5 years and 2 years post-treatment.

All patients reported grade 0 toxicity for musculoskeletal and connective tissue disorders, arthritis and avascular necrosis, superficial soft-tissue fibrosis, deep connective-tissue fibrosis, soft-tissue necrosis-upper limb, myositis, myalgia, generalized muscle weakness and bone pain as defined by Common Terminology Criteria for Adverse Events v. 4 at each time point.

For the patient group, the mean percentage dose to the ipsilateral arm was $4.9 \pm 2.9\%$ (270 cGy over five fractions). The maximum point dose measured was 26.7% (1469 cGy based on a prescription of 5500 cGy delivered in five fractions to an extremely peripheral lesion.)

DISCUSSION

Confidence in immobilization and patient positioning is a prerequisite in the implementation of SABR, allowing high doses of radiation to be delivered to the tumour while safely constraining doses delivered to the critical OARs. The aim of this study was to evaluate a novel patient positioning and immobilization device for lung SABR developed in our centre.

We have shown population random intrafraction errors of 1.31–1.66 mm (along all two-dimensional axes) which are comparable to previously published work assessing commercially available devices. Grills et al¹⁶ reported a study of 24 patients receiving SABR to the lung to assess the impact of daily image guidance. They reported setup errors for patients' setup using either a stereotactic body frame or an alpha cradle. They found similar population random intrafraction errors for patients immobilized in a stereotactic body frame (0.8–1.0 mm) and alpha cradle (1.0–1.3 mm). Li et al⁴ reported on a larger study of 133 patients receiving SABR to the lung treated between 2006 and 2009. In this study, three different immobilization methods were employed, using vacuum cushions, abdominal compression or a chest board. They reported population mean intrafraction

errors similar to ours: 0.1–1.3 mm (Vac-LokTM cushions), 0.5–0.8 mm (abdominal compression) and 0.2–1.1 mm (chest board). Our maximum errors are shown to be in the anteroposterior direction, which again agreed with Li et al.⁴

We have recorded small interfraction mean errors, in the range of 0.0 to -0.66 mm. This again compares well with levels reported in the literature. Worm et al¹⁵ have reported on a study of 19 SABR patients with lung cancer, immobilized using a stereotactic body frame. They report interfraction errors of 0.0–1.4 mm, which are considerably higher than ours. Yeung et al⁷ also reported higher interfraction errors (0.3–1.1 mm) in a study of 22 SABR patients with lung cancer immobilized with a body fix system.

The stability and accuracy achieved with our immobilization system can be seen in the errors between pre- and post-CBCT matched to bone. We have shown these bony mismatches to be very small, in the range of -0.06–1.54 mm for orthogonal axis data. This shows that the immobilisation system reliably stabilises the patient setup and maintains this for the time required to deliver SABR.

The TPE values also highlight the efficiency of the immobilization. We have measured mean values of the order of 1 mm along all orthogonal axes. This is significantly smaller than Worm et al¹⁵ who reported mean lung tumour TPE of 5.6 ± 1.8 mm. Our baseline shifts are shown to be <1 mm (0.67 mm), agreeing well with others¹⁵ and in some cases are considerably smaller (Josipovic et al⁸ report mean baseline shifts of 2.2 mm).

Figure 4. Error frequency data for the difference between pre- and post-treatment cone beam CT bony match errors (three-dimensional vectors).

Table 5. Baseline shifts, tumour-positioning errors (TPEs) and patient-positioning errors (PPEs) for axial and three-dimensional (3D) vector data

Orientation	Tumour positioning errors, TPE (mm)			Patient positioning errors, PPE (mm)			Baseline shifts (mm)		
	Group mean	SD of systematic error, Σ	RMS error	Group mean	SD of systematic error, Σ	RMS error	Group mean	SD of systematic error, Σ	RMS error
Anteroposterior	1.03	2.48	1.48	1.66	3.52	2.10	0.62	3.01	1.07
Superior-inferior	1.21	3.10	2.38	2.49	2.91	2.90	1.26	2.49	0.90
Lateral	-1.00	2.97	1.94	-0.73	2.72	1.69	0.29	1.53	0.58
3D vector	4.60	2.55	1.71	5.05	3.43	6.77	0.67	2.56	0.95

RMS, root mean square; SD, standard deviation.

The thermoplastic device has been extremely well tolerated by all of the patients. Radiotherapy staff have found it easy to position the patient in a reproducible manner. Although setup for other commercial devices can take up to 50 min,²² we schedule a 20-min treatment slot, with setup taking an average of 9 min.

There were initial concerns regarding potential arm toxicity due to the dose delivered to normal tissue in the arm inherent in the arms-down patient setup combined with VMAT delivery. It should be noted that toxicity to the arm was recorded for each patient at baseline and these patients have now been followed up prospectively in clinic for 2 years, and there have no reports of skin, soft tissue or bone toxicity in the arm of any patient.

The mean doses measured to the ipsilateral arm (4.9% or 270 cGy over 5 fractions) are not clinically significant. It should be stressed that when planning, no attempts were made to specifically minimize arm doses. If the doses were higher, with VMAT delivery, there is significant further scope to delineate arm structures and to further optimize the plans by including specific dose constraints for the arms and to include the use of avoidance sectors if necessary. These low-dose values measured suggest minimal risk with this technique.

We are confident that this study demonstrates an acceptable accuracy using this immobilization device when delivering lung SABR with VMAT in an arms-down position. We have worked in conjunction with Klarity to produce a SABR-specific thermoplastic mould that is cut from a four-point fixation template with an additional 2 cm of thermoplastic material at the inferior end. This additional material has proven useful, particularly when making moulds for female patients.

CONCLUSION

This analysis has reported on the setup accuracy with the use of a novel immobilization device for lung SABR. These results demonstrate that patient setup with arms-down in a thermoplastic four-point fixation immobilization is achieved that compares favourably with those published for a range of commercially available immobilization devices. The department has found the thermoplastic immobilization device efficient and easy to use. Patients tolerated the device and immobilization extremely well, with no patient unable to proceed to treatment because of a difficulty in achieving satisfactory setup. Prospective clinical follow-up over 2 years post-treatment has revealed no arm toxicity using this technique. The doses measured to the ipsilateral arm are not clinically significant in this patient population.

When delivering SABR lung treatments, consideration should be given to a simple device such as the one reported here, coupled with comfortable patient positioning.

ACKNOWLEDGMENTS

The authors acknowledge the input from others in the Beatson lung SABR working group: Graham Lumsden, Vivienne MacLaren, Andrew Aitken, Linda McLaren, Bernadette Boyle, Kirstie Brown, Rebecca Muirhead, Jennifer McPhee and Margaret Omand. Their thanks also go to the team in the Mould Room.

REFERENCES

- Onishi H, Shirato H, Nagata Y, Hiraoka M, Fujino M, Gomi K, et al. Stereotactic body radiotherapy (SBRT) for operable stage I non-small-cell lung cancer: can SBRT be comparable to surgery? *Int J Radiat Oncol Biol Phys* 2011; **81**: 1352–8. doi: <https://doi.org/10.1016/j.ijrobp.2009.07.1751>
- Lagerwaard FJ, Versteegen NE, Haasbeek CJ, Slotman BJ, Paul MA, Smit EF, et al. Outcomes of stereotactic ablative radiotherapy in patients with potentially operable stage I non-small cell lung cancer. *Int J Radiat Oncol Biol Phys* 2012; **83**: 348–53. doi: <https://doi.org/10.1016/j.ijrobp.2011.06.2003>
- Higgins J, Bezjak A, Hope A, Panzarella T, Li W, Cho JB, et al. Effect of image-guidance frequency on geometric accuracy and setup margins in radiotherapy for locally advanced lung cancer. *Int J Radiat Oncol Biol Phys* 2011; **80**: 1330–7. doi: <https://doi.org/10.1016/j.ijrobp.2010.04.006>
- Li W, Purdie TG, Taremi M, Fung S, Brade A, Cho BC, et al. Effect of immobilization and performance status on intrafraction motion for stereotactic lung radiotherapy: analysis of 133 patients. *Int J Radiat Oncol Biol Phys* 2011; **81**: 1568–75. doi: <https://doi.org/10.1016/j.ijrobp.2010.09.035>
- Li W, Moseley DJ, Bissonnette JP, Purdie TG, Bezjak A, Jaffray DA. Setup reproducibility for thoracic and upper gastrointestinal radiation therapy: Influence of immobilization method and on-line cone-beam CT guidance. *Med Dosim* 2010; **35**: 287–96. doi: <https://doi.org/10.1016/j.meddos.2009.09.003>
- Wang J, Zhong R, Bai S, Lu Y, Xu Q, Zhou XJ, et al. Evaluation of positioning accuracy of four different immobilizations using cone-beam CT in radiotherapy of non-small-cell lung cancer. *Int J Radiat Oncol Biol Phys* 2010; **77**: 1274–81. doi: <https://doi.org/10.1016/j.ijrobp.2009.09.049>
- Yeung AR, Li JG, Shi W, Newlin HE, Chvetsov A, Liu C, et al. Tumor localization using cone-beam CT reduces setup margins in conventionally fractionated radiotherapy for lung tumors. *Int J Radiat Oncol Biol Phys* 2009; **74**: 1100–7. doi: <https://doi.org/10.1016/j.ijrobp.2008.09.048>
- Josipovic M, Persson GF, Logadottir A, Smulders B, Westmann G, Bangsgaard JP. Translational and rotational intra- and inter-fractional errors in patient and target position during a short course of frameless stereotactic body radiotherapy. *Acta Oncol* 2012; **51**: 610–17. doi: <https://doi.org/10.3109/0284186X.2011.626448>
- Gutierrez AN, Stathakis S, Crownover R, Esquivel C, Shi C, Papnikolaou N. Clinical evaluation of an immobilisation system for stereotactic body radiotherapy using helical tomotherapy. *Med Dosim* 2011; **36**: 126–9. doi: <https://doi.org/10.1016/j.meddos.2010.02.003>
- Suzuki O, Nishiyama K, Ueda Y, Miyazaki M, Tsujii K. Influence of rotational setup error on tumor shift in bony anatomy matching measured with pulmonary point registration in stereotactic body radiotherapy for early lung cancer. *Jpn J Clin Oncol* 2012; **42**: 1181–6. doi: <https://doi.org/10.1093/jjco/hys167>
- Shirvani SM, Juloori A, Allen PK, Komaki R, Liao Z, Gomez D, et al. Comparison of 2 common radiation therapy techniques for definitive treatment of small cell lung cancer. *Int J Radiat Oncol Biol Phys* 2013; **87**: 139–47. doi: <https://doi.org/10.1016/j.ijrobp.2013.05.040>
- Dahele M, Verbakel W, Cuijpers J, Slotman B, Senan S. An analysis of patient positioning during stereotactic lung radiotherapy performed without rigid external immobilization. *Radiother Oncol* 2012; **104**: 28–32. doi: <https://doi.org/10.1016/j.radonc.2012.03.020>
- Jiang B, Dai J, Zhang Y, Zhang K, Men K, Zhou Z, et al. Comparison of setup error using different reference images: a phantom and lung cancer patients study. *Med Dosim* 2012; **37**: 47–52. doi: <https://doi.org/10.1016/j.meddos.2011.01.001>
- Watanabe M, Onishi H, Kuriyama K, Komiyama T, Marino K, Araya M, et al. Intrafractional setup errors in patients undergoing non-invasive fixation using an immobilization system during hypofractionated stereotactic radiotherapy for lung tumors. *J Radiat Res* 2013; **54**: 762–8. doi: <https://doi.org/10.1093/jrr/rrt001>
- Worm ES, Hansen AT, Petersen JB, Muren LP, Praetegaard LH, Hoyer M. Inter- and intrafractional localisation errors in cone-beam CT guided stereotactic radiation therapy of tumours in the liver and lung. *Acta Oncol* 2010; **49**: 1177–83. doi: <https://doi.org/10.3109/0284186X.2010.498435>
- Grills IS, Hugo G, Kestin LL, Galerani AP, Chao KK, Wloch J, et al. Image-guided radiotherapy via daily online cone-beam CT substantially reduces margin requirements for stereotactic lung radiotherapy. *Int J Radiat Oncol Biol Phys* 2008; **70**: 1045–56. doi: <https://doi.org/10.1016/j.ijrobp.2007.07.2352>
- Matsugi K, Narita Y, Sawada A, Nakamura M, Miyabe Y, Matsuo Y, et al. Measurement of interfraction variations in position and size of target volumes in stereotactic body radiotherapy for lung cancer. *Int J Radiat Oncol Biol Phys* 2009; **75**: 543–8. doi: <https://doi.org/10.1016/j.ijrobp.2008.12.091>
- Takahashi W, Yamashita H, Kida S, Masutani Y, Sakumi A, Ohtomo K, et al. Verification of planning target volume settings in volumetric modulated arc therapy for stereotactic body radiation therapy by using in-treatment 4-dimensional cone beam computed tomography. *Int J Radiat Oncol Biol Phys* 2013; **86**: 426–31. doi: <https://doi.org/10.1016/j.ijrobp.2013.02.019>
- Ikushima H, Balter P, Komaki R, Hunjun S, Bucci MK, Liao Z, et al. Daily alignment results of in-room computed tomography-guided stereotactic body radiation therapy for lung cancer. *Int J Radiat Oncol Biol Phys* 2011; **79**: 473–80. doi: <https://doi.org/10.1016/j.ijrobp.2009.11.009>
- Wang L, Feigenberg S, Fan J, Jin L, Turaka A, Chen L, et al. Target reposition accuracy and PTV margin verification using three-dimensional cone-beam computed tomography (CBCT) in stereotactic body radiotherapy (SBRT) of lung cancers. *J Appl Clin Med Phys* 2012; **13**: 3708. doi: <https://doi.org/10.1120/jacmp.v13i2.3708>
- Moore K. An assessment of patient intra-fraction motion for lung SABR using VMAT. *Radiother Oncol* 2013; **106**(Suppl. 2): S362.
- Han K, Cheung P, Basran PS, Poon I, Yeung L, Lochray F. A comparison of two immobilization systems for stereotactic body radiation therapy of lung tumors. *Radiother Oncol* 2010; **95**: 103–8. doi: <https://doi.org/10.1016/j.radonc.2010.01.025>
- National Cancer Institute. Common Terminology Criteria for Adverse Events v4.0 (CTCAE). Available at: http://ctep.cancer.gov/protocolDevelopment/electronic_applications/ctc.htm. Accessed October 14, 2016.
- Hurkmans CW, Cuijpers JP, Lagerwaard FJ, Widdier J, van der Heide UA, Schuring D, et al. Recommendations for implementing stereotactic radiotherapy in peripheral stage IA non-small cell lung cancer: report from the Quality Assurance Working Party of the randomised phase III ROSEL study. *Radiat Oncol* 2009; **4**: 1–14. doi: <https://doi.org/10.1186/1748-717X-4-1>
- van Herk M. Errors and margins in radiotherapy. *Semin Radiat Oncol* 2004; **14**: 52–64. doi: <https://doi.org/10.1053/j.semradonc.2003.10.003>