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A Comprehensive Assessment by Tumor Site of Patient Setup using Daily MVCT Imaging from Over Three Thousand Eight Hundred Helical Tomotherapy Treatments

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Abstract

Purpose—To assess patient setup corrections based on daily megavoltage CT (MVCT) imaging for four different anatomical treatment sites treated on tomotherapy.

Method and Materials—Translational and rotational per-fraction setup corrections, based on registration of daily helical MVCT to planning CT images, were analyzed for 1179 brain and head and neck (H&N), 1414 lung, and 1274 prostate tomotherapy treatment fractions. Frequencies of 3D vector lengths, overall distributions of setup corrections, and patient-specific distributions of random and systematic setup errors were analyzed.

Results—Brain and H&N had lower magnitude positioning corrections and smaller variations in setup errors in the translational directions, but were comparable in roll rotations. 3D vector translational shifts of larger magnitudes occurred more frequently for lung and prostate than for brain and H&N treatments, yet this was not observed for roll rotations. The global systematic error for prostate was 4.7 mm in the vertical direction, most likely due to couch sag caused by large couch extension distances. Patient-to-patient variations in systematic errors and magnitudes of random translational errors ranged from 1.6–2.6 mm for brain and H&N and 3.2–7.2 mm for lung and prostate while roll rotational errors ranged from 0.8–1.2° for brain and H&N and 0.5–1.0° for lung and prostate.

Conclusions—Differences in setup were observed between brain, H&N, lung, and prostate treatments. Patient setup can be improved if daily imaging is performed. This analysis can assess the utilization of daily image guidance and allows for further investigation into improved anatomical site-specific and patient-specific treatments.

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Keywords

Image-guidance; Tomotherapy; Setup error; Patient positioning; MVCT

Introduction

Image-guided radiotherapy (IGRT) uses online imaging at treatment delivery in order to increase the probability that radiation is delivered as closely as possible to the original plan [1]. Modern radiotherapy techniques provide dose distributions that conform to target volumes while avoiding neighboring normal tissues. Increasingly conformal and complex treatment plans have steep dose gradients which increases the need for more accurate setup and delivery. Image guidance systems can improve the ability to accurately deliver highly conformal dose distributions in applications where setup uncertainty or organ motion is high [2].

A variety of image-guidance systems are currently available and include port films, electronic portal imaging, camera-based systems, orthogonal fluoroscopic imaging, ultrasound, implanted fiducial-based tracking systems, helical and cone beam CT. This study analyzes patient positioning corrections that were performed during treatments using a TomoTherapy Hi-ART II® (TomoTherapy Inc., Madison, WI) unit, which has an on-board CT detector array to generate volumetric images for the purposes of patient localization [3,4,5,6].

Several concerns regarding the paradigm shift of daily imaging in radiotherapy have been expressed, including a departure from the conventional practice of once-a-week port films, increased workload, reduced patient throughput, and possible deleterious clinical effects from the increased imaging dose. Preliminary conceptual discussions of the cost-benefit analysis for IGRT have started appearing in the literature, in which some argue for thorough evaluation based on clinical data from robust datasets of sufficient numbers of patients [7,8]. The purpose of this study is to assess the utilization of daily pre-treatment imaging for different disease sites by quantifying setup errors treated with tomotherapy at our institution.

Methods and Materials

Over 1000 patients have been treated on tomotherapy since August 2002 [9], and every patient receives an MVCT image prior to every treatment fraction. As part of a Program Project Research effort, a robust and extensive data set available for analysis of the complete course of therapy for every patient with daily MVCT imaging has been prospectively collected. Positioning corrections were analyzed for brain, head and neck (H&N), lung, and prostate patients receiving helical tomotherapy treatments between May 2004 and June 2007.

Patient Immobilization and Initial Setup

H&N and brain patients were immobilized with thermoplastic head masks and head rest sponges. Lung patients were typically immobilized with BodyFix® (Medical Intelligence, Schwabmünchen, Germany) full or half body vacuum molds. Prostate patients were either immobilized in the prone position with lower body custom mold belly boards or in the supine position with foam knee pillows and foot rings and no additional immobilization. Prostate patients were simulated with a bladder filled with contrast and instructed to have a comfortably full bladder prior to treatment. A rectal balloon was used in all prostate cancer patients for intra-fraction immobilization. Three external fiducials per patient were used for setup, which consisted of skin tattoos for prostate and lung patients, and markings on masks for HN and brain patients. Initial positioning of all patients was performed by alignment of fiducials to the red movable setup lasers in the treatment room.

Image Acquisition and Registration

Treatment planning images were acquired on a GE Discovery™ LS CT scanner (GE Medical Systems, Milwaukee, WI) using procedures consisting of 2.5 mm slice thicknesses for brain, H&N, and lung, and 2.5, 3.75, or 5.0 mm for prostate treatments according to clinical judgment. For lung patients, treatment planning and subsequent registration for daily setup were performed on regular free-breathing CT images. Many patients received an additional 4DCT and/or PET scans for delineation of target volume contours, which were then overlaid on the original free-breathing images. Therefore, the free-breathing images were still used for treatment planning and daily image registration, while the target volume contours came from the 4DCT and/or PET images.

Helical megavoltage CT (MVCT) images were acquired at every treatment fraction after the patient was immobilized and positioned using immobilization devices and localization lasers. Available options for MVCT image slice width consisted of coarse (6 mm), normal (4 mm), and fine (2 mm) slice thickness [11]; any of which were available to use for any particular treatment fraction and based on clinical judgment. Lengths of MVCT images in the superior-inferior direction were chosen by radiation therapists and/or physicians and included the entire target volume whenever possible and any additional structures needed for image registration. When the target length was extensive, resulting in a scan that would exceed the maximum of 80 slices currently allowed by the imaging system or would have an excessively long scan time, only a portion of the target volume was imaged. Sometimes in these instances more than one volume would be sampled, for example the superior, central and inferior portions of a target could all be imaged. The entire prostate was encompassed in the scan, whereas entire H&N nodal target volumes were not always included.

MVCT to planning CT image registration was performed and checked on the first treatment fraction by the treating physician and weekly thereafter. In situations where the clinical need dictated, the physician checked all or several subsequent registrations. Image registration was based on bony anatomy for brain, bony and soft tissue anatomy for H&N, and detectable parenchymal target volume for lung, with additional landmarks such as the carina, also being employed. For prostate treatments, registration was based on the prostate and the detectable bladder, and to a lesser extent on rectal balloon visualization as well as local bony anatomy.

Image registration was first performed using an automatic process and then manually checked and adjusted if necessary prior to treatment. The available automatic algorithms consisted of bone technique, an extracted feature fusion (EFF) algorithm using only voxels with density values $> 1.1 \text{ g/cm}^3$, bone and tissue technique, which uses a threshold of values $> 0.3 \text{ g/cm}^3$, and full image technique, a mutual information algorithm using the full image [10,11]. Bone and tissue technique was most commonly employed, however any of the three automatic algorithms were available for use and based on specific tumor anatomy and location. Boswell *et al.* [11] tested the accuracy of the integrated setup verification process and found that, when excluding outliers of $> 1 \text{ cm}$, the accuracy was approximately within one half of the voxel size of the image sets in each translational direction. Outliers occurred 2.5% of the time with their dataset, but only when introduced translations to the phantom were $> 3 \text{ cm}$ [11]. In order to prevent outliers caused by the automatic registration, manual checks and fine multi-planar adjustments were always performed at this institution.

Positioning Corrections

Positioning corrections were applied by automatic couch shifts in the longitudinal and vertical directions, manual couch shifts in the lateral direction, and roll rotations by automatic adjustment of the treatment angles. Pitch and yaw rotations were not used because they currently cannot be performed without physically moving the patient. Consequently, image

registration and patient setup corrections were restricted to lateral, longitudinal, and vertical translations as well as roll rotations.

Patient Selection

Patients were grouped into primary anatomical treatment site, and selection was based on a number of criteria. Patients treated for recurrent or metastatic disease were included in the analysis only if the treatment volumes were solely located within the individual anatomical site analyzed in this study. No additional disease characteristics were used as exclusion criteria in order to include as full a range of patients as possible. Patients having a minimum number of five fractions treated on tomotherapy were included in analysis. Only the positioning corrections from the fusion of the initial MVCT for each treatment fraction were used in this analysis. If the patient underwent more than one MVCT, or had a fraction treated in back to back sub-fractions, any new corrections were not included. Data used for analyzing roll rotations were restricted to those patients whose treatment started during or after February 2005 because corrections for roll were not possible in the system software prior to that time. Translational setup corrections were analyzed for 18 brain (340 fractions), 30 H&N (839 fractions), 74 lung (1414 fractions), and 59 prostate patients (1274 fractions). Of these, rotational setup corrections were analyzed for 15 brain (300 fractions), 29 H&N (815 fractions), 57 lung (1130 fractions), and 45 prostate patients (980 fractions).

Data Collection and Analysis

Setup correction data were obtained from individual patient archives. An in-house program was developed using MATLAB® (MathWorks, Natick, MA) to automatically extract the values from the archive files. Phantom tests were performed to verify the accuracy of this data collection method, and the coordinate system of the collected data is depicted in Figure 1.

Data analysis consisted of three approaches. Frequencies of 3D vector lengths, overall distributions of setup corrections, and patient-specific distributions of setup errors were analyzed. Frequencies of 3D vector lengths were calculated from the lateral, longitudinal, and vertical setup corrections in order to assess how often translational corrections of various magnitudes occurred. Overall distributions of setup corrections, which groups together all fractions for all patients, were plotted in order to assess ranges of corrections that were made in different directions. Distributions of patient-specific setup errors were quantified in order to assess systematic and random components of setup corrections and patient-to-patient variations.

A four-parameter model was used to analyze the setup error of a population of patients, with each patient having his/her individual setup error [12,13]. The four-parameter model separates the total distribution of positioning corrections (that consists of all fractions for all patients) into a distribution of patient-specific systematic setup errors and a distribution of patient-specific random setup errors. Systematic error can be defined as the mean (μ_i) of positioning corrections for that patient, and random error can be defined as the standard deviation (σ_i) [12].

The following formalism has been presented by Yan, et al [12], and is outlined here for completeness. We assessed three parameters out of the four-parameter model, which we termed global systematic error (mean of the systematic error distribution), patient-to-patient variation in systematic errors (standard deviation of the systematic error distribution), and magnitude of patient-specific random errors (root-mean-square of the random error distribution).

The overall global systematic error, or the group systematic error [14], is defined as $M(\mu_i)$, which is calculated by Equation 1:

$$M(\mu_i) = \sum_{i=1}^P \frac{N_i \mu_i}{N} \text{ where } \mu_i = \sum_{k=1}^{N_i} \frac{m_k}{N_i} \quad (1)$$

where μ_i is the individual systematic error for patient i , P is the total number of patients, N is the total number of treatment fractions, N_i is the number of treatment fractions for patient i , and m_k is the measured positioning correction for the k^{th} fraction for patient i . $\Sigma(\mu_i)$ characterizes the width of the systematic error distribution, which we defined as the variation in systematic error. Equation 2 gives the variation in systematic errors:

$$\Sigma(\mu_i) = \sqrt{\frac{\sum_{i=1}^P N_i (\mu_i - M(\mu_i))^2}{(N - 1)}} \quad (2)$$

$RMS(\sigma_i)$ is the root-mean-square (RMS) of the random error distribution, which we defined as the magnitude of random errors. Equation 3 calculates the magnitude of random errors:

$$RMS(\sigma_i) = \sqrt{\sum_{i=1}^P \frac{(N_i - 1)(\sigma_i)^2}{(N - 1)}} \text{ where } \sigma_i = \sqrt{\frac{\sum_{k=1}^{N_i} (m_k - \mu_i)^2}{(N_i - 1)}} \quad (3)$$

where σ_i is the individual random error for patient i .

The systematic and random error distributions are related to the overall distribution of setup corrections by Equation 4:

$$\Sigma_{\text{overall}} = \sqrt{\Sigma^2(\mu_i) + RMS^2(\sigma_i)} \quad (4)$$

This equation indicates that the overall variation in positioning corrections is composed of the standard deviation of the systematic error distribution and the RMS of the random error distribution. The RMS value of the random error distribution is a valid descriptor of random errors because it can show patient-to-patient differences especially when the number of measurements per patient is limited [14]. Statistical analysis was performed with Matlab's Statistics Toolbox software. The Kruskal-Wallis and Mann-Whitney U tests were used from this toolbox in order to avoid violation of the normality and homogeneity of variance assumptions of alternative parametric tests.

Results

Table 1 shows cumulative frequencies of the 3D vector length setup corrections calculated from translational shifts. 3D vector shifts of larger magnitude occurred more frequently for lung and prostate than for brain and H&N treatments. For brain and H&N treatments, only 1.5% and 1.2% of treatment fractions were shifted ≥ 10 mm 3D vector distance, while this occurred for 48.9% and 48.1% of lung and prostate treatments, respectively. Frequency

analysis was also performed on the magnitudes of roll rotations. As shown in Table 2, similar behavior was not observed for roll rotations. Frequencies of small rotations were more comparable between treatment sites. Prostate had the lowest frequencies of larger rotations with 0.3% of fractions $\geq 3^\circ$ versus 5.0%, 4.2%, and 5.9% for brain, H&N and lung, respectively.

Overall distributions of translational and rotational setup corrections are displayed in Figures 2 and 3. Translational distributions for brain and H&N treatments are narrow and sharply peaked about 0 mm, while lung and prostate distributions are wider in nature. The translational distribution for prostate treatments shows an asymmetric offset towards the positive vertical direction. Rotational distributions are similar between brain, H&N, and lung, with the prostate distribution appearing the narrowest.

Mean setup correction values for each individual patient averaged over his/her full course of treatment (error bars indicating two standard deviations of the mean) are shown in Figures 4 and 5. These figures provide a graphical indication of the setup behavior of each patient. They show smaller inter- and intra-patient variation for brain and H&N than for lung and prostate treatments for translational couch shifts. Roll rotations graphically appear to be more comparable between sites, possibly with the exception of prostate treatments. Additionally, these values are plotted chronologically by patient treatment start date, and they indicate no distinguishable trending over time.

Tables 3, 4 and Figure 6 show results of patient-specific setup error analysis. The global systematic errors ($M(\mu_i)$) for all treatment sites are within 2 mm of zero except for prostate, which has a global systematic error of 4.7 mm in the positive vertical direction and 2.3 mm in the positive longitudinal direction. Statistical testing indicates that the systematic error distribution in the vertical direction is significantly different for the prostate compared with the other three treatment sites ($p < 0.001$).

Variations in systematic errors ($\Sigma(\mu_i)$) and magnitudes of random errors ($RMS(\sigma_i)$) are plotted in Figure 6. They range from 1.6 - 2.6 mm for brain and H&N and 3.2 - 7.2 mm for lung and prostate in all translational directions, and 0.8 - 1.2° for brain and H&N and 0.5 - 1.0° for lung and prostate for roll rotations. Variations in systematic errors and magnitudes of random errors are smaller for brain and H&N than for lung and prostate in all translational directions. Prostate treatments have a variation in systematic errors in the vertical direction of 7.2 mm, which is almost twice the magnitude as in the lateral and longitudinal directions. This indicates that there is high patient-to-patient variation in the vertical direction for the prostate treatments analyzed in this study. Statistical testing indicates that the random error distributions in all translational directions are significantly different ($p < 0.001$) for brain and H&N compared with lung and prostate treatments. On the other hand, rotational random error distributions are comparable between sites, with the prostate random error distribution having the only significant difference ($p < 0.001$) between treatment sites.

Discussion

Brain and H&N had lower frequencies of large 3D vector shifts and smaller variations in systematic and random errors for translational shifts than lung and prostate. This behavior, however, was not mirrored in the roll rotations where brain and H&N rotation frequencies and variations were comparable with lung and larger than prostate treatments. One possible explanation for the setup differences between the various treatment sites could be the use of different immobilization systems. The thermoplastic mask immobilization system is used for all brain and H&N treatments whereas the BodyFix® system is employed for lung treatments and either a belly board or no external immobilization is used for prostate. Variations between external fiducials and target volume location, including deformation of prostate and/or bladder

shapes or changes in lung tumor volume over the treatment course, may also be a cause for setup variations. As opposed to positioning translations, roll rotations were more comparable between treatment sites. Despite rigid anatomy and standardized immobilization systems, external anatomical shape can contribute to rotational setup errors for brain and H&N treatments. Because of the curved shape of the head and easy movement around the occipito-odontoid axis, roll rotations may occur within the immobilization mask. For prostate treatments, the external shape of the anatomy may provide more natural resistance to roll rotations. Additionally, the rotational corrections for all treatment sites were relatively small, with a maximum overall systematic error of 0.3° and a maximum variation of setup error of 1.2° . The small magnitudes of rotations could be an additional explanation for the similarity of results between treatment sites.

Results of setup error analysis are due in part to restricting specific degrees of freedom during image registration. If a yaw offset exists, when restricting yaw and pitch rotations during fusion, the restriction will increase the lateral shift correction. If a pitch offset exists, the restriction will increase the vertical and longitudinal shift correction. This is relevant is for couch sag discrepancies, which will cause pitch offsets.

For prostate treatments, a large global systematic error was seen in the vertical direction, most likely due to increased effects of couch sag. The planning image is acquired with the CT simulation couch extended into the bore, and the absolute CT couch sag is already taken into account when placing the setup lasers in the treatment planning software. For tomotherapy treatments, however, the patient is positioned to the setup lasers outside the bore, but treated inside the bore, which does not take into account the absolute tomotherapy couch sag. Our quality assurance measurements have found that couch sag increases with lateral couch extension past the tabletop support and with body weight. Treatment in the head-first position for prostate patients does result in additional deflection of the couch because the larger extensions required causes more of the patient's weight to be located past the tabletop support. This deflection is accommodated by the vertical shift of the patient, likely resulting in some of the extra vertical systematic error.

A large patient-to-patient variation in systematic translational errors was also seen for the prostate and lung treatments. For the prostate cohort, a combination of factors may contribute to this result, which include variations in immobilization system (either no immobilization or belly board) and treatment position (supine, prone, head first, feet first). A secondary factor may be variations in rectal and bladder filling, which have been noted to largely affect prostate position in the vertical direction [15,16], although they are presumed to have been reduced in this study due to the use of rectal balloons and attempts of bladder filling consistency between simulation and treatment. For the lung cohort, intra-fraction motion is an additional factor. At this institution, image registration is based on detectable tumor volume and additional relevant anatomical structures. Differences in appearances of the lung tumor over the treatment course would have a larger effect when registering to the tumor rather than the solely to bony anatomy. Differences in motion artifacts exist between the MVCT and the free breathing conventional CT image sets due mainly to differences in gantry rotation period [17], which affects the registration process and subsequent shift data.

In addition to patient-specific variables, setup errors are dependent on many institution-specific variables. Various components of the entire treatment process will affect measured setup errors. External fiducial type and placement location, as well as positioning laser accuracy, can affect initial patient setup. If the positioning lasers are not accurately lined up to patient fiducials at the simulation room, in the planning station, and at the treatment room, measured setup errors will occur. Overall procedures governing the use of the image-guidance system will affect measurements, for detected setup errors will depend on the accuracy of image registration and

the quality and content of the images. The objects being aligned during image registration, for example bony anatomy as opposed to tumor, will affect resultant setup corrections. If different lengths and portions of the target are imaged on different days, this could have an effect on the size and variation of setup corrections due to the inclusion or exclusion of certain anatomic features. An additional factor is human behavior. Inter-observer variation in the interpretation of daily images will affect the registration process. Differences in overall anatomic knowledge along with the technique (automatic vs. manual) and time spent on image fusion could likely affect resultant setup corrections. In addition, setup errors depend on how well the patient was positioned prior to imaging, which depends on the training, skill level, and attention of staff members. Care should be taken to ensure the most accurate patient setup and image registration possible.

Daily imaging can be of greater benefit in treatment sites with higher frequencies of larger magnitude setup corrections or greater patient-to-patient variation in setup errors, which we found for lung and prostate in the translational directions, but not in the roll rotational direction. This study, although it cannot directly make any conclusions of the impact of daily imaging in terms of clinical outcome such as tumor control or normal tissue complications, is the first step in determining the optimal usage of IGRT by assessing magnitudes of positioning corrections for individual treatment sites. A subsequent step is to assess the impact of these corrections on the treatment dose distribution. Factors such as degree of conformity of dose distributions, dose gradient steepness, and planning margin expansion contribute to the dosimetric impact of daily imaging. Studies that simulate the dosimetric effects of positioning corrections from daily image-guided treatments [18,19,20] have found that the dosimetric impact of non-corrected setup error can be considerable in some cases. Brain and H&N treatments had smaller translational setup errors than lung and prostate, but not rotational setup errors. Guckenberger *et al.* found that rotational setup errors may have clinical relevance for selected patients with non-spherical, elongated target volumes and sharp dose gradients close to organs at risk [20]. Dose distributions of these characteristics are common in many extensive H&N treatments. Despite the smaller translational setup errors for brain and H&N, the dosimetric impact of various sizes of rotational setup errors may be noteworthy in specific cases and therefore should not be unconditionally ignored.

Conclusions

Patient setup can be improved if daily imaging is performed. For institutions that are unable to perform daily imaging, off-line correction strategies based on setup error analysis would benefit treatment sites with greater patient-to-patient variations in setup errors, which we found to be lung and prostate, although brain and H&N should not be unconditionally ignored due to rotational setup corrections. Multiple factors affect measured setup errors including anatomical variations, imaging and registration characteristics, and human behavior. Setup error analysis, however, separates patient positioning corrections detected by image guidance into global systematic error and patient-to-patient variations in errors. This allows institution-specific improvements to be made in order to decrease global systematic errors and allows for further investigation into improved anatomical site-specific and patient-specific treatments.

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References

1. Dawson LA, Jaffray DA. Advances in image-guided radiation therapy. *J Clin Oncol* 2007;25:938–946. [PubMed: 17350942]

2. Mackie TR, Kapatoes J, Ruchala K, et al. Image guidance for precise conformal radiotherapy. *Int J Radiat Oncol Biol Phys* 2003;56:89–105. [PubMed: 12694827]
3. Mackie TR, Balog J, Ruchala K, et al. Tomotherapy. *Semin Radiat Oncol* 1999;9:108–117. [PubMed: 10196402]
4. Welsh JS, Lock M, Harari PM, et al. Clinical implementation of adaptive helical tomotherapy: a unique approach to image-guided intensity modulated radiotherapy. *Tech Cancer Res Treat* 2006;5:465–479.
5. Forrest LJ, Mackie TR, Ruchala K, et al. The utility of megavoltage computed tomography images from a helical tomotherapy system for setup verification purposes. *Int J Radiat Oncol Biol Phys* 2004;60:1639–1644. [PubMed: 15590196]
6. Welsh JS, Bradley K, Ruchala KJ, et al. Megavoltage computed tomography imaging: a potential tool to guide and improve the delivery of thoracic radiation therapy. *Clin Lung Cancer* 2004;5:303–306. [PubMed: 15086969]
7. Ling CC, Yorke E, Fuks Z. From IMRT to IGRT: frontierland or neverland? *Radiother Oncol* 2006;78:119–122. [PubMed: 16413622]
8. Amols HI, Jaffray DA, Orton CG. Image-guided radiotherapy is being overvalued as a clinical tool in radiation oncology. *Med Phys* 2006;33:3583–3586. [PubMed: 17089824]
9. Mackie TR. History of tomotherapy. *Phys Med Biol* 2006;51:R427–R453. [PubMed: 16790916]
10. Meeks SL, Harmon JF, Langen KM, et al. Performance characterization of megavoltage computed tomography imaging on a helical tomotherapy unit. *Med Phys* 2005;32:2673–2681. [PubMed: 16193798]
11. Boswell S, Tomé W, Jeraj R, et al. Automatic registration of megavoltage to kilovoltage CT images in helical tomotherapy: an evaluation of the setup verification process for the special case of a rigid head phantom. *Med Phys* 2006;33:4395–4404. [PubMed: 17153418]
12. Yan D, Wong J, Vicini F, et al. Adaptive modification of treatment planning to minimize the deleterious effects of treatment setup errors. *Int J Radiat Oncol Biol Phys* 1997;38:197–206. [PubMed: 9212024]
13. Yan D, Lockman D, Martinez A, et al. Computed tomography guided management of interfractional patient variation. *Semin Radiat Oncol* 2005;15:168–179. [PubMed: 15983942]
14. van Herk M. Errors and margins in radiotherapy. *Semin Radiat Oncol* 2004;14:52–64. [PubMed: 14752733]
15. Langen KM, Jones DT. Organ motion and its management. *Int J Radiat Oncol Biol Phys* 2001;50:265–278. [PubMed: 11316572]
16. Booth JT, Zavgorodni SF. Set-up error and organ motion uncertainty: a review. *Australas Phys Eng Sci Med* 1999;22:29–47. [PubMed: 10474974]
17. Smeenk C, Gaede S, Battista JJ. Delineation of moving targets with slow MVCT scans: implications for adaptive non-gated lung tomotherapy. *Phys Med Biol* 2007;52:1119–1134. [PubMed: 17264374]
18. Hong TS, Tomé WA, Chappell RJ, et al. The impact of daily setup variations on head-and-neck intensity-modulated radiation therapy. *Int J Radiat Oncol Biol Phys* 2005;61:779–788. [PubMed: 15708257]
19. Orton NP, Tomé WA. The impact of daily shifts on prostate IMRT dose distributions. *Med Phys* 2004;31:2845–2848. [PubMed: 15543793]
20. Guckenberger M, Meyer J, Vordermark D, et al. Magnitude and clinical relevance of translational and rotational patient setup errors: a cone-beam CT study. *Int J Radiat Oncol Biol Phys* 2006;65:934–942. [PubMed: 16751076]

Figure 1.
Coordinate system of positioning corrections

Figure 2.
Overall distributions of translational corrections (mm) truncated at 30 mm.

Figure 3.
Overall distributions of roll rotations (°).

Figure 4. Brain and H&N individual patient mean positioning corrections in chronological order, error bars indicating two standard deviations of the mean.

Figure 5. Lung and prostate individual patient mean positioning corrections in chronological order, error bars indicating two standard deviations of the mean.

Figure 6. Variations in systematic setup errors and magnitudes of random setup errors for translations and rotations by treatment site.

Table 1

Cumulative frequency (%) of translational setup corrections of various 3D vector lengths

3D vector length (mm)	Brain	H&N	Lung	Prostate
≥ 0	100.0	100.0	100.0	100.0
≥ 2	91.2	85.0	95.5	95.4
≥ 4	54.7	54.7	89.4	89.3
≥ 6	17.1	22.9	77.9	79.2
≥ 8	4.2	7.2	62.9	64.7
≥ 10	1.5	1.2	48.9	48.1
≥ 15	0.3	0.1	17.8	20.5
≥ 20	0.3	0.0	5.5	7.4

Table 2

Cumulative frequency (%) of roll corrections of various magnitudes

Roll Magnitude (°)	Brain	H&N	Lung	Prostate
≥ 0	100.0	100.0	100.0	100.0
≥ 1	31.3	29.6	27.4	18.9
≥ 2	15.0	14.0	12.1	1.8
≥ 3	5.0	5.9	4.2	0.3
≥ 4	0.7	3.2	1.8	0.1
≥ 5	0.0	1.2	0.4	0.0

Table 3

Results of setup error analysis showing global systematic errors

	Global Systematic Error			
	Lateral (mm)	Longitudinal (mm)	Vertical (mm)	Roll (°)
Brain	0.1	0.6	-0.5	0.4
H&N	1.2	1.2	-0.1	0.1
Lung	0.6	0.4	-1.0	0.2
Prostate	0.2	2.3	4.7	0.3

Table 4
Results of setup error analysis showing patient-to-patient variations in systematic errors and magnitudes of random errors

	Variation in Systematic Errors				Magnitude of Random Errors			
	Lateral (mm)	Longitudinal (mm)	Vertical (mm)	Roll (°)	Lateral (mm)	Longitudinal (mm)	Vertical (mm)	Roll (°)
Brain	1.8	2.6	2.1	0.8	1.8	1.7	2.0	0.9
H&N	2.3	1.9	1.6	0.8	1.8	1.9	1.9	1.2
Lung	4.3	5.2	5.2	0.7	3.9	6.1	5.9	1.0
Prostate	3.7	3.6	7.2	0.5	3.2	4.7	4.4	0.5