Received:
6 August 2013

Revised:
19 December 2013

Accepted:
3 January 2014

doi: 10.1259/bjr.20130494

Cite this article as:

Cheng K-F, Wu VWC. Comparison of the effectiveness of different immobilization systems in different body regions using daily megavoltage CT in helical tomotherapy. *Br J Radiol* 2014;87:20130494.

FULL PAPER

Comparison of the effectiveness of different immobilization systems in different body regions using daily megavoltage CT in helical tomotherapy

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Objective: Effective immobilization is crucial for the accurate delivery of radiotherapy. This study aimed to compare the effectiveness of the commonly used immobilization systems for different body regions using megavoltage CT (MVCT).

Methods: Daily treatment set-up data from 212 patients treated by helical tomotherapy (Accuray, Sunnyvale, CA) in 6 body regions (52 head and neck, 41 chest, 38 abdomen, 36 pelvis, 18 breast and 27 cranium) were obtained. Based on a verification tool using the pre-treatment MVCT, set-up corrections for each patient were recorded. Mean systematic and random errors of lateral, longitudinal, vertical and roll directions and three-dimensional vectors were compared between immobilization systems of each region.

Results: Smaller set-up deviations were observed in the Orfit system (Orfit Industries NV, Wijnegem, Belgium) of the head and neck region, while the performance of immobilization systems for the chest, abdomen and

pelvis regions was similar. Larger differences were noted in the breast group, where the prone BodyFIX® system (Medical Intelligence, Medizintechnik GmbH, Schwabmünchen, Germany) was less stable than the supine VacLok® system (CIVCO Medical Solutions, Orange City, IA).

Conclusion: Differences were found between the immobilization systems in the head and neck region, in which the Orfit system was relatively more effective, whereas the VacLok and BodyFIX systems performed similarly in the chest, abdomen and pelvis regions. For the breast case, the supine position with VacLok was much more stable than the prone breast technique. The results provided references for the estimation of clinical target volume-planning target volume margins.

Advances in knowledge: This is the first article on comprehensive comparisons performed in immobilization systems for main body regions that provides some practical recommendations.

The goal of radiotherapy is to maximize tumour control and minimize complications in the surrounding normal tissue. The success of radiotherapy depends mostly on the accuracy and the reproducibility of daily treatment delivery.^{1,2} Many studies have shown that an effective immobilization system can reduce positioning variations^{3–6} and improve the outcome of radiotherapy treatment. With the introduction of many commercially available immobilization accessories, oncology departments have developed their own immobilization systems for specific cancer patients and radiotherapy techniques based on their available resources and treatment protocols. As many choices of immobilization devices are now available in the market, more than one immobilization system may have been developed for the treatment of a specific disease. It is the interest of the clinicians to understand the effectiveness of individual immobilization devices and come up with an

optimal system that offers the least set-up deviation during treatment.

Because of this, many studies have been performed in the past to investigate the effectiveness of different immobilization systems, most of which used portal imaging as the verification method. Since portal images can only provide two-dimensional (2D) information, it is difficult to detect rotational set-up errors. The recent integration of CT in radiotherapy treatment machines has solved this problem and provides a three-dimensional (3D) verification application. Such systems include the integration of cone beam CT in a linear accelerator and the megavoltage (MV) CT in helical tomotherapy (Accuray, Sunnyvale, CA). Many previous studies, including the one by Li et al,⁷ have already demonstrated that the 3D approach in cone beam CT was superior to the 2D radiographic

Table 1. Breakdown of the recruited subjects according to the sites and total number of treatment fractions from the megavoltage CT data retrieved from the helical tomotherapy unit (Accuray, Sunnyvale, CA)

Body region treated by helical tomotherapy	Total no. of cases	Total no. of treatment fractions
Head and neck	52	1482
Chest	41	862
Abdomen	38	750
Pelvis	36	971
Breast	18	427
Cranium	27	429

portal images used in the verification of patients treated at the head and neck region.

MVCT is inherent in the helical tomotherapy unit, which is used for the daily set-up and verification of the patient position. Such a system provides more detailed set-up data and is more reliable in assessing positional deviations compared with the portal imaging method. Furthermore, the data collected from the MVCT verification system can be used to generate the systematic and random errors of each treatment, which are useful for the evaluation of set-up accuracy. The systematic error is the average error over all treatment fractions, whereas the random error is the average magnitude of errors that are expected to be distributed as a gaussian function about a mean.

The aim of this study was to evaluate the effectiveness of different immobilization systems by assessing the systematic and random errors generated from MVCT data of helical tomotherapy for different body regions. The results would provide reference information for the choice of immobilization devices and establish an optimal system for specific treatment conditions, as it is expected that an optimal immobilization system would lead to more accurate treatment and better treatment outcomes.

METHODS AND MATERIALS

MVCT data of cancer patients who were treated by helical tomotherapy at the regions of head and neck, chest, breast, abdomen, pelvis and cranium were retrieved from the database of the helical tomotherapy unit. The breast cases were separated from the chest group. The exclusion criteria were patients who had <10 fractions in the treatment course, patients with recurrence and metastasis, and patients with treatment involving two or more regions. As a result, a total of 212 patients with 4867 treatment fractions were recruited. A breakdown of the information from these patients in the six body regions is shown in Table 1. 3D (*x*, *y* and *z* directions) translational deviations, including the lateral (*lat*), longitudinal (*lng*) and vertical (*vrt*) directions and the roll rotation corrections for each fraction of the treatment for each patient were recorded. Apart from the cranial region, where only a single immobilization was used, two commonly used immobilization systems for each of the other five body regions were included in the study. The descriptions of the immobilization systems and their codes for each treatment region are shown in Table 2, and their diagrams are shown in Figures 1–4.

Table 2. Descriptions of the different immobilization systems for each body region treated by helical tomotherapy (Accuray, Sunnyvale, CA)

Body region	Codes	Descriptions of immobilization system
Head and neck (Figure 1)	H&N-HR	Supine on large T-base plate, headrest with or without tongue depressor, and with large thermoplastic cast
	H&N-OF	Supine on Orfit base plate with headrest, and thermoplastic cast reinforced with Orfitlight, and with or without tongue depressor
Chest (Figure 2)	Chest-VL	Supine on VacLok® and headrest, with both arms raised overhead
	Chest-BF	Same as Chest-VL except replace VacLok with BodyFIX®
Abdomen (Figure 2)	Abdo-VL	Supine on VacLok and headrest, with both arms raise up overhead
	Abdo-BF	Same as Abdo-VL except replace VacLok with BodyFIX
Pelvis (Figure 2)	Pelvis-VL	Supine on VacLok, with leg support under patient's ankles, and both arms of patient keeping on chest and cross each other
	Pelvis-BF	Same as Pelvis-VL except replace VacLok with BodyFIX
Breast (Figure 3)	Breast-VL	Supine on VacLok and headrest, with both arms raised overhead
	Breast-PB	Prone on prone breast board, with a small VacLok under head, and a contralateral breast wedge
Cranium (Figure 4)	Cran-SC	Supine on small base plate and headrest with small thermoplastic cast.

BodyFIX® is manufactured by Medical Intelligence, Medizintechnik GmbH, Schwabmünchen, Germany; the base plate, headrest, prone breast board, thermoplastic cast and VacLok® are manufactured by CIVCO Medical Solutions, Orange City, IA; and Orfitlight is manufactured by Orfit Industries NV, Wijnegem, Belgium.

Figure 1. Photos showing the two immobilization systems for the head and neck region. (a) Supine with headrest (CIVCO Medical Solutions, Orange City, IA) and (b) supine with Orfit system (Orfit Industries NV, Wijnegem, Belgium).

The readings of daily positional deviations were recorded when the patients underwent treatment by helical tomotherapy. During each treatment fraction, all patients were immobilized in their respective immobilization systems. The set-up was conducted with the patients in the treatment position using the three-point technique, in which the ceiling and wall laser beams were made to coincide with the marks, either on skin or immobilization shell, at the anterior set-up centre and the lateral horizontal levels on both sides of the body, respectively. They were set up in the treatment position and underwent a helical MVCT scan at the treatment region with the slice thickness and spacing following the local protocol. The kV planning CT, which was taken earlier in the same treatment position for planning purpose, was displayed side by side with the MVCT image in the workstation. The kV planning CT images were then matched with the MVCT images following local protocols for different body regions using the verification programme in the helical tomotherapy unit. The MVCT images were first automatically registered to corresponding structures in the kV planning CT images followed by the refinement made by therapists using manual function. When image registration was completed, the positional deviations at the longitudinal, vertical, lateral and roll rotational directions were displayed in the monitor and recorded. In case a readjustment and rematching of the patient's position was required, only readings of the first matching were taken for analysis. In other words, all readings were recorded before any correction protocol was applied.

The evaluation of the effectiveness of each immobilization system was based on their respective systematic and random errors, which were calculated from the positional deviations as a result of image registration. These two parameters were frequently used in investigating set-up accuracy in radiotherapy.^{8–12} For each patient, an average systematic error was calculated by averaging the set-up errors in all fractions of a treatment course. For patients within the same body region, a group systematic error was calculated and denoted by $\sum$. The random error was the fraction-to-fraction variation around the systematic mean and was the standard deviation of the set-up error over all treatment fractions. The mean of the random errors for the patients in the same group was denoted by σ .

Another parameter used for the assessment of set-up accuracy was the 3D vector, which was an indicator of the resultant displacement of the treatment position from the reference position.^{3,4,13} It was calculated by the formula:

$$\begin{aligned} \text{3D vector} \\ &= \sqrt{[(\text{lateral deviation})^2 + (\text{longitudinal deviation})^2 + (\text{vertical deviation})^2]} \end{aligned}$$

The larger the value of the 3D vector, the greater would be the overall set-up displacement. In addition, the frequencies of the 3D vector >0, >2, >4, >6, >8, >10, >12 and >15 mm for each of the immobilization systems were analysed to identify the pattern of displacement in each immobilization system.

Figure 2. Photos showing the two immobilization systems for the chest, abdomen and pelvis regions. (a) Supine with VacLok® (CIVCO Medical Solutions, Orange City, IA) and headrest and (b) supine with BodyFIX® (Medical Intelligence, Medizintechnik GmbH, Schwabmünchen, Germany) and headrest.

Figure 3. Photos showing the two immobilization systems for breast region. (a) supine on VacLok® (CIVCO Medical Solutions, Orange City, IA) and headrest (CIVCO Medical Solutions) and (b) prone on prone breast board (CIVCO Medical Solutions), with small VacLok under head and a contralateral breast wedge.

Both the 3D vectors and their frequency patterns were compared between the different immobilization systems of the same treatment region. For the treatment of each body region, the differences of the mean systematic ($\sum$) and random (σ) errors of each direction and the 3D vector between the two immobilization systems were analysed by Student's *t*-test using the Graphpad Prism® 5 software (GraphPad Software, Inc., La Jolla, CA).

RESULTS

The calculated systematic and random errors and the 3D vectors with statistic results are shown in Table 3. The cumulative frequencies of 3D vector magnitudes are shown in Table 4. All these parameters were compared between the two immobilization systems for each body region.

For the head and neck region, most of the mean translation errors and the 3D vector were greater in the H&N-HR, in which the differences in $\sum$ lat, σ lat, σ vrt and 3D vector reached significance ($p < 0.05$; Table 3). The mean roll rotation errors of the H&N-OF were greater than that of the H&N-HR, with only the systematic error reaching significance. The cumulative frequencies of 3D vectors showed that 3D vectors ≥ 4 and ≥ 6 mm more frequently occurred in H&N-HR (82.2% and

40.7%, respectively) than in H&N-OF (52.8% and 8.3%, respectively; Table 4). In the chest region, only the $\sum$ lng and σ roll of Chest-BF were greater than that of the Chest-VL. The differences of the other parameters, including mean 3D vector, did not show significant difference. The cumulative frequencies of 3D vectors were also similar in both groups. For the abdomen, only the σ roll and mean 3D vector of Abdo-BF were greater than Abdo-VL, with slightly higher 3D vector frequencies. However, the rest of the parameters did not show significant differences.

For the pelvis region, only the σ vrt was significantly different between the two groups, in which the Pelvis-VL was greater than Pelvis-BF. The mean 3D vector and the cumulative frequencies of 3D vector were similar. For the breast cases, the $\sum$ lng, σ lat, σ lng and σ vrt of the Breast-PB group were significantly greater than Breast-VL by 2.2, 3.8, 2.0 and 1.7 mm, respectively (all $p < 0.05$). The mean 3D vectors of Breast-PB and Breast-VL were 13.9 and 7.2 mm, respectively, which were also significantly larger ($p < 0.05$). The cumulative frequencies of 3D vector in the two groups were also different, in which the 3D vectors ≥ 6 mm were more frequent in Breast-PB (91.2%) than in Breast-VL (66.2%). There was 10.4% of the 3D vectors in Breast-PB ≥ 20 mm, while it was 0.0% in Breast-VL. For the cranium, the calculated systematic ($\sum$) and random (σ) errors in all translations variations were < 1.5 mm, which was relatively small when compared with other body regions. Besides, its respective 3D vector frequencies were also lower than those of the other regions.

DISCUSSION

Our results showed that there were differences in set-up accuracy between the different immobilization systems in some of the body regions. In general, the overall set-up accuracy was satisfactory, with most of the mean set-up deviations falling < 10 mm. Among the different body regions, the prone treatment of the breast region showed the largest set-up deviation, whereas those of the abdomen and pelvis regions were relatively larger, most likely owing to the lack of a rigid thermoplastic shell and the presence of body movements. Based on the same reason, it was logical to note that the set-up deviation was smallest in the cranial region followed by the head and neck region.

Figure 4. Photo showing the two immobilization systems for cranial region: supine with base plate (CIVCO Medical Solutions, Orange City, IA), headrest (CIVCO Medical Solutions) and thermoplastic cast (CIVCO Medical Solutions).

Table 3. Calculated systematic errors, random errors and three-dimensional (3D) vectors with statistic result

Codes	Σ lat (mm)	Σ lng (mm)	Σ vrt (mm)	Σ roll (degree)	σ lat (mm)	σ lng (mm)	σ vrt (mm)	σ roll (degree)	Mean 3D vector
H&N-HR	1.5	1.2	1.3	<u>0.6</u>	<u>1.1</u>	<u>1.0</u>	<u>1.1</u>	0.7	<u>5.6</u>
H&N-OF	1.0	1.2	1.3	<u>1.0</u>	<u>0.8</u>	<u>0.8</u>	<u>0.8</u>	0.9	<u>4.2</u>
Chest-BF	2.5	<u>2.3</u>	2.7	0.5	1.3	1.8	2.2	<u>0.4</u>	7.5
Chest-VL	1.8	<u>1.4</u>	2.8	0.5	1.4	1.9	2.4	<u>0.7</u>	7.6
Abdo-BF	1.2	3.5	3.4	0.6	1.8	2.8	2.6	<u>0.6</u>	<u>9.0</u>
Abdo-VL	2.0	2.4	3.3	0.5	1.9	2.0	2.2	<u>0.4</u>	<u>8.0</u>
Pelvis-BF	1.8	2.2	1.6	0.7	1.6	1.5	<u>1.7</u>	0.4	8.1
Pelvis-VL	2.1	1.9	3.1	0.5	1.6	1.6	<u>2.1</u>	0.5	8.1
Breast-VL	1.9	<u>1.8</u>	2.4	0.5	<u>1.7</u>	<u>1.8</u>	<u>2.3</u>	0.7	<u>7.2</u>
Breast-BF	2.7	<u>4.0</u>	4.6	0.8	<u>5.5</u>	<u>3.8</u>	<u>4.0</u>	1.0	<u>13.9</u>
Cran-SC	1.0	1.4	1.2	0.7	0.9	1.0	0.7	0.8	4.3

Σ , systematic errors; σ , random errors; lat, lateral; lng, longitudinal; roll, roll rotation; vrt, vertical.

p-value <0.05 is considered significant. Statistically significant results are represented by underlined numbers.

Comparing immobilization systems of individual regions

For the head and neck region, results showed that the H&N-OF system provided relatively better set-up accuracy than the H&N-HR in the translational directions but not in the roll direction. A possible explanation of the relatively large roll deviation in the H&N-OF was the 5-point cast fixation method of the Orfit system (Orfit Industries NV, Wijnegem, Belgium). Compared with the Type S thermoplastic cast of CIVCO Medical Solutions (Orange City, IA), despite the Orfit cast being more stable, there was a tendency of applying unbalanced force from each side when fixing the cast on the base plate that resulted in a slight rotation of the patient's head. In the regions of chest, abdomen and pelvis, the main difference between the two immobilization systems was the use of VacLok® (CIVCO Medical Solutions) and BodyFIX® (Medical Intelligence, Medizintechnik GmbH, Schwabmünchen, Germany). The comparable systematic and random errors between the two systems showed that they demonstrated similar performance in immobilization, and therefore set-up accuracy would not be the main reason in selecting between these two systems. Instead, financial consideration and patient comfort may be more relevant factors for consideration. For the breast region, our result showed that the Breast-VL system was significantly more effective than the Breast-PB system and therefore would provide a more accurate set-up. Despite some previous studies reporting that prone breast board (CIVCO Medical Solutions) set-up in breast treatment offered some dosimetric benefits,^{14–16} there was a concern of set-up accuracy. In this study, although the patients' body weight and breast sizes were not assessed before the decision of treatment position, the oncologists tended to select Breast-PB for patients with larger breast size. This might explain the poorer accuracy in the Breast-PB system, in which the treatment region was more mobile in patients with large breast, and it would be

more difficult to achieve high reproducibility in the treatment set-up.

Implications on estimation of clinical target volume–planning target volume margins

In radiotherapy planning, the margin given to the clinical target volume (CTV) to become the planning target volume (PTV) takes into consideration the geometric set-up uncertainties. Therefore, if the set-up uncertainty can be reduced, the CTV/PTV margin can also be reduced, resulting in a smaller PTV and better sparing of the adjacent normal structures. This will facilitate dose escalation and better tumour control.^{17,18} It is expected that the magnitudes of the CTV/PTV margin will follow a similar pattern as the set-up deviations obtained from this study.

In this study, a relatively larger systematic error was detected in the vertical direction compared with the other directions, and they were more prominent in the chest, abdomen and pelvis regions. This phenomenon could be due to, in part, the effect of couch sag, which happened when a large portion of the patient was advanced into the bore of the helical tomotherapy unit; the weight of the patient that exerted on the extended couch would lead to a slight couch drop.

CONCLUSIONS

Among the different body regions, the immobilization for the cranium produced the least deviation, while the prone breast system was the worst. Differences were found when comparing the effectiveness of the two immobilization systems in the head and neck region, in which the H&N-OF system was slightly more effective, whereas the VacLok and BodyFIX systems did not show much difference in the chest, abdomen and pelvis regions. For the breast case, the supine position with VacLok was much more stable than the prone breast technique.

Table 4. The cumulative frequencies of three-dimensional (3D) vector length

3D vector (mm)	H&N-HR (%)	H&N-OF (%)	Chest-BF (%)	Chest-VL (%)	Abdo-BF (%)	Abdo-VL (%)	Pelvis-BF (%)	Pelvis-VL (%)	Breast-VL (%)	Breast-PB (%)	Cran-SC (%)
≥0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
≥2	98.9	98.5	99.0	99.1	100.0	99.6	100.0	98.6	99.0	100.0	97.2
≥4	82.2	52.8	91.2	87.2	95.5	95.1	96.3	92.6	90.1	96.0	54.3
≥6	40.7	8.3	65.5	65.6	81.8	78.9	84.3	74.2	66.2	91.2	11.4
≥8	7.4	0.3	43.0	43.2	55.5	49.6	52.7	47.6	35.8	86.4	0.7
≥10	0.8	0.0	22.1	24.1	28.6	17.9	16.7	24.1	13.2	76.8	0.0
≥12	0.0	0.0	5.5	10.6	18.2	14.2	4.6	11.2	5.0	61.6	0.0
≥15	0.0	0.0	0.0	1.1	7.7	1.3	0.0	2.6	1.3	41.6	0.0
≥20	0.0	0.0	0.0	0.0	1.8	0.2	0.0	0.1	0.0	10.4	0.0

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