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FULL PAPER

Pilot study on interfractional and intrafractional movements using surface infrared markers and EPID for patients with rectal cancer treated in the prone position

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Objective: To evaluate interfractional and intrafractional movement of patients with rectal cancer during radiotherapy with electronic portal imaging device (EPID) and surface infrared (IR) markers.

Methods: 20 patients undergoing radiotherapy for rectal cancer with body mass index ranging from 18.5 to 30 were enrolled. Patients were placed in the prone position on a couch with a leg pillow. Three IR markers were put on the surface of each patient and traced by two stereo cameras during radiotherapy on a twice-weekly basis. Interfractional isocentre movement was obtained with EPID images on a weekly basis. Movement of the IR markers was analysed in correlation with the isocentre movement obtained from the EPID images.

Results: The maximum right-to-left (R-L) movement of the laterally located markers in the horizontal isocentre plane was correlated with isocentre translocation with statistical significance ($p = 0.018$ and 0.015 , respectively). Movement of the surface markers was cyclical. For centrally located markers, the 95% confidence intervals for the

average amplitude in the R-L, cranial-to-caudal (C-C) and anterior-to-posterior (A-P) directions were 0.86, 2.25 and 3.48 mm, respectively. In 10 patients, intrafractional movement exceeding 5 mm in at least one direction was observed. Time-dependent systematic movement of surface markers during treatment, which consisted of continuous movement towards the cranial direction and a sail back motion in the A-P direction, was also observed.

Conclusion: Intrafractional movement of surface markers has both cyclic components and time-dependent systematic components. Marker deviations exceeding 5 mm were mainly seen in the A-P direction. Pre- or post-treatment EPID images may not provide adequate information regarding intrafractional movement because of systematic movement in the A-P direction during radiotherapy.

Advances in knowledge: This work uncovered a sail back motion of patients in the A-P direction during radiotherapy. Pre- or post-treatment EPID images may not provide accurate positioning of patients in the A-P direction because of this time-dependent intrafractional motion.

Patients treated in the prone position are reported to be more susceptible to positioning errors during radiotherapy.¹⁻³ Set-up errors in relation to patient position have been frequently reported in patients treated for prostate cancer. Bayley et al¹ showed that for patients with prostate cancer treated in the prone position, isocentre positioning errors were 0.0 ± 3.7 and 0.1 ± 4.3 mm in the anterior-to-posterior (A-P) and cranial-to-caudal (C-C) directions, respectively. Isocentre positioning errors ranged from -7.6 to 8.8 mm in the A-P direction. However, for errors in the C-C direction, there was no significant difference between the supine and prone positions. Weber et al² also reported that the prone position was more unstable than the supine

position with a greater distribution of isocentre translocation (prone 4.7 mm vs supine 4.2 mm) in the A-P direction. In addition, systematic set-up variation was larger in the prone position than in the supine position (2.7 vs 1.9 mm). Griffiths et al³ demonstrated that the probability of set-up errors exceeding 5 mm was 12% in the right-to-left (R-L) direction and 33% in the C-C direction. These findings suggest that efforts should be made to reduce set-up uncertainties for patients, especially those treated in the prone position, for more accurate treatment delivery, specifically in an era of intensity-modulated radiotherapy and image-guided radiotherapy. Unlike prostate cancer, patients with rectal cancer are advised to be treated in the

prone position to minimize the radiation exposure to the small bowel. But set-up instabilities for patients with rectal cancer have not been studied as much as those for patients with prostate cancer, as described above.

As one of the methods of monitoring patient motion, a non-invasive infrared (IR) monitoring system within the radiotherapy treatment room has been established at the Department of Radiation Oncology, Seoul National University Hospital, Seoul, Republic of Korea, and the reliability of the system has previously been reported.⁴ An IR monitoring system as a tool for measuring patient motion can be easily set up using IR cameras and IR markers that are placed on the surface of the patient. This system is not only non-invasive but is also capable of detecting surface motion in real time.

The primary goals of this pilot study were to monitor and analyse patterns in patient motion, which may consist of systematic and/or random components, during radiotherapy using the IR monitoring system. The secondary goal was to validate the applicability of the IR monitoring system by correlation with electronic portal imaging device (EPID) images.

METHODS AND MATERIALS

Patient eligibility

The following criteria were used to determine eligibility for enrolment in the study: age between 19 and 70 years, diagnosis of rectal cancer, radiotherapy treatments in the prone position and signed informed consent prior to registration. Patients with an increased risk of set-up instability in the prone position were

excluded. Exclusion criteria were body mass index, defined as mass in kilograms divided by square of height in metres, <18.5 or >30 , active psychiatric illness and having ileostomy or colostomy. All patients were interviewed at least once a week during radiotherapy. Height, weight and waist circumference of each patient were recorded prior to the treatment. Weight and waist circumference were checked on weekly basis during radiotherapy. This study was approved by the institutional review board prior to patient accrual.

Patient set-up and treatment

Patients were positioned in the prone position on a couch with a leg fix. The patient's head was placed in a prone pillow to minimize roll. Long surface laser marks were used to minimize the pitch, yaw and roll. The patient set-up was reviewed using EPID images taken at least weekly. The patient was brought to the simulator to check the set-up reproducibility under fluoroscopic guidance when the isocentre translocation exceeded 5 mm in any direction. All patients were treated to the pelvis followed by a tumour bed boost using a three-dimensional (3D) conformal radiotherapy technique with 6- and 15-MV photon beams. The clinical target volume (CTV) of pelvic radiotherapy included mesorectum harbouring primary gross tumour with craniocaudal extension of at least 1 cm and draining presacral and internal iliac lymph nodes. Boost CTV included mesorectum harbouring primary gross tumour with identical craniocaudal extension. In a minority of cases with lateral nodal involvement, lymph node enlargements >1 cm in the short diameter were also added to the CTV. The planning target volume (PTV), pelvic and boost were

Figure 1. Beams' eye view (BEV) of the clinical target volume (CTV) and planning target volume (PTV). Posterior-to-anterior (a) and right-to-left (b) BEV showing CTV, pelvic in light grey, and PTV, pelvic in white. Posterior-to-anterior (c) and right posterior oblique (d) BEV showing CTV, boost in dark grey, and PTV, boost in light grey.

generated with a 10 mm margin from the CTV, pelvic and boost, respectively (Figure 1). The dose for pelvic and boost radiotherapy was 45 Gy in 25 fractions and 5.4 Gy in 3 fractions, respectively.

Intrafractional movement measurement

The IR monitoring system used in this study is as described previously (Figure 2a).⁴ In brief, two stereo cameras (HVR2300C; HyVISION System, Sunnam, Korea) with an IR filter (BpW092; Schneider, Bad Kreuznach, Germany) were installed in the radiotherapy treatment room. A motion-detecting algorithm was developed with an accuracy of 0.5 ± 0.5 mm and a resolution of 0.1 mm by daily calibration. Intrafractional monitoring of IR markers was performed on a twice-weekly basis (*i.e.* Monday and Wednesday or Tuesday and Thursday). IR marker locations were dotted on the surface of the patient at the time of simulation. Marker A was placed at the cross-point of the L5-S1 junction and the mid-axis of the posterior radiation port. Marker B was put 10 cm left from the isocentre, and Marker C was in the opposite position to Marker B (Figure 2b). Marker positions were recorded from the patient set-up until the end of daily treatment. Frequency of acquisition was 6 frames per second. As another method of evaluating intrafractional patient motion, the source-to-skin distance (SSD) was measured on the axis of the isocentre in the posterior direction at the time of patient set-up and at the end of daily treatment.

Interfractional movement measurement

EPID images were obtained routinely at least once a week at the end of daily treatment. EPID images were compared with the reference images taken on the simulation. A total of 94 pairs of posteroanterior and right-left EPID images were obtained. The Pelvis1 protocol in the Off-line Review v. 1.0 (Varian® Medical Systems, Palo Alto, CA) program, which automatically calculates translocation of the isocentre, was used to detect translocation of the isocentre. The magnitude of the isocentre translocation was calculated from the measured R-L, C-C and A-P directional shifts using the following equation: magnitude of isocentre translocation = $(\Delta x^2 + \Delta y^2 + \Delta z^2)^{1/2}$, where Δ = the difference between the reference image and the EPID image, x = R-L, y = C-C and z = A-P direction.

Statistical analyses

Statistical analyses were performed using the SPSS® software, release v. 18.0.0 (SPSS Inc., Chicago, IL). A p -value < 0.05 was

considered statistically significant. Categorical and continuous data were compared between the groups using Fisher's exact test and Student's t -test, respectively. Paired t -tests were performed to compare the weight and waist circumference before and after radiotherapy.

RESULTS

The mean age of the patients was 55.9 years, ranging from 41.0 to 76.0 years. 16 males and 4 females were enrolled. Six patients were treated postoperatively. All patients were ambulatory and at least capable of light work. The mean height of the patients was 164.2 cm, and the mean weight before and at the end of radiotherapy was 63.6 and 63.5 kg, respectively. Each patient's weight and waist circumference were stable during the course of radiotherapy (Table 1).

Cyclic intrafractional movement of surface markers

Movement of the surface markers was cyclic as illustrated in Figure 3, showing cyclic movement of Marker A for Patient 1 during the first 30 s on the first day of radiotherapy.

The average amplitudes of Marker A movement for all patients were 0.58, 1.67 and 2.57 mm in the R-L, C-C and A-P directions, respectively. Corresponding values for Marker B were 0.71, 1.96 and 2.27 mm, respectively, and those for Marker C were 0.70, 1.93 and 2.22 mm, respectively. The 95% confidence intervals of average amplitude in the R-L, C-C and A-P directions also for all patients were 0.86, 2.25 and 3.48 mm for Marker A, 1.21, 2.65 and 3.13 mm for Marker B and 1.10, 2.62 and 2.94 mm for Marker C, respectively (Table 2).

Time-dependent systematic movement of surface markers

The mean position of markers over 30 s for all patients is displayed according to the elapsed treatment time (Figure 4). The mean position of all markers over 30 s had changed with statistical significance ($p < 0.001$), and the standard deviation of marker movement increased over time, which indicates instability of patient position over time. In the R-L direction, movement of markers was less than that in the C-C or A-P direction. In the C-C direction, a continuous increase of marker position with time was seen. Movement of markers in the A-P direction showed a sail back motion: markers moved away from the gantry head for 1 min and remained for about another 1 min. After these 2 min,

Figure 2. Intrafractional movement monitoring system using stereotactic cameras (a). Two stereotactic cameras for detecting infrared markers were installed in the radiotherapy treatment room as shown. Diagram of marker position shows the relative position of infrared markers (b).

Table 1. Clinical characteristics of enrolled patients

Characteristics	Mean $\pm$ standard deviation	<i>p</i> -value
Height (cm)	164.2 $\pm$ 8.5	–
Weight (kg)		0.799
At the start of radiotherapy	63.6 $\pm$ 9.7	
At the end of radiotherapy	63.5 $\pm$ 9.6	
Waist circumference (cm)		0.107
At the start of radiotherapy	85.7 $\pm$ 6.9	
At the end of radiotherapy	84.9 $\pm$ 7.2	
Body mass index (kg m^{-2})	23.6 $\pm$ 3.0	–

the markers started to move back towards the gantry over time and returned to their initial set-up position at about 3 min from the start.

Percentage of time for intrafractional surface marker movement exceeding 5 mm

The percentage of time for intrafractional surface marker movement exceeding 5 mm is displayed in Table 3. Intrafractional movement larger than 5 mm in at least one direction occurred in 10 patients. Patient 6 showed the largest motion of Marker C, and the

percentage of time for Marker C translocation exceeding 5 mm was 50.6%. Patient 17 had the most frequent marker deviation exceeding 5 mm, which was found in 40% of the observations.

Interfractional isocentre translocation and intrafractional surface marker movement correlation
The mean absolute isocentre translocation was 0.35 ± 0.31 cm, with the mean absolute translocations of 0.12 ± 0.12 , 0.19 ± 0.21 and 0.20 ± 0.19 cm in the *x*, *y* and *z* directions, respectively (Table 4).

Figure 3. Representative cyclic movement of Marker A in Patient 1 for the first 30 s during the first day of radiotherapy. A-P, anterior-to-posterior direction; C-C, cranial-to-caudal direction; R-L, right-to-left direction.

Table 2. Amplitude of surface marker movement

Patient	Marker A			Marker B			Marker C		
	R-L (mm)	C-C (mm)	A-P (mm)	R-L (mm)	C-C (mm)	A-P (mm)	R-L (mm)	C-C (mm)	A-P (mm)
Mean	0.58	1.67	2.57	0.71	1.96	2.27	0.70	1.93	2.22
Standard deviation	0.22	0.45	0.71	0.39	0.53	0.67	0.31	0.54	0.56
0–95% amplitude	0.86	2.25	3.48	1.21	2.64	3.13	1.10	2.62	2.94

A-P, anterior-to-posterior direction; C-C, cranial-to-caudal direction; R-L, right-to-left direction.

The incidence of isocentre translocation exceeding 5 mm in one direction was 4.3% (4/94), which was less frequent than expected. Based on these data, a 3D margin of 5 mm may be sufficient to cover set-up errors for 99% of patients with rectal

cancer treated in the prone position.⁵ Correlations between clinical parameters, the mean and the maximum marker movement in each direction, SSD changes and the isocentre translocation from weekly EPID images were also evaluated.

Figure 4. Time-dependent movements of (a) Marker A, (b) Marker B and (c) Marker C. Marker positions are displayed with the mean and standard deviation. All markers show a continuous increase in the cranial-to-caudal (C-C) direction. In the anterior-to-posterior (A-P) direction, the position of all three surface markers decreases for the first 1 min, stabilizes for the next 1 min, and then increases. As a result, the position of the surface markers in the A-P direction was nearly identical to the initial position after 3 min. R-L, right-to-left direction. Bars, standard deviation.

Table 3. Patients with intrafractional surface marker motion exceeding 5 mm in any direction. Most of the marker motion exceeding 5 mm occurred in the anterior-to-posterior direction and other directional movements were marked

Patient	Marker A >5 mm			Marker B >5 mm			Marker C >5 mm		
	Frequency (%)	Percentage of time (%)	Range (%)	Frequency (%)	Percentage of time (%)	Range (%)	Frequency (%)	Percentage of time (%)	Range (%)
2	1/8 (12.5)	8.4	8.4	1/8 (12.5)	9.56	9.6	1/8 (12.5)	4.6	4.6
4	–	–	–	1/11 (9.1)	2.5	2.5	–	–	–
6	–	–	–	1/11 (9.1)	17.3 ^a	17.3	1/11 (9.1)	50.6 ^a	50.6
9	2/9 (22.2)	35.9	34.3, 37.5	1/9 (11.1)	9.4	9.4	1/9 (11.1)	37.5	37.5
11	1/9 (11.1)	6.0	6.0	–	–	–	1/9 (11.1)	2.1	2.1
14	–	–	–	1/9 (11.1)	2.1	2.1	–	–	–
16	1/10 (10.0)	3.0	3.0	–	–	–	–	–	–
17	4/10 (40.0)	7.3	1.2–14.0	2/10 (20.0)	10.3	7.8, 12.7	2/10 (20.0)	7.8	3.7, 11.8
19	–	–	–	–	–	–	1/8 (12.5)	5.0 ^b	5.0
20	1/10 (10.0)	1.5	1.5	1/10 (10.0)	2.9	2.9	1/10 (10.0)	5.0 ^b	5.0

^aRight-to-left (R-L) and anterior-to-posterior directional movement.

^bR-L directional movement.

None of the clinical parameters including age, gender, surgery, height, weight and waist circumference were correlated with interfractional isocentre translocation (data not shown).

Generally, post-treatment position of the surface markers followed normal distribution for the R-L, C-C and A-P directions (Figure 5). Average movements of Marker A were 0.0603, 0.0453 and -0.185 mm in the R-L, C-C and A-P directions, respectively. Marker B and C showed the largest average movement in the C-C direction. There was a difference in average marker movement for each direction between Marker A and Markers B and C. Isocentre translocation in the R-L direction was significantly correlated with intrafractional R-L and A-P maximum movement for Markers B and C. Overall, isocentre translocation was correlated with intrafractional R-L maximum movement for Markers B and C (Table 5).

INTERFRACTIONAL SOURCE-TO-SKIN DISTANCE CHANGE

SSD was measured at the time of patient set-up and after radiotherapy treatment on a daily basis. The mean change of SSD for all patients was -0.012 cm ranging from -0.7 to 1.0 cm with standard deviation of 0.24 . Absolute SSD change exceeding 5 mm occurred in 4.8% ($10/210$) of observations. However, SSD change was not significantly correlated with the isocentre translocation ($p = 0.899$).

DISCUSSION

Interfractional set-up errors in pelvic tumours have been improved with the use of various immobilization devices such as aquaplast moulds or alpha cradles and imaging devices including pre-treatment cone beam CT.⁶⁻⁸ However, there are fewer studies focusing on intrafractional motion compared with interfractional movement in patients with rectal cancer. In the present study, correlation between intrafractional surface marker motion and isocentre translocation obtained from EPID images was investigated. The maximum movement for Markers B and C at the horizontal isocentre plane in the R-L direction was correlated with isocentre translocation on EPID images with statistical significance ($p = 0.018$ and 0.015 , respectively). This may suggest that intrafractional maximum R-L movement of markers reflects the position instability during radiotherapy.

Time-dependent intrafractional patient motion has been previously reported in patients with prostate cancer.^{9,10} In patients with prostate cancer treated in the supine position,

intrafractional motion as well as internal organ motion increased over time.¹⁰ However, in the present study, where patients were treated in the prone position for rectal cancer, intrafractional motion was more complex than it was in the supine position for prostate cancer. Surface markers demonstrated characteristic intrafractional movements in each direction. R-L movement of surface markers was smaller than the others, and a trend towards left deviation was observed. The marker position in the C-C direction demonstrated a continuous increase, which means a systematic movement towards the cranial direction during a treatment session. As for the A-P movement, a rather unique sail back motion was observed. All three surface markers moved away from the gantry head for the first 1 min, stabilized during the next 1 min, and then returned to the initial set-up position about 3 min after the initial set-up (Figure 4). Additionally, most surface marker movement exceeding 5 mm was observed in the A-P direction, as shown in Table 5. Some patients had surface marker deviation exceeding 5 mm for a significant percentage of time during radiotherapy treatment. Taken together, it is strongly suggested that in the present series, isocentre verification using EPID images before or after radiotherapy only does not guarantee accurate beam delivery during radiotherapy, especially in the A-P direction. Although isocentre translocation measured from EPID images in the present series shows that a $3D$ margin of 5 mm would be sufficient to cover set-up errors, it is also suggested that a wider margin >5 mm from CTV to PTV would be required to take intrafractional patient motion into account.

Tournel et al evaluated isocentre movement based on the bony anatomy using cone beam CT and compared 100 pre- and post-treatment scans to investigate intrafractional movement of patients with rectal cancer. They showed that intrafractional isocentre movements in rectal cancer were -0.59 ± 2.45 , -0.52 ± 1.99 and 0.94 ± 1.09 mm in the R-L, A-P and C-C directions, respectively.¹¹ These results are similar to the present finding in that average R-L and A-P movements were smaller than C-C movement and that there was an anterior deviation during radiotherapy. However, based on results from the present study, these data should be carefully interpreted because it could be postulated that if the whole treatment time takes more than 2 min, which is not unusual in conformal radiotherapy, post-treatment scans will not represent the actual position of the isocentre during radiotherapy.

Table 4. Isocentre translocations in each direction

Variables (cm)	Mean absolute	Minimum	Maximum	Standard deviation
Right-to-left	0.19	-0.6	0.5	0.21
Cranial-to-caudal	0.20	-0.5	0.6	0.19
Anterior-to-posterior	0.12	-0.6	0.5	0.12
IsoTrans	0.35	0.0	0.68	0.31

IsoTrans, isocentre translocation at each treatment compared with simulation film.

Figure 5. Post-treatment positions of (a) Marker A, (b) Marker B and (c) Marker C of all patients are displayed with the mean and standard deviation (SD). The mean position of all markers over 30 s had changed with statistical significance ($p < 0.001$) and the SD of marker movement increased over time, which indicates instability of the patient's position over time. Generally, movement of surface markers followed a normal distribution. A-P, anterior-to-posterior direction; C-C, cranial-to-caudal direction; R-L, right-to-left direction.

Translational movement is only one of the components of patient movement during radiotherapy. If the position of the isocentre is corrected with only translational movement, a substantial proportion of peripheral PTV can be missed from the treated volume. Ahmad *et al*¹² reported that with only translational correction, residual A-P displacement for the L4 vertebral body >5 mm was found in 47% of patients treated for cancer of the uterine cervix in the prone position. In the present

study, surface marker motion showed a different pattern of movement according to its location. Marker A, which was centrally located, had the largest movement in the A-P direction, whereas laterally located Markers B and C had the largest movement in the C-C direction. This not only reveals individualized movement of the markers depending on the location but also suggests, together with previous findings, indirect evidence of complex intrafractional patient movement

Table 5. Correlation between interfractional isocentre translocation and intrafractional surface marker movement. Numbers in bold are p -values <0.05 , representing values of statistical significance

Variable	EPID R-L		EPID C-C		EPID A-P		IsoTrans	
	PCC	p -value	PCC	p -value	PCC	p -value	PCC	p -value
Marker A								
R-L max	-0.284	0.213	0.465	0.034	-0.112	0.629	0.359	0.110
C-C max	-0.033	0.886	-0.158	0.495	0.176	0.447	0.047	0.840
A-P max	-0.490	0.024	0.343	0.128	-0.500	0.021	0.120	0.605
R-L mean	0.026	0.909	0.139	0.549	-0.083	0.721	-0.298	0.189
C-C mean	-0.168	0.465	-0.038	0.871	0.097	0.676	0.156	0.499
A-P mean	0.251	0.273	-0.066	0.777	0.002	0.995	-0.103	0.657
Marker B								
R-L max	-0.449	0.041	0.454	0.039	-0.185	0.421	0.512	0.018
C-C max	-0.215	0.350	-0.190	0.410	0.231	0.314	0.087	0.707
A-P max	-0.477	0.029	0.375	0.094	-0.379	0.090	0.165	0.474
R-L mean	0.133	0.564	0.223	0.331	0.110	0.634	-0.323	0.153
C-C mean	-0.209	0.363	-0.131	0.571	-0.074	0.750	0.169	0.465
A-P mean	0.268	0.240	-0.090	0.697	-0.129	0.577	-0.096	0.678
Marker C								
R-L max	-0.449	0.041	0.428	0.053	-0.178	0.439	0.521	0.015
C-C max	-0.153	0.509	-0.296	0.193	0.218	0.342	-0.069	0.766
A-P max	-0.482	0.027	0.409	0.066	-0.373	0.096	0.219	0.339
R-L mean	0.116	0.617	0.395	0.077	0.027	0.907	-0.092	0.692
C-C mean	-0.253	0.269	-0.046	0.842	-0.258	0.258	0.363	0.106
A-P mean	0.272	0.233	0.153	0.509	-0.166	0.472	0.024	0.917
Source-to-surface distance.	0.272	0.234	0.124	0.591	0.124	0.591	-0.030	0.899

A-P, translocation of isocentre or marker in anterior-to-posterior direction; A-P max, absolute maximum of A-P during radiotherapy; A-P mean, mean of A-P during radiotherapy; C-C, translocation of isocentre or marker in cranial-to-caudal direction; C-C max, absolute maximum of C-C during radiotherapy; C-C mean, mean of C-C during radiotherapy; EPID, electronic portal imaging device; IsoTrans, isocentre translocation; PCC, Pearson correlation coefficient; R-L, translocation of isocentre or marker in right-to-left direction; R-L max, absolute maximum of R-L during radiotherapy; R-L mean, mean of R-L during radiotherapy, where the mean position of the marker was calculated for the first 10 s and the last 10 s, and then the difference between the two values was obtained.

composed of rotational movement as well as translational movement.

The IR surface markers in this cohort of patients with rectal cancer had a distinctive movement pattern during daily radiotherapy. Surface markers had both systematic time-dependent movement and cyclic movement with 2–3 s intervals. The clinical correlation between cyclic time-dependent surface marker movement and organ motion has been studied for lung cancer.^{13–15} It was shown that these movements were heavily influenced by respiratory motion. Thus, respiratory-gated radiotherapy using surface markers has become a fundamental technique for lung cancer radiotherapy. Patient movement is also influenced by respiration for pelvic tumours. Cyclic movement of surface markers has also been reported by Weiss et al.¹⁶ They evaluated interfractional and intrafractional movement of IR markers during radiotherapy in prone-positioned

patients with gynaecological tumours. IR surface markers were tracked using the ExacTrac® system (Brainlab AG, Munich, Germany). They observed that in most patients, the main breathing direction was from dorsocaudal to anteroposterior. The mean 3D breathing amplitude of the surface marker was 2.4 mm. In the present study, as shown in Figure 3, patient movement was also cyclic. The average amplitude of cyclic movement was less than 1 mm in the R-L direction, but up to 2.0 mm in the C-C and up to 2.6 mm in the A-P direction. The average amplitude of A-P movement covering 95% of cases reached 3.48 mm. Combined with a sail back motion of IR markers, this may contribute to surface marker movement exceeding 5 mm in the A-P direction. Consequently, to cover the PTV with a 5 mm expansion margin from the CTV, only a few millimetres of set-up errors in the A-P direction are allowed during daily radiotherapy. In this regard, set-up verification methods using either fiducial markers or a two-dimensional/3D imaging device will

be helpful to secure accurate delivery of radiotherapy. Use of a belly board, which is commonly applied for treatment in the prone position, may also reduce respiration-related motions.^{17,18} A belly board also offers the advantage of reducing the irradiated small bowel volume.¹⁹ However, in the present study, a belly board was not employed based on concerns related to larger daily set-up variation.²⁰

There are several limitations to this study. First, the patients accrued for this study were relatively fit patients. Patients with BMI <18.5, which is considered underweight, or over 30, which is considered obese, were excluded. Patients with a stoma were also excluded. Other various conditions that may lead to larger set-up errors were excluded, as well. As set-up inaccuracy could increase in these patients, intrafractional movement might increase as well. Second, the real-time surface marker motion of patients during radiotherapy does not represent the real motion of the treated target volume or internal organs. It is known that respiration can induce internal organ motion within the pelvis,²¹ but the correlation between surface motion and organ motion has not been well studied. Finally, for practical reasons, monitoring of surface marker movement and obtaining EPID images were not performed on a daily basis. This may have caused some sampling errors.

Despite these limitations, results from the present study show that intrafractional time-dependent surface motion of patients

during radiotherapy in the prone position can be monitored without extra exposure to radiation. Our results also suggest possible drawbacks of the present EPID-based isocentre verification in quality assurance for radiotherapy delivery.

In conclusion, for patients with rectal cancer treated in the prone position, intrafractional movement of surface markers has both a cyclic component and a time-dependent systematic component. R-L movement of surface markers was less than in other directions, and surface marker deviation exceeding 5 mm was mainly seen in the A-P direction. In some patients, pre- or post-treatment EPID images may not provide adequate information for intrafractional movement because of a sail back movement in the A-P direction during radiotherapy. Further studies investigating the correlation between the surface motion and target volume and/or internal organ motion are warranted. As for the IR system in this study, intrafractional and interfractional set-up errors could be detected with relative ease and this in turn may provide additional steps to improve the quality of daily radiotherapy treatments.

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