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Technical note

The accuracy of surface imaging in detecting secondary patient motion caused by pitch and roll corrections in pelvic radiotherapy

Annele Heikkilä [a,b], Eeva Boman [b,c,*], Antti Aula [b,c], Marko Laaksomaa [c], Tuomas Koivumäki [d], Michiel Postema [a,e]

[a] Department of Biomedical Technology, Faculty of Medicine and Health Technology, Tampere University, Korkeakoulunkatu 8, 33720 Tampere, Finland
[b] Department of Clinical Physiology, Nuclear Medicine and Medical Physics, Tampere University Hospital, Wellbeing Services County of Pirkanmaa, P.O. Box 2000, 33521 Tampere, Finland
[c] Department of Oncology, Tampere University Hospital, Wellbeing Services County of Pirkanmaa, P.O. Box 2000, 33521 Tampere, Finland
[d] Department of Medical Physics, Hospital Nova of Central Finland, Wellbeing Services County of Central Finland, Hoitajantie 3, 40620 Jyväskylä, Finland
[e] School of Electrical and Information Engineering, University of the Witwatersrand, Johannesburg, Jan Smutslaan 1, 2050 Braamfontein, South Africa

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ABSTRACT

Background and objective: Correction of rotational setup errors by tilting the treatment couch improves target dose accuracy and prevents healthy tissue overdosage in external beam radiotherapy. However, couch tilts may cause secondary patient motion. This study aimed to quantify the secondary motion caused by pitch and roll corrections and to evaluate the feasibility of surface imaging for detecting the secondary motion in pelvic radiotherapy.
Methods: Setup cone-beam computed tomography images and surface imaging data of 337 fractions of 22 patients were retrospectively collected. The secondary motion was quantified by the residual setup deviations observed in verification cone-beam computed tomography images acquired in 91 fractions with > 1° pitch or roll corrections. The secondary motion observed in the surface imaging data was compared to that observed in the cone-beam computed tomography images in 73 fractions.
Results: Average residual errors of 0.7 mm/1° (R = 0.95) and –1.3 mm/1° (R = −0.87) were observed in longitudinal and lateral directions after pitch and roll corrections, respectively. The 95% limits of agreement between surface imaging and cone-beam tomography imaging residual errors were (–2.2, 1.5) mm in longitudinal direction and (–1.3, 1.1) mm in lateral direction.
Conclusion: Pelvic radiotherapy patients seemed to have shifted downwards on the treatment couch during couch tilts. The secondary motion could be accurately detected by surface imaging, although respiratory motion reduced the accuracy in longitudinal direction.

1. Introduction

Setup errors have gained a lot of recent attention from the scientific community [1,2]. Rotational setup errors may decrease the dose coverage of the treatment target and increase the dose to the organs-at-risk in pelvic radiotherapy [3–7]. Rotational setup errors can be corrected by a six-degrees-of-freedom treatment couch. However, the couch tilts may lead to secondary motion. Examples of secondary motion are the patient shifting downwards on the treatment couch due to gravity or the patient counteracting the couch movements [8,9].

The first objective of this study was to quantify the secondary motion caused by couch tilts in pelvic radiotherapy in cone-beam computed tomography (CBCT) images. The second objective was to determine the accuracy of surface imaging in secondary motion detection.

Previous research has highlighted the importance of rotational error correction for elongated structures far from the isocentre, as opposed to round, isocentric structures [5,10–13]. Several studies have reported that rotational setup errors may have substantial dosimetric effect on the organ-at-risk doses in pelvic radiotherapy [3–6] and dose coverage of the pelvic lymph node and seminal vesicles planning target volumes in prostate radiotherapy [5,7]. Increased setup accuracy may also allow for the reduction of treatment target margins, leading to reduced doses to organs at risk [6,14].

* Corresponding author at: Department of Clinical Physiology, Nuclear Medicine and Medical Physics, Tampere University Hospital, Wellbeing Services County of Pirkanmaa, P.O. Box 2000, 33521 Tampere, Finland.
E-mail address: eeva.boman@pirha.fi (E. Boman).

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Two previous studies reported that residual errors in longitudinal and lateral directions were correlated with pitch and roll corrections, respectively, in lightly immobilised patients [8,9]. The authors recommended that rotational corrections should not be used for lightly immobilised patients [8] or that a verification CBCT scan should be acquired after rotational corrections [9]. Couch movements did not induce significant secondary motion for patients immobilised with thermoplastic masks or double-vacuum immobilisation systems [8,15].

Acquiring a verification CBCT scan after rotational corrections increases the duration of the treatment fraction and the radiation exposure to the patient. Effective doses from CBCT scans of the trunk have been reported to range between 1.1 and 24 mSv [16]. Although the CBCT imaging dose is low compared to the radiotherapy treatment dose, the cumulative imaging dose over the whole treatment course can be high.

Surface imaging might be an alternative or additional method for monitoring the secondary patient motion [17,18]. Surface imaging is based on the reflection of visible or infrared light from the patient surface [18]. In deeply seated treatment targets, the patient surface is not necessarily an accurate surrogate for the target position. Prior studies have focused on the agreement between intrafractional motion in surface imaging data and CBCT images in radiotherapy for head and neck [19], thoracic [17,20,21] and abdominal targets [17]. Only few studies have quantified the intrafractional motion in pelvic radiotherapy using surface imaging [22,23]. These studies, however, did not verify the intrafractional motion by CBCT imaging.

In this study, the verification CBCT scans and surface imaging data acquired after pitch and roll corrections higher than 1° were used to quantify the secondary motion caused by couch tilts. To our knowledge, the accuracy of surface imaging in detecting the secondary motion has not been investigated in earlier studies. Surface imaging could potentially reduce the need for verification CBCT scans recommended by previous research [9], reducing the radiation dose and workload associated with them. In addition, this study serves to confirm and strengthen the previous research on secondary motion in lightly immobilised patients [8,9,24,25].

2. Materials and methods

This study was approved by Wellbeing Services County of Pirkanmaa (research permit no. R25821). Online CBCT image registration data, six-dimensional couch corrections and surface imaging data of 22 pelvic radiotherapy patients were retrospectively collected. The patient cohort included 10 female patients (176 fractions) and 12 male patients (166 fractions), resulting in a total of 342 fractions. However, five fractions were excluded because they were delivered using a linear accelerator without a six-degrees-of-freedom treatment couch due to schedule changes or maintenance breaks. Thus, a total of 337 fractions were included. The treatment targets included rectum ($n = 13$), prostate bed ($n < 5$), cervix ($n < 5$) and bone metastases of the pelvic area ($n < 5$). The exact numbers of patients that underwent radiotherapy of the cervix, prostate bed, and bone metastases are not reported to protect patient identities. Only treatments with bone based localisation were included. Treatments with fiducial marker or soft tissue based setup corrections were excluded.

2.1. Computed tomography simulation and treatment delivery

For 20 patients, treatment planning computed tomography (CT) images were acquired using a Brilliance Big Bore CT scanner (Philips Healthcare, Best, The Netherlands) or a Somatom Confidence CT scanner (Siemens Healthineers, Erlangen, Germany). For one patient, the treatment planning was based on a magnetic resonance image which was acquired using an Ingenia Ambition X scanner (Philips Healthcare). For one patient, the treatment planning was based on a hybrid positron emission tomography-CT image which was acquired using a Biograph Vision 600 scanner (Siemens Healthineers). All patients were treated in supine position and immobilised using an indexed Kneefix™ knee support (CQ Medical, Avondale, Pennsylvania, USA) and an indexed head support (Orfit Industries, Wijnegem, Belgium). No immobilisation was used in the pelvic area.

The treatments were delivered using a TrueBeam linear accelerator equipped with a PerfectPitch six-degrees-of-freedom couch (Varian Medical Systems, Palo Alto, California, USA). During the treatment fractions, the patients were first aligned using an AlignRT surface imaging system (Vision RT Ltd., London, UK). The region-of-interest used for the surface tracking consisted of a belt-shaped area at the patient's hips, excluding the lower stomach to minimise the effect of respiratory motion (Fig. 1). The pants and underwear of the patients were slightly lowered to avoid interference with the surface imaging system. Second, a CBCT scan, referred to as the "initial CBCT", was acquired. The slice thickness of the CBCT images was 2 mm. The initial CBCT image was rigidly registered to the treatment planning CT image using automatic bone anatomy image registration with six degrees of freedom. A reference surface was acquired immediately prior to performing the couch translations and rotations. This effectively zeroed the translational and rotational deviations of the surface imaging system, referred to as the "deltas". Thus, in case of no secondary motion, the translational and rotational deltas after couch movements would exactly correspond to the couch translations and rotations. The couch rotations were performed around the isocentre. According to our institutional guidelines, a verification CBCT scan was acquired after pitch or roll corrections exceeding 1°. The verification CBCT image was registered to the treatment planning CT image similarly as the initial CBCT image. After the resulting couch translations and rotations were performed, a new reference surface was acquired prior to treatment delivery.

2.2. Quantification of secondary motion

The couch translations and rotations, as well as the online CBCT image registration results, were transferred for offline data analysis. As the couch corrections obtained from the initial CBCT scan should translate the patient to the correct treatment position, secondary patient motion during the couch movements would appear as non-zero residual setup errors in the verification CBCT image. The couch translation and rotation directions were defined as in Fig. 2.

For the fractions with a verification CBCT scan, surface imaging deltas after the couch translations and rotations were extracted by a custom programme in MATLAB® v. R2018b (The MathWorks, Inc., Natick, Massachusetts, USA). The programme allowed the user to manually select the time window for calculating the mean and standard deviation of the deltas. A time window with ≥10-s duration right after the couch movements was selected to average out the effect of respiratory motion. The residual errors in surface imaging data were calculated by subtracting the couch translations and rotations from the surface imaging deltas (Fig. 1). The surface imaging residual errors were negated to transform them to the CBCT coordinate system.

2.3. Statistical analysis

Linear regression coefficients and Pearson correlation coefficients for the relationship between the CBCT residual setup errors and pitch and roll corrections were calculated using the regress function in MATLAB. Other statistical tests were conducted using SPSS v. 29 (IBM, Armonk, New York, USA). The normality of CBCT imaging residual errors, surface imaging residual errors, and the difference between CBCT imaging residual errors and surface imaging residual errors was tested using Shapiro–Wilk test. As most of the parameters were not normally distributed, medians and interquartile ranges were reported and non-parametric tests were used. The accuracy of the surface imaging in detecting the secondary motion compared to CBCT images was

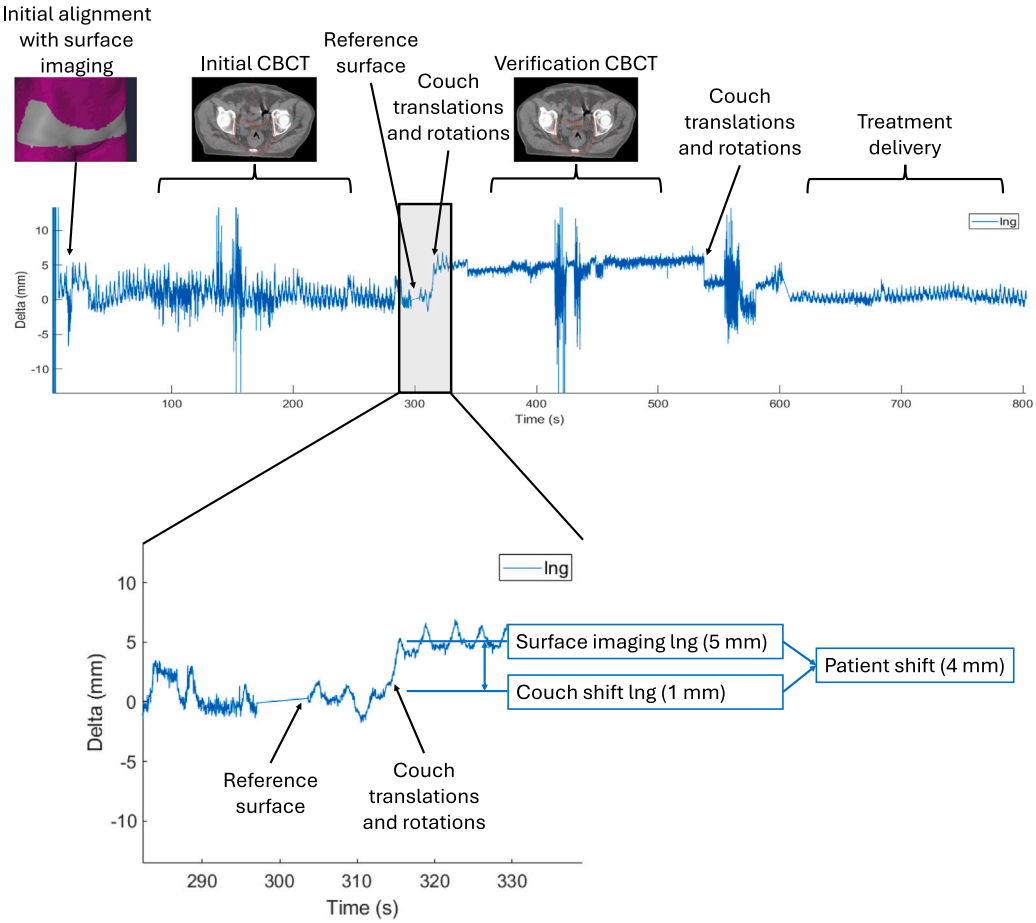

Fig. 1. An illustration of the workflow of the treatment fractions and surface imaging data extraction. The graphs show the longitudinal (lng) surface imaging delta as a function of time. In the top figure, the workflow for the whole treatment fraction is shown. In the bottom figure, a zoomed-in version of the data collected during the couch translations and rotations is shown. In this fraction, a 3° pitch correction was performed in addition to longitudinal 1 mm couch shift. The patient shifted 4 mm in the longitudinal direction, which was seen as a 4 mm difference between the longitudinal delta and the longitudinal couch shift in the surface imaging data. The shift was corrected by couch translation after the verification CBCT. Only the surface imaging delta for longitudinal direction is shown for clarity. Other directions were processed similarly.

quantified by Bland-Altman analysis. The limits of agreement were estimated using the 2.5th and 97.5th percentiles calculated using the HAVERAGE method of SPSS. Wilcoxon signed-rank test was used to determine if there was a statistically significant difference between the medians of the surface imaging residual errors and CBCT residual errors. The surface imaging accuracy of female and male patients was compared using Mann–Whitney U-test.

3. Results

3.1. Quantification of secondary motion from CBCT images

All patients except one exhibited pitch or roll corrections greater than 1° at least once during the treatment course. Pitch corrections exceeding 1° were performed in 92 fractions (27%) out of the 337 fractions included in this study. Roll corrections exceeding 1° were performed in 40 fractions (12%). Altogether, pitch or roll corrections exceeding 1° were performed in 111 fractions (33%). Out of these fractions, the verification CBCT scan had been omitted in 17 cases with rotational corrections ranging from 1.1° to 1.8°, and online image registration results were missing in 3 cases. Thus, 91 verification CBCT images from 20 patients were included in the following analysis.

The CBCT residual error in longitudinal direction was found to be strongly correlated to the pitch correction (R = 0.95, p < 0.001, Fig. 3a). The slope of the regression line was 0.7 mm/1° (95% confidence interval (CI): [0.6, 0.7] mm/1°) and the intercept was 0.2 mm (95% CI: [0.1, 0.3] mm). The CBCT residual error in lateral direction was strongly correlated to the roll correction (R = −0.87, p < 0.001, Fig. 3b). The slope of the regression line was –1.3 mm/1° (95% CI: [–1.5, –1.2] mm/1°) and the intercept was 0.2 mm (95% CI: [0.0, 0.4] mm).

In addition, moderate linear correlations were observed between roll rotation of the treatment couch and roll residual error (R = −0.50), and between roll rotation of the treatment couch and yaw residual error (R = −0.48), as shown in Supplementary Material, Fig. S2. The correlations between couch rotations and residual errors in other directions were weak or negligible (−0.3 < R < 0.3, Supplementary Material, Fig. S1–S2).

3.2. Accuracy of surface imaging in detecting secondary motion

At 18 fractions with a verification CBCT image, the time point of couch movements was unclear from the surface imaging data. These fractions were excluded from the analysis evaluating the accuracy of surface imaging in detecting the secondary patient motion, resulting in 73 fractions from 18 patients to be included (48 fractions of female patients and 25 fractions of male patients).

There were statistically significant (p < 0.05) differences between the distribution of residual errors in CBCT and surface imaging data in vertical and longitudinal directions, and pitch rotations (Table 1). The absolute differences between the surface imaging residual errors and

Table 1
Residual errors observed in cone-beam computed tomography (CBCT) images and surface imaging data (AlignRT) after > 1° pitch or roll corrections, and the difference between residual errors in surface imaging data and CBCT images (AlignRT–CBCT). The residual errors are reported as median(interquartile range) and the differences are reported as median(95% limits of agreement). The statistics for the first column were calculated for the 91 fractions with a verification CBCT image. The statistics for the second and third column were calculated for the 73 fractions with a verification CBCT image and adequate surface imaging data.

	CBCT	AlignRT	AlignRT–CBCT
vrt	–0.3(–0.5, –0.2) mm	–0.1(–0.4, 0.2) mm	0.2(–1.3, 1.4) mm*
lng	0.3(–1.0, 1.5) mm	–0.6(–1.4, 1.2) mm	–0.3(–2.2, 1.5) mm*
lat	–0.1(–0.7, 0.8) mm	–0.2(–0.7, 0.6) mm	0.0(–1.3, 1.1) mm
pitch	0.0°(–0.2°, 0.0°)	0.0°(–0.1°, 0.2°)	0.1°(–0.9°, 1.5°)*
yaw	0.0°(–0.1°, 0.2°)	0.0°(–0.1°, 0.1°)	0.0°(–0.8°, 1.3°)
roll	0.0°(–0.1°, 0.2°)	0.0°(0.0°, 0.1°)	0.0°(–2.2°, 0.8°)

*Statistically significant difference between CBCT and AlignRT residual errors ($p < 0.05$).
Abbreviations: vrt = vertical, lng = longitudinal, lat = lateral.

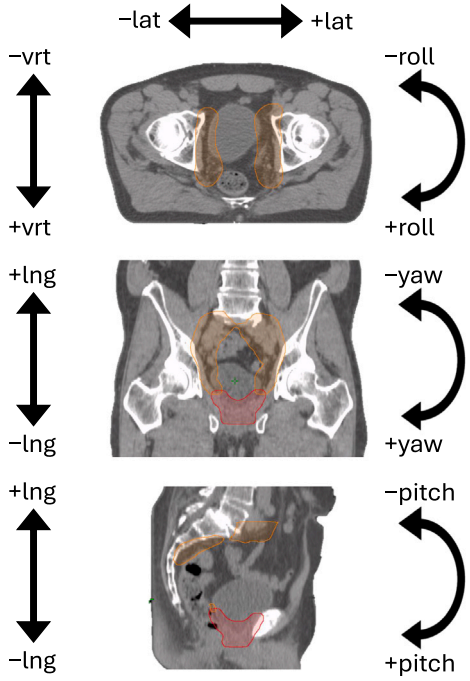

Fig. 2. Definition of the translation and rotation directions in this study. Lat, vrt and lng stand for the lateral, vertical and longitudinal directions, respectively. The residual errors were defined as the shift that was required to align the cone-beam computed tomography image to the planning computed tomography image.

CBCT imaging residual errors were less than 1 mm in 93%, 82% and 92% of fractions in vertical, longitudinal, and lateral direction, respectively. The absolute differences between the surface imaging residual errors and CBCT imaging residual errors were less than 1° in 95%, 97% and 97% of fractions in pitch, yaw, and roll, respectively. The surface imaging accuracy of male patients was lower in vertical direction and higher in longitudinal direction compared to female patients (Table 2). Bland-Altman plots of the differences between surface imaging residual errors and CBCT imaging residual errors are shown in Fig. 4 and Supplementary Material, Fig. S3.

There was a significant ($p < 0.05$) proportional bias between the surface imaging and CBCT residual errors in longitudinal and lateral directions (Fig. 4). In longitudinal direction, the slope of the regression line between the difference and the average of surface imaging and CBCT residual errors was 0.3 (95% CI: [0.2, 0.4], $R = 0.56$), indicating that the higher the magnitude of the longitudinal residual error, the more the surface imaging data overestimated its magnitude in average. In lateral direction, the slope of the regression line between the difference and the average of surface imaging and CBCT residual errors was –0.2 (95% CI: [–0.3, –0.1], $R = -0.47$), indicating with higher magnitude of the lateral residual error, the surface imaging data led to greater underestimation of its magnitude. It was not feasible to investigate proportional bias in the vertical and rotational directions because of the limited range of residual errors in these directions.

4. Discussion

In this study, we reported the correlation between the pitch and roll couch rotations and residual errors seen in verification CBCT images and surface imaging data of 22 pelvic radiotherapy patients. We showed that the residual errors in longitudinal and lateral directions were strongly correlated with the pitch and roll corrections with regression slopes of 0.7 mm/1° and –1.3 mm/1°, respectively. We also reported that the absolute differences between the surface imaging residual error and CBCT imaging residual error were in most cases less than 1 mm or 1°. This study mostly focused on the residual errors in longitudinal and lateral directions, because the residual errors in other directions were in average closer to zero, and the correlations between residual errors and rotational corrections were weaker compared to longitudinal and lateral directions. Furthermore, these directions are the most logical directions for secondary movement, because the gravity will naturally pull the patient in these directions when the couch is tilted.

Based on the results, the patients seem to shift downwards on the treatment couch during pitch and roll rotations of the treatment couch. The magnitude of the shift was similar to that observed in previous studies [8,9]. Roll corrections caused larger patient shifts than pitch corrections in average, which was similar to an earlier study [9]. The correlation between CBCT residual errors and couch tilts in our study was stronger than in previous studies [8,9]. In one of these previous studies [9], the residual errors were determined from an intervention CBCT image acquired in the middle of treatment delivery, whereas in our study, the verification CBCT image was acquired directly after the couch rotations, which may partly explain the stronger correlation observed in our study.

We interpret the patient shift as a deformational process, as did the authors of an earlier study [8]. As the couch tilts, the friction holds the posterior soft tissues of the patient in place. The bony structures and anterior soft tissues of the patient shift lower with respect to the treatment couch due to gravity. The anatomy and body composition of the individual patients, as well as the treatment target, may affect the extent of the shift. We were not able to test the correlation between the magnitude of the shift and the factors related to patient size or body composition because these factors were not available in the retrospectively collected data.

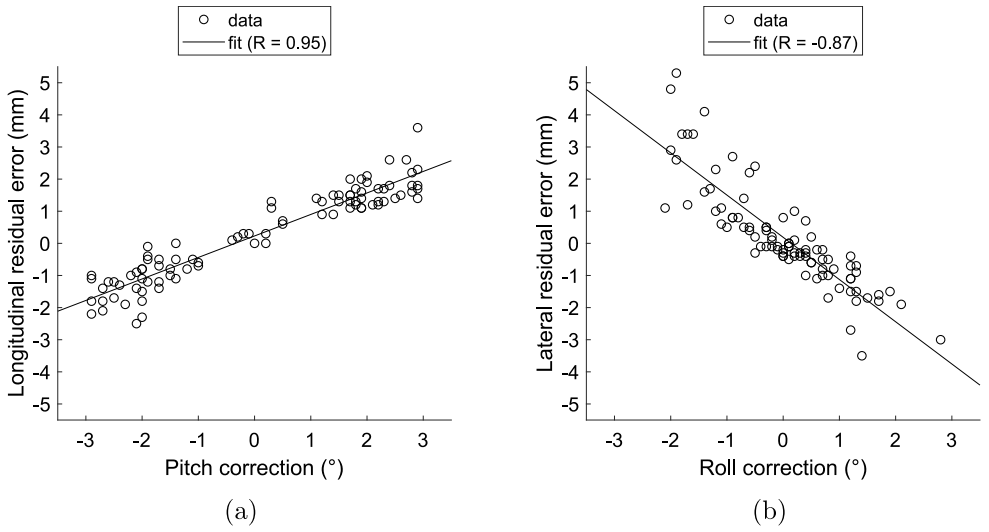

Fig. 3. Residual errors after pitch (a) and roll (b) corrections. The errors were determined from cone-beam computed tomography images acquired after the rotational correction. The open circles represent residual errors in individual fractions, and the solid line represents the linear fit to the data. The linear fit equations were $y = 0.7$ mm/° * $x + 0.2$ mm in (a), and $y = -1.3$ mm/° * $x + 0.2$ mm in (b).

Table 2
The accuracy of surface imaging data compared to CBCT image data in female patients (48 fractions) and male patients (25 fractions) after > 1° pitch or roll corrections. The results are reported as median (interquartile range).

	female	male
vrt	0.1(–0.3, 0.3) mm*	0.4(0.2, 0.6) mm*
lng	–0.5(–0.9, –0.2) mm*	0.0(–0.3, 0.5) mm*
lat	0.0(–0.4, 0.3) mm	0.1(–0.3, 0.3) mm
pitch	0.1°(–0.1°, 0.4°)	0.0°(–0.1°, 0.3°)
yaw	0.0°(–0.2°, 0.2°)	0.0°(–0.3°, 0.1°)
roll	0.0°(–0.4°, 0.1°)*	0.1°(0.0°, 0.2°)*

Statistically significant difference between female and male patients ($p < 0.05$).
Abbreviations: vrt = vertical, lng = longitudinal, lat = lateral.

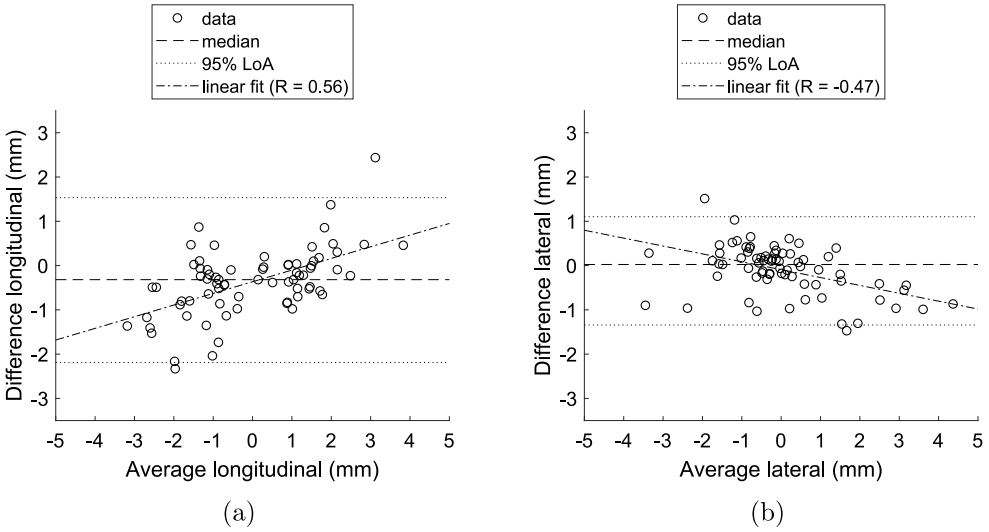

Fig. 4. Bland-Altman plots illustrating the agreement between longitudinal (a) and lateral (b) residual setup errors in surface imaging data compared to verification cone-beam computed tomography images. The open circles represent the difference between the surface imaging residual errors and cone-beam computed tomography residual errors as a function of the average of the surface imaging residual errors and cone-beam computed tomography residual errors. The dashed line shows the median of the differences, and the dotted lines show the 95% limits of agreement (LoA), that is, the 2.5th and 97.5th percentiles. The dash-dotted lines show the linear regression lines between the difference and average of surface imaging residual errors and cone-beam computed tomography residual errors. The linear fit equations were $y = 0.3$ * $x - 0.4$ mm in (a), and $y = -0.2$ * $x - 0.1$ mm in (b).

In addition to the strong correlations between the longitudinal residual error and pitch correction, and between the lateral residual error and roll correction, there were also moderate correlations between residual errors and couch rotations in a few other directions. The negative correlation between roll residual error and roll rotation of the treatment couch could be explained by the patient counteracting the couch tilt by muscle tension.

Although our institutional guideline was to acquire a verification CBCT image after pitch or roll corrections exceeding 1°, the verification image was missing in 17 fractions out of the 111 fractions with >1° corrections. The reason for the missing verification images is probably the tight time schedules and high workload experienced by the radiographers. This highlights the need for a faster way to monitor the secondary patient movement.

No studies on the accuracy of surface imaging in intra-fractional monitoring of pelvic radiotherapy exist to the authors' knowledge. The correlation between the surface and target positions may not be straightforward due to physiological motion of the internal organs. One group reported that the average magnitudes of the difference between surface imaging intrafractional errors and CBCT intrafractional errors were 1.7 mm, 2.5 mm, 1.7 mm, 0.5°, 0.5°, and 0.3° in vertical, longitudinal, lateral, pitch, roll, and yaw directions, respectively, in treatment of thoracic and abdominal targets [17]. Another group reported that the three-dimensional 95% limits of agreement of the difference between surface imaging intrafractional errors and CBCT intrafractional errors were (–3.3, 4.3) mm for female patients and (–5.9, 9.5) mm for male patients in lung stereotactic radiotherapy [20]. The higher deviations for male patients were explained by the flatter shape of their chest, which may cause surface misregistrations. Differences in surface imaging accuracy between female and male patients were not observed in a more recent study [21], which reported that the 95% limits of agreement of the difference between surface imaging and CBCT intrafractional errors were (−2.01, 2.12) mm, (−2.34, 2.71) mm, and (−3.83, 3.89) mm in vertical, lateral, and longitudinal directions, respectively. The authors concluded that surface imaging is accurate enough for intrafractional monitoring in lung stereotactic radiotherapy.

In our study, the surface imaging system was accurate in detecting lateral, vertical, pitch, roll and yaw residual errors, with less than 1 mm or 1° difference in the residual errors compared to the CBCT image in more than 90% of fractions. In longitudinal direction, the difference was higher than 1 mm in 18% of fractions, and the 95% limits of agreement were (–2.2, 1.5) mm. However, the surface imaging system tended to overestimate the magnitude of the longitudinal CBCT residual error. Thus, we expect that the surface imaging system would rarely miss secondary motion exceeding the institutional tolerance limits. It is recommended to acquire a verification CBCT or planar kilovoltage image to verify the magnitude of the residual error if the difference between the longitudinal surface imaging delta after couch tilt and actual longitudinal couch motion exceeds the tolerance limits. In lateral direction, the accuracy of surface imaging compared to CBCT imaging may be high enough for compensation of the secondary motion based on the surface imaging deltas only, depending on the institutional tolerance levels. Although statistically significant differences in the surface imaging accuracy in longitudinal, vertical and roll directions were observed between female and male patients, we do not consider these differences clinically significant. In addition, only 25 fractions of male patients were available for the comparison.

Currently, the AlignRT surface imaging system used in this study does not display the couch movements or indicate how much the deltas differ from them. Thus, the residual error calculations should be done manually, which is labour-intensive and susceptible to human errors. Implementing a feature to display the residual error after couch tilts in the commercial surface imaging systems would make the workflow more practical.

The reduced accuracy in longitudinal direction, which was also observed in earlier studies [17,21], may be explained by respiratory motion. We extracted the surface imaging deltas as an average of at least 10 s time window to minimise the effect of respiratory motion. However, the deltas were defined in relation to the reference surface acquired in a random respiratory phase. Some surface imaging systems have an option to select the respiratory phase for the reference surface [17]. Selecting the phase with the average respiratory amplitude may reduce the uncertainties in the longitudinal and vertical residual errors. In addition, although we excluded the lower stomach from the surface imaging region-of-interest to mitigate the impact of respiratory motion, the region-of-interest may not be optimal for the surface monitoring. Nevertheless, the accuracy of surface imaging in our study seems higher compared to previous studies on the accuracy of surface imaging in intrafractional monitoring of thoracic and abdominal targets [17,20,21], which may be explained by the respiratory motion having a lower impact on the surface imaging data in the pelvic region. Although the previous studies investigated the accuracy of surface imaging in intrafractional motion detection and not in context of couch movements, the results are comparable to our study, because in both scenarios, the aim was to find out if the patient motion observed in surface imaging data corresponds to the target motion observed in CBCT imaging data.

A limitation of this study was that it was not possible to completely eliminate other sources of patient movement, such as muscle relaxation, during the setup verification procedure. Another limitation was the relatively small patient cohort, with only 22 patients included. In addition, the analysis of secondary motion following rotational corrections was based on 91 treatment fractions, and the evaluation of surface imaging accuracy on 73 fractions. With the quite limited number of fractions with verification CBCT images and interpretable surface imaging data, other sources of movement and individual patient properties may have an impact on the results. Furthermore, the dosimetric impact of the residual shifts was not evaluated. Some previous studies have evaluated the dosimetric effect of three-dimensional or six-dimensional setup errors observed in setup images in intensity modulated radiotherapy [26,27] or volumetric modulated arc therapy treatments [28] of pelvic targets. One of the studies reported that six-dimensional setup errors observed during treatment caused –16.2 to +2.5 percentage point changes in the fraction-specific near-minimum dose to the prostate [28]. In another study, a combination of approximately 4 mm setup errors in vertical, longitudinal and lateral directions reduced the target coverage by 7.1 percentage points in a representative patient [27]. However, the dosimetric effect of the secondary motion cannot be deduced from these studies as the studies did not report the typical dosimetric impact of a given translational setup error. In addition, the residual errors in verification CBCT images and the surface imaging residual errors were not recorded simultaneously but right after each other, which may increase the deviations between CBCT and surface imaging data. Finally, this study was conducted using the AlignRT surface imaging system, and the results on the accuracy of surface imaging may not be generalisable for other surface imaging systems.

It is important to select appropriate institutional threshold values for the surface imaging system in order to detect the secondary movement. The threshold values should consider the accuracy of the surface imaging system, fixation method, treatment planning technique, and planning target volume margin, which may vary between radiotherapy departments.

Traditionally, light immobilisation is used in pelvic radiotherapy. The findings of our study and earlier studies [8,9] indicate that the secondary motion induced by couch tilts may significantly reduce the treatment accuracy in lightly immobilised patients. Potential solutions for managing the secondary motion include surface monitoring, as demonstrated in our study, verification CBCT scans, as proposed in an earlier study [9], or improved immobilisation when couch tilts are used in pelvic radiotherapy.

5. Conclusions

We conclude that the surface imaging system can be used to detect secondary motion caused by couch tilts. However, we recommend verifying the longitudinal residual errors observed by surface imaging by CBCT or planar kilovoltage imaging.

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Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Antti Aula reports a relationship with VisionRT that includes: travel reimbursement. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.ejmp.2025.105097.

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