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A comparison of patient position displacements from body surface laser scanning and cone beam CT bone registrations for radiotherapy of pelvic targets

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Abstract

Background and purpose. Optical surface detection has attractive features as a mean in radiotherapy for patient positioning tasks such as set-up, monitoring and gating. To aid in hitting radiotherapy targets the correlation between detected surface displacements and internal structure displacements is crucial. In this study, we compare set-up displacements derived from a body surface laser scanning (BSLS) system to displacements derived from bone registrations with a cone beam computed tomography (CBCT) system in order to quantify the accuracy and applicability of BSLS for fractionated treatments in the pelvic region. *Material and methods.* Displacements from concurrent BSLS and CBCT registrations were compared for 40 patients treated in the pelvic region for a total of 170 set-ups. Surface data captured by BSLS at the first treatment fraction (BSLSref) was used as main reference for the BSLS system, while bony structures from the planning CT were used as a reference for the CBCT method. As comparison, the patient outline extracted from the planning CT was used as BSLS reference (CTref). The displacements detected by the CBCT system (skin-marks-only) was also used for comparison. *Results.* The mean differences (± 1 SD) between the BSLS and CBCT displacements were −0.01 (± 0.17) cm, 0.00 (± 0.21) cm and 0.01 (± 0.17) cm in the lateral, longitudinal and vertical directions, respectively. The median length of the difference was 0.26 cm (0.24–0.29 cm, 95% CI). The median of the difference between CBCT and BSLS displacements based on CTref was 0.37 cm (0.30–0.39 cm) and the median for skin-marks-only was 0.38 cm (0.34–0.42 cm). *Conclusions.* The BSLS system is a good supplement to the CBCT system for accurate set-up for fractions when no CBCT is deemed necessary for pelvic targets. Inter-fractional skin movement in relation to bone was estimated to be 0.2 cm in the lateral (X), longitudinal (Y) and vertical direction (Z), respectively.

Modern systems for radiotherapy planning and delivery can provide tightly conformed dose distributions with steep dose gradients for sparing normal tissues and risk organs in the vicinity of the targets. To fully utilize the treatment potential accurate patient set-up and alignment with the geometry of the planning data is necessary. Several image guided radiotherapy (IGRT) techniques [1] estimate displacements by minimizing a measure of the deviation found by registering an image taken at the actual treatment position versus the image set used for planning of the treatment. Cone beam computed tomography (CBCT) kV systems can be used to track tissue structures in 3D or 4D, but the time resolution for treatment gantry mounted systems is limited by the maximum allowed gantry rotation speed (one revolution per minute). CBCT also imposes an extra radiation dose (5–40 mGy [2], 1–83 mGy [3] per acquisition) to large tissue volumes, which might have radiation protection significance when large patient populations are exposed.

A zero dose, non-invasive technique to obtain set-up displacements is to capture the patient surface location with an optical surface imaging system, and

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register the surface data to a reference surface [4–16]. The reference surface can be extracted from the image set used for treatment planning, or captured when the correct alignment and set-up position has been verified by other means, such as CBCT.

Optical imaging systems have been used clinically for patients treated in the pelvic region [13,16,17] and appears to be a simple, fast and reproducible method for patient set-up which can minimize the random day-to-day set-up errors. Such methods can be based on projected optical light (speckle photogrammetry) [4–7,11,13], and laser-based optical system [8–10,12,14,16], but also other methods exist [17,18]. Some systems use 'markers attached on the patient's surface to intercept motion and determine set-up displacements [19–21]. A benefit of optical systems, besides being non-invasive, is that image acquisition is fast and since it not uses ionizing radiation, the radiotherapists can stay in the room to assist and comfort the patient. However, the applicability of surface imaging systems is ultimately limited by the degree of correlation between movements of the surface and the deeper located anatomical structures of interest. The aim of this study is to investigate the correlation in patient position displacements derived from registrations of body surface laser scanning (BSLS) data compared to patient position displacements derived from registrations of bones in CBCT data for treatments in the pelvic region.

Materials and Methods

Equipment

We used a commercially available BSLS system (c4D v3.2.8, Sentinel®, C-rad Positioning AB, Sweden) which consists of a ceiling-mounted unit that can be installed both at treatment and imaging gantries. The system scans a laser beam transversally in discrete steps along the longitudinal direction over a preselected area. The laser light reflection from the skin is captured by a CMOS (complementary metal-oxide semiconductor) camera, and the location of the reflected line is determined by means of optical triangulation [22] and discretized into a set of points. The maximum resolution is determined by the interval between the contours, and the resolution of the camera. The surface of the patient is thus described in 3D space [8] (Figure 1). The captured point sets can be registered and further analyzed in the integrated software package [8–10,16].

The origin of the BSLS coordinate system is defined to coincide with the isocenter of the treatment

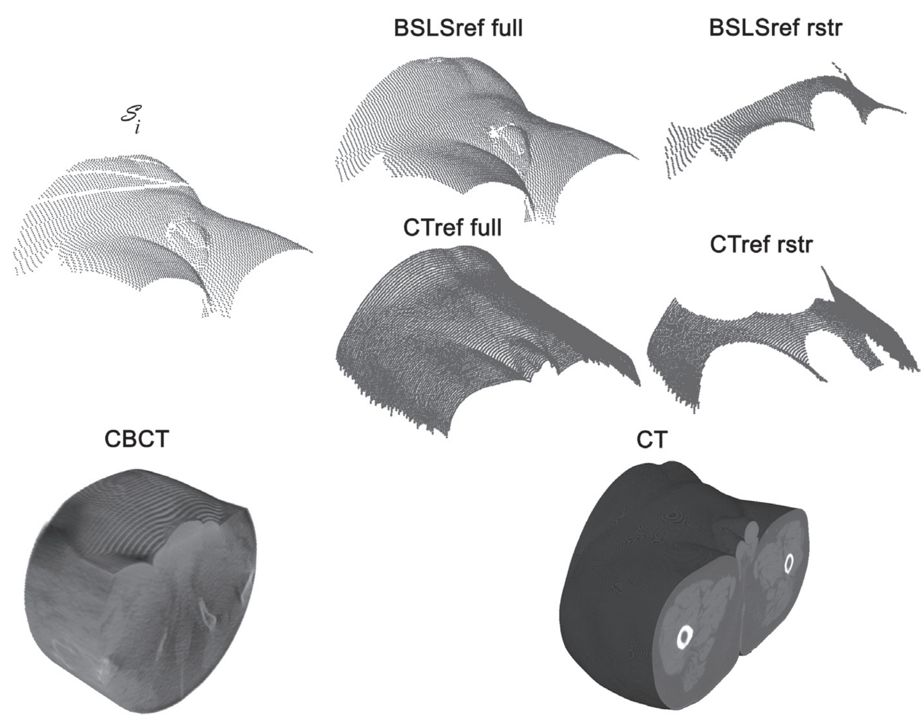

Figure 1. Visualization of the different data sets used. The BSLS set-up scans are stored as point sets $\mathcal{S}_i$ where i indicates fraction. Both the BSLS scanned reference (BSLSref) and the DICOM imported external structure (CTref) are stored as point sets in the BSLS system with slightly higher resolution than the BSLS set-up scan to facilitate a good registration. The BSLS registration was made twice, once to the full reference surface and once to the restricted (rstr for short) reference surface to determine how deformations in potential moving parts affected the registrations. The bony structures in the CBCT volume are automatically extracted by the CBCT software in the registration process. The white lines in $\mathcal{S}_i$ stems from shadows of the treatment head touch guard.

gantry (Elekta Synergy®, Elekta Oncology Systems), typically recalibrated on a weekly basis by means of a dedicated phantom aligned with the light field of the treatment unit. During the period of data collection about 100 calibrations were done with resulting standard deviations of 0.05 cm, 0.04 cm and 0.04 cm in the lateral (X), longitudinal (Y) and vertical directions (Z), respectively. No systematic drift over time was observed. The surface used for registration was averaged over 4–5 scans during a total time of 5 seconds to handle breathing motion. The resolution of the BSLS scanned surface points were on average 4–5 points per cm^2 but varied over the scanned surface, mainly due to changing incident angle onto the patient topography. The acquisition time for each laser line position was 13 milliseconds. At creation of a BSLS scanned reference surfaces the resolution was automatically increased slightly by the BSLS software to facilitate a good registration (cf. Figure 1). The patient outline contour was segmented in the treatment planning system (Oncentra®, Nucletron/Elekta, Sweden) based on 3–5 mm CT slices acquired by a Philips Brilliance® CT Big Bore 16 slice CT system (Amsterdam, The Netherlands) and imported via DICOM to the BSLS system.

A CBCT system (XVI® ver. 4.5, Elekta Oncology Systems) mounted on the same treatment unit as the BSLS system was used as the reference patient positioning system. The system consists of an x-ray tube and an amorphous silicon panel detector, both mounted orthogonal to the treatment beam. Prior to a treatment, a sequence of x-ray images can be captured from different projection angles during gantry rotation and a volumetric image set reconstructed (cf. Figure 1). The CBCT system was used to extract the position of the bone structures, hence the bulk of soft tissues is not considered in this work since fluoroscopy, ultra sound or some other tracking method might be more suitable for tracking the complex soft-tissue movements in the pelvic area. In this work, we focus on the correlation of bone and skin positioning.

Data collection

Registration data for 170 set-ups for 40 patients (13 women and 27 men) treated in the pelvic region was retrospectively extracted from the clinical databases of the CBCT and BSLS systems. Thirteen patients were immobilized by customized vacuum cushions (PAR Scientific®, Odense, Denmark) and 27 patients were supported by a kneefix (CIVCO®, Iowa, USA). Elevation blocks were added below the kneefix in a few cases to increase patient comfort. Eight patients were treated with volumetric modulated arc therapy (VMAT), two patients with static field IMRT, and 30 patients were treated with conventional static field radiotherapy. The isocenter was always placed in the target region, generally 10–15 cm below the skin surface.

The BSLS acquired data consist of a set of points $\mathcal{S}_i$ captured at fraction i. The CBCT and BSLS data were acquired concurrently after a set-up based on skin-marks for the second and third fractions, and then once a week (every fifth fraction) (cf. Figure 2). The data sets of the BSLS system were always created before or during the CBCT scan to minimize the time between the acquisitions. To avoid system

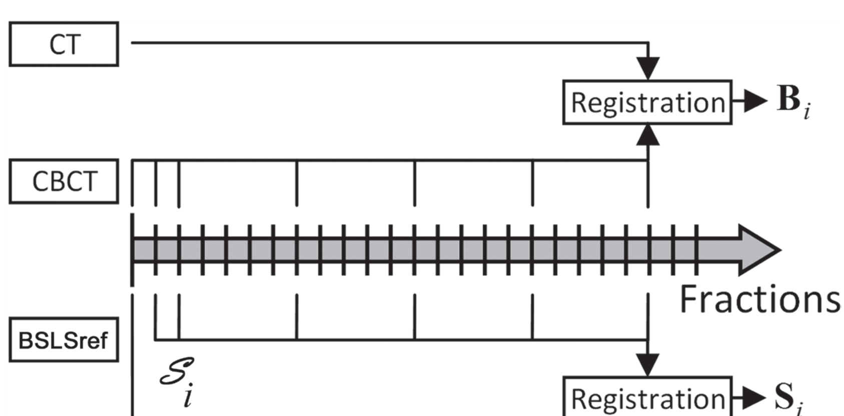

Figure 2. Data acquisition pattern for a treatment of 25 fractions. The BSLS set-up scan $\mathcal{S}_i$ was captured at fraction 2 and 3 and then once a week. The $\mathcal{S}_i$ data set was rigidly registered to the BSLS reference data set scanned by the BSLS system for the first fraction (BSLSref) to derive the set-up displacements $\mathcal{S}_i$. Additionally, $\mathcal{S}_i$ was rigidly registered to an alternative BSLS reference surface created from the patient outline contour extracted from the treatment planning system (CTref). The CBCT images were acquired the first 3 fractions and then once a week concurrent to the S_i. The bony structures in the CBCT images were registered to the corresponding structures in the planning CT images to derive the set-up displacements B_i.

warm up effects [10] the BSLS system was routinely kept switched on during stand by.

Image registrations and patient positioning uncertainties

The BSLS registration was done with a rigid body iterative closest point algorithm that rejects outliers [23]. The algorithm iteratively finds the transformation matrix for rigid body translation and rotation that minimizes the root mean square error norm between corresponding points (selected by proximity) in $\mathcal{S}_i$ and in the BSLS reference.

The main type of BSLS reference surface used in this study was captured by the BSLS system concurrent with a CBCT acquisition for the first treatment fraction after set-up according to skin-marks. Before being used as references, these data sets were rigidly transformed according to the result from the CBCT registration. This transformation corrects for all degrees of freedom compared to use of the automatic table movement, which is limited to translational movements. It also avoids introducing a systematic error due to table movement uncertainties (in the order of ± 0.04 cm 1SD). The subsequent $\mathcal{S}_i$ data were registered to the transformed BSLS references (a.k.a. *BSLSref*), hence the BSLSref method solely determines the inter-fraction variation between CBCT registrations and BSLS registrations based on a scanned reference surface. The method is independent on errors introduced prior the first treatment fraction, e.g. due to CT laser calibration uncertainty, treatment planning patient outline contour delineation, etc. The patient outline contour extracted from the treatment planning system (a.k.a. *CTref*) was tested as an alternative reference surface using 128 of the 170 registrations.

Each registration to BSLSref and CTref was made twice; once with all points included in the reference surface (a.k.a. *full* surface registration) and once with stomach and legs excluded (a.k.a. restricted surface registration, *rstr* for short) to minimize the effect of deformations, due to, e.g. different grades of stomach fillings or leg placements (cf. Figure 1). Outlying points, such as a piece of a cloth present in the scanning area, were excluded automatically by the software for each specific registration.

In the CBCT software, a box-shaped registration volume covering the target volume and some firm bony structures in the vicinity of the target was defined by a clipbox tool. The patient positioning displacement vector of the bony anatomy $\mathbf{B}_i$ (a.k.a. *skin-marks-only)* after set-up based on skin-marks at fraction i was determined by registering the CBCT images within the clipbox volume to the planning CT images by means of an automatic rigid body bone registration algorithm allowing translation and rotation integrated in the CBCT software [24,25]. The CBCT set-up correction is given in the order of translation-rotation, i.e. the rotation should be done around the isocenter point after performed translation. The opposite sign of the translation vector corresponds to the displacement vector $\mathbf{B}_i$. Similar to the formalism by Ploeger et al. [17], we view the $\mathbf{B}_i$ vector to consist of a true, but unknown, bone displacement $\mathbf{b}_i$, and its registration deviation $\boldsymbol{\delta}_{i,\mathrm{B}}$ yielding

$$\mathbf{B}_i = \mathbf{b}_i + \boldsymbol{\delta}_{i,\mathrm{B}}. \tag{1}$$

The BSLS set-up correction is given in the same order as in the CBCT system, i.e. the rotation should be done around the isocenter point after performed translation. We view the surface displacement to be composed of a true, unknown displacement vector $\mathbf{b}_i$ of the bony anatomy, and a vector $\boldsymbol{\delta}_{i,\mathrm{BS}}$ due to inter-fractional skin movement in relation to the bony anatomy, and a vector $\boldsymbol{\delta}_{i,\mathrm{S}}$ to represent the surface registration accuracy. The set-up displacement determined by the BSLS system can thus be expressed on the form

$$\mathbf{S}_i = \mathbf{b}_i + \boldsymbol{\delta}_{i,\mathrm{BS}} + \boldsymbol{\delta}_{i,\mathrm{S}}. \tag{2}$$

Hence, the difference between the set-up displacements determined by the BSLS and the CBCT system is given by the deviation vector

$$\Delta_i = \mathbf{S}_i - \mathbf{B}_i = \boldsymbol{\delta}_{i,\mathrm{BS}} + \boldsymbol{\delta}_{i,\mathrm{S}} - \boldsymbol{\delta}_{i,\mathrm{B}} \tag{3}$$

where we explicitly get $\mathbf{S}_i$ and $\mathbf{B}_i$ from the BSLS and CBCT data, respectively. The deviation vector Δ_i consists of a lateral, longitudinal and vertical component. Rotations are subtracted separately for rotational deviation determination. As the sum of the variances of $\boldsymbol{\delta}_\mathrm{S}$, $\boldsymbol{\delta}_\mathrm{B}$, and $\boldsymbol{\delta}_\mathrm{BS}$ should equal the variance of Δ we can utilize this relation to estimate the variance of $\boldsymbol{\delta}_\mathrm{BS}$. In rigid phantom studies, the standard deviation of $\boldsymbol{\delta}_\mathrm{S}$ is reported to be in the order of 0.05 cm [4,6,8] and the standard deviation of $\boldsymbol{\delta}_\mathrm{B}$ to be less than 0.03 cm [26]. We will for short use ${}^{\mathrm{BSLSref}}_{\mathrm{rstr}}\Delta$ to denote the difference between $\mathbf{S}_i$ and $\mathbf{B}_i$, based on the restricted BSLSref surface, ${}^{\mathrm{BSLSref}}_{\mathrm{full}}\Delta$ to denote the difference based on full BSLSref surface, ${}^{\mathrm{CTref}}_{\mathrm{rstr}}\Delta$ to denote the difference based on restricted CTref surface and ${}^{\mathrm{CTref}}_{\mathrm{full}}\Delta$ to denote the difference based on the full CTref surface.

Data analysis

The data distribution of Δ_i (Equation 3) was analyzed by assuming a multinormal distribution (see Supplementary Appendix to be found online at http://informahealthcare.com/doi/abs/10.3109/0284186X.2013.802836) and for each orthogonal component separately, i.e. in the lateral, longitudinal and vertical directions. Correlations between the different directions ($c_{lat,long}$, $c_{lat,vert}$ and $c_{long,vert}$) were analyzed from the coefficients of the covariance matrix (see Supplementary Appendix to be found online at http://informahealthcare.com/doi/abs/10.3109/0284186X.2013.802836). The iso-probability surface that encloses 90% of the estimated probability distribution was derived together with its intersection radii r_{lat}^{90}, r_{long}^{90} and r_{vert}^{90} along each coordinate axes. Furthermore, the median of the deviation vector lengths $|\Delta_i|$ was determined together with its 95% confidence limits.

In the present CBCT and BSLS softwares, the registrations are given in lateral, longitudinal and vertical direction separately and not the 3D vector length as such. For simplicity, our clinical tolerances are therefore specified in each direction separately forming a cuboid instead of a vector length tolerance sphere or ellipsoid, which would have been more natural. The determined 3D probability distribution can be used to calculate the probability P_{cube} that a CBCT registration would have fallen within the tolerance cube if the set-up position has been corrected according to the BSLS registration. P_{cube} is derived by integrating the 3D multinormal probability distribution (see Supplementary Appendix to be found online at http://informahealthcare.com/doi/abs/10.3109/0284186X.2013.802836) over the lateral, longitudinal and vertical limits of the tolerance cube.

The data analysis was done with in-house developed Matlab programs. The normality of the deviation distributions in the separate directions was tested by an Anderson-Darling test, the equality of the medians of the deviation vectors by a Mann-Whitney non-parametric two sample rank test, and the time tendency by a Pearson two-tailed test of correlation. In all tests $p < 0.05$ was considered statistically significant. The tests were performed by Minitab® 15 statistical software.

Results

The medians of the radial difference $\left|{}^{BSLSref}_{rstr}\Delta\right|$ and $\left|{}^{BSLSref}_{full}\Delta\right|$ were 0.26 cm (0.24–0.29 cm, 95% CI) and 0.33 cm (0.30–0.36 cm, 95% CI), respectively, based on data that passed all methods (128 registrations). Both were significantly smaller ($p = 0.00$ and $p = 0.046$) than the median of the skin-marks-only distribution, of 0.38 cm (0.34–0.42 cm, 95% CI). The median of $\left|{}^{BSLSref}_{rstr}\Delta\right|$ was also significantly ($p = 0.00$) smaller than $\left|{}^{BSLSref}_{full}\Delta\right|$. No significant ($p = 0.35$) improvement of the median of $\left|{}^{CTref}_{rstr}\Delta\right|$ (0.37 cm) was seen compared to the median of skin-marks-only. The median of the $\left|{}^{CTref}_{full}\Delta\right|$ distribution (0.46 cm) was significantly ($p = 0.00$) larger than the median of skin-marks-only, hence surface registrations to CTref did not improve patient set-up significantly compared to skin-marks-only (Table I).

The mean values (± 1 SD) of ${}^{BSLSref}_{rstr}\Delta$ along the lateral, longitudinal and vertical directions were −0.01 (± 0.17) cm, 0.00 (± 0.21) cm and 0.01 (± 0.17) cm, respectively, based on data that passed the method with a BSLS scanned reference surface (170 registrations). The corresponding mean values of ${}^{BSLSref}_{full}\Delta$ were 0.02 (± 0.22) cm, 0.01 (± 0.26) cm and 0.02 (± 0.25) cm, respectively (Table I). The mean values of both ${}^{CTref}_{rstr}\Delta$ and ${}^{CTref}_{full}\Delta$ were generally higher in the vertical direction compared to ${}^{BSLSref}_{rstr}\Delta$ and ${}^{BSLSref}_{full}\Delta$ and the standard deviation of ${}^{CTref}_{full}\Delta$ was slightly higher in the longitudinal and vertical direction compared to ${}^{BSLSref}_{full}\Delta$. The mean values (± 1 SD) of skin-marks-only in lateral, longitudinal and vertical

Table I. Statistics for the differences between the BSLS displacements and the corresponding CBCT displacements. The mean deviations (± 1 SD) are given in lateral, longitudinal and vertical direction. The radii along the coordinate axes of the iso-probability ellipsoid that encapsulate 90% of the probability distribution are given by $\{r_{lat}^{90}, r_{long}^{90}, r_{vert}^{90}\}$. The medians of the deviation vector's absolute values are given together with the 95% confidence limits. The fraction of the probability density function inside a cube extending ± 0.3 cm and ± 0.5 cm along the coordinate axes is given by the values for $P_{0.3}$ and $P_{0.5}$, respectively. Data passing all methods (128 registrations) were used for comparison between the methods.

Data set	$\overline{\Delta}_{lat}$ (±1SD) [cm]	$\overline{\Delta}_{long}$ (±1SD) [cm]	$\overline{\Delta}_{vert}$ (±1SD) [cm]	$\{r_{lat}^{90}, r_{long}^{90}, r_{vert}^{90}\}$ [cm]	Median $\|\Delta\|$ (95 %) [cm]	$P_{0.3}$, $P_{0.5}$ [%]
BSLSref rstr (n = 170)	−0.01 (± 0.17)	0.00 (± 0.21)	0.01 (± 0.17)	{0.42, 0.50, 0.41}	0.25 (0.23-0.28)	71.9, 97.5
(n = 128)	−0.01 (± 0.18)	0.02 (± 0.23)	0.01 (± 0.19)	{0.43, 0.52, 0.43}	0.26 (0.24-0.29)	67.0, 96.1
BSLSref full (n = 170)	0.02 (± 0.22)	0.01 (± 0.26)	0.02 (± 0.25)	{0.54, 0.62, 0.58}	0.34 (0.31-0.36)	48.4, 88.0
(n = 128)	0.00 (± 0.23)	0.05 (± 0.24)	0.01 (± 0.25)	{0.56, 0.53, 0.55}	0.33 (0.30-0.36)	50.9, 89.4
CTref rstr (n = 128)	0.04 (± 0.21)	0.01 (± 0.24)	0.14 (± 0.25)	{0.53, 0.59, 0.61}	0.37 (0.30-0.39)	46.1, 86.6
CTref full (n = 128)	0.13 (± 0.23)	0.08 (± 0.35)	0.20 (± 0.36)	{0.58, 0.75, 0.76}	0.46 (0.40-0.52)	26.0, 63.6
Skin-marks-only (n = 128)	−0.07 (± 0.29)	−0.14 (± 0.23)	−0.04 (± 0.26)	{0.71, 0.56, 0.65}	0.38 (0.34-0.42)	36.7, 80.0

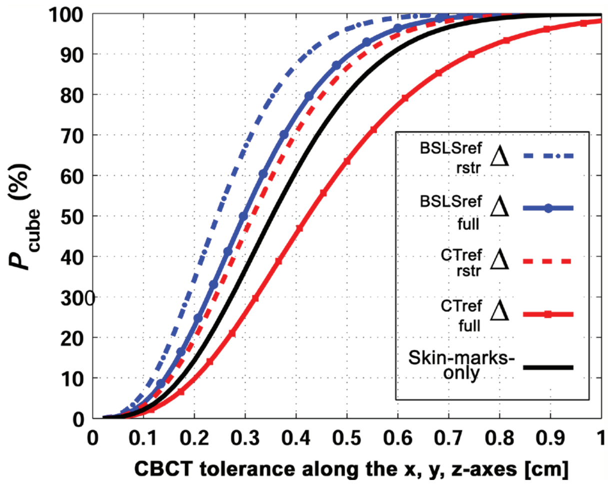

Figure 3. The probability P_{cube} that the CBCT determined correction is within a tolerance cube when the position is corrected according to a BSLS registration or a Skin-mark-only set-up (neglecting table top uncertainties). The indices refer to different reference surfaces for the BSLS system.

direction were -0.07 (± 0.29) cm, -0.14 (± 0.23) cm and -0.04 (± 0.26) cm, respectively.

The tolerance cube extension can be reduced for a constant P_{cube} value if the BSLS corrections are applied compared to skin-marks-only. This is true for all reference surfaces except the full CT reference (Figure 3).

The ellipsoid that encapsulates 90% of the estimated pdf for ${}^{BSLSref}_{rstr}\Delta$ was slightly elongated in the longitudinal direction but no strong correlation was found between the lateral, longitudinal or the vertical directions, implying that they can be analyzed separately without losing any important information (Figure 4). The corresponding ellipsoids for ${}^{BSLSref}_{full}\Delta$, ${}^{CTref}_{rstr}\Delta$, ${}^{CTref}_{full}\Delta$, are very similar and are not shown. There was a small tendency for $\left|{}^{CTref}_{rstr}\Delta\right|$ and $\left|{}^{CTref}_{full}\Delta\right|$ to increase over time. The increment was about 0.1–0.2 cm over a time period of 45 days. No clear trend was seen for $\left|{}^{BSLSref}_{rstr}\Delta\right|$ or $\left|{}^{BSLSref}_{full}\Delta\right|$ (Figure 5).

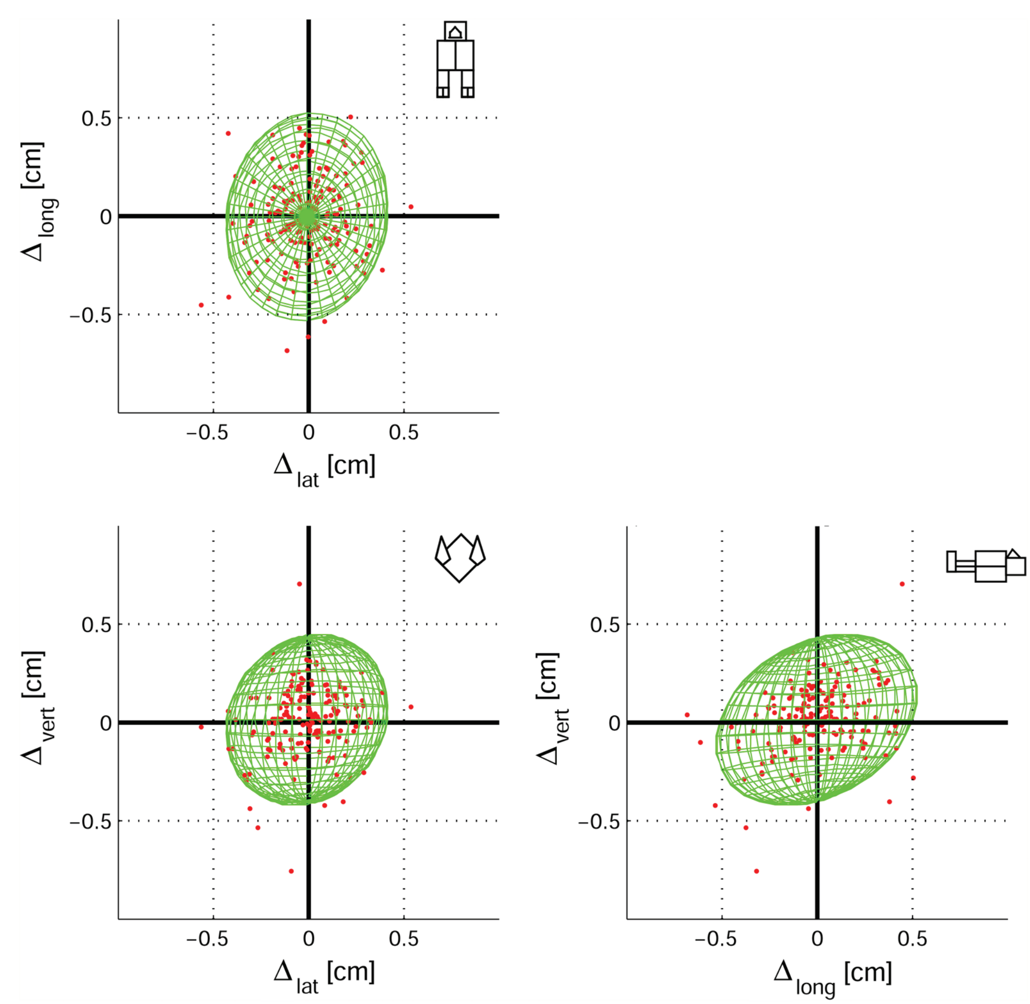

Figure 4. Distribution of the deviation values ${}^{BSLSref}_{rstr}\Delta$ viewed from front (a), feet (b) and left (c). The green surface meshes show the iso-probability surfaces that encapsulate 90% of the estimated multinormal probability distribution. A small tendency of correlation between longitudinal and vertical is seen in c. No correlation was found between the other directions. The shape of the distribution of the other types of references are similar are not shown.

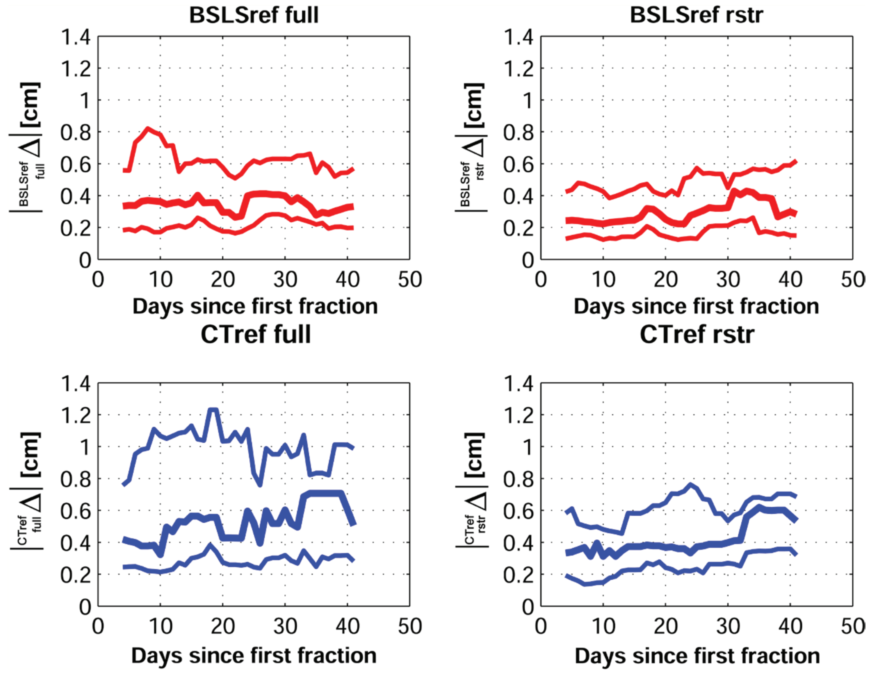

Figure 5. Moving median values (7 day window) of the deviation vector lengths (thick line), versus the number of days since first fraction for different references; a full BSLS scanned reference surface (upper left panel), a restricted BSLS scanned reference surface (upper right panel), a full CT ref surface (low left), and a restricted CT ref surface (low right). The thin lines represent one standard deviation from the median values.

Table II. Rotational difference between the BSLS and CBCT registrations. *Rot* denotes rotation around the vertical axis, *roll* rotation around the longitudinal axis, and *pitch* rotation around the lateral axis.

BSLS Reference	BSLS – CBCT Mean diff Rot (± 1 SD) [°]	BSLS – CBCT Mean diff Roll (± 1 SD) [°]	BSLS – CBCT Mean diff Pitch (± 1 SD) [°]
BSLSref rstr	0.0 (± 0.6)	−0.3 (± 0.8)	0.2 (± 1.4)
BSLSref full	−0.1 (± 1.0)	0.1 (± 1.8)	−0.5 (± 1.0)
CTref rstr	1.0 (± 1.0)	0.8 (± 0.8)	1.6 (± 1.6)
CTref full	0.6 (± 1.1)	−0.7 (± 0.9)	−1.0 (± 2.2)

The mean rotational difference between the BSLS and CBCT registrations were less than 1° for the BSLS ref surface and less than 2° for the CT ref surface. The standard deviation of the rotational difference was about 1–2° (Table II).

Using the standard deviation of Δ as presented in Table I together with the previously determined standard deviation of $\boldsymbol{\delta}_S$ and $\boldsymbol{\delta}_B$, the standard deviation of $\boldsymbol{\delta}_{BS}$ was estimated to be less than 0.2 cm, 0.2 cm and 0.2 cm in the lateral, longitudinal and vertical directions, respectively, for all reference surfaces except the full CTref where $\boldsymbol{\delta}_{BS}$ was estimated to 0.4 cm in longitudinal and vertical direction.

Discussion and conclusions

Set-up displacements derived from the BSLS system was compared to set-up displacements derived from bone registrations with the CBCT system. The BSLS system verified the position of patients treated in the pelvic region with a radial accuracy of 0.25 cm (0.23–0.28 cm, 95% CI) relative to the CBCT system with the BSLSref method. The BSLS system thereby constitutes a good complement to skin-marks with additional information about pose and supplements the objectiveness of the CBCT system for fractions when no CBCT is acquired or else available.

The surface registrations based on BSLSref had less deviation to the CBCT registrations compared to the deviation between surface registrations based on CTref and CBCT registrations. This is congruent with results presented by Moser et al. [16] but not with results presented by Pallotta et al. [27]. It has previously been shown that delineation of patient outline contour from the treatment planning system is critical and may not correspond to the surface detected by the BSLS system thus risking the introduction of a systematic deviation for the CTref method [14,16]. Another important aspect is that the BSLSref method benefits over the CTref method because the BSLSref is corrected according to the CBCT registration, i.e. most of the systematic errors introduced prior to the first treatment fraction are avoided in the BSLSref method. The method of skin-marks-only also benefits over CTref method because skin-marks are redrawn if the systematic deviation, as determined from the first three CBCT registrations, exceeded 0.2 cm. The extended time between CTref acquisition and treatment compared to the time between BSLSref and treatment also increase the risk of surface deformations in the CTref method.

The benefit of using CTref instead of BSLSref is that CTref is directly linked to the treatment plan. A surface registration to CTref does not only verify the pose and position of the patient, but it also enables an indirect verification of the skin-marks in relation to the isocenter before any radiation at the treatment unit is delivered. Nevertheless, our results showed that surface registrations to BSLSref deviated less to the CBCT registrations and thereby tends to be the most accurate substitute for the CBCT system. Additionally, the BSLS software failed to register the surface to the CTref in more cases than it failed to register the surface to the BSLSref, especially for the restricted cases.

Moser et al. [16] presented large deviations between surface registrations and megavoltage CT registrations in the case when the patient outline contour was extracted from the treatment planning system and used as reference surface. The distance between the rotation center and the surface was not specified. If this is large, a small surface deformation might result in a large translational error in the rigid registration algorithm. Patients might lose weight during the course of treatment, which results in a lower level of the stomach, giving a negative pitch around the lateral axis, i.e. the surface must be elevated in the cranial end to match the reference. If the rotation center is positioned deep below the surface, a larger translation cranially and posteriorly is needed to compensate for the translation of the surface during the rotational correction. This is congruent with their results as they present large medians in the cranial and posterior directions. The scanned reference surface reduces this effect because the correlation between the reference surface and inner anatomy is updated. In our study, the rotation center is estimated to be 10–15 cm below the surface. In some cases, surface deformation might be causing large deviations (approx. 0.3–0.5 cm) between the BSLS and the CBCT registrations.

Pallotta et al. [27] investigated surface scanning in the pelvic region for two groups (22 + 14 patients). The patient outline contour extracted from the treatment planning CT was used as reference surface. Patients in the second group wore less clothing, had extended scanning regions and an alternative reference surface created at the first treatment fraction after correction. They determined the 90th percentile of the absolute difference of surface registrations to CBCT registrations to be 0.42, 0.58 and 0.64 cm in the lateral, longitudinal and vertical direction respectively in the first group and 0.39, 0.50 and 0.46 cm in the second group. Our corresponding results were very similar 0.44, 0.63, and 0.63 cm (CTfull) however, we achieved less deviation to the CBCT registrations in the restricted cases (CTref rstr; 0.37, 0.38, 0.46 cm and BSLSref rstr; 0.30, 0.41, 0.27 cm) contradictory to the results presented by Pallotta et al. Since Pallotta et al. changed two parameters between the two groups (reference surface size and amount of clothing) the total change in results cannot be assigned to one single parameter. It might have been the amount of clothing that changed the results. In our study, we registered each surface two times, with and without stomach and legs included within the reference surface. The restricted surfaces showed better agreement with the CBCT registrations compared to the full reference surface, probably due to a reduced degree of deformation in the restricted case. In this study, the restricted reference surfaces were restricted by circular excluding regions while Pallotta et al. changed the size by changing the size of the cube in which the reference surface was defined.

To analyze whether patient anxiousness at the startup of the treatment influenced the results, a subset of the BSLS data was registered to a reference surface created at the third fraction (91 registrations, 20 patients) instead of the first fraction. The deviations between the BSLS and CBCT registrations were, however, very similar, i.e. no positioning effects of the anticipated patient treatment startup anxiety were observed for the first fraction.

A BSLS reference surface can be acquired by an additional BSLS system at the CT when the planning study is captured, and translated from that position to the finally planned isocenter. Coordinate information from different systems is, however, needed to accomplish this. Also, additional margins must be added for inter-system variations, e.g. calibration uncertainties, which are not studied here. In this study, the BSLS reference is effectively set to the planning CT via the reference of the CBCT system to minimize systematic deviations between the systems.

In similar fashion to this study, Krengli et al. [15] investigated the correlation between body surface registrations and bone registrations, where the latter was determined by two orthogonal portal images for 16 prostate patients. However, they only reported the correlation factor and not the difference between the two methods registrations. Brahme et al. [8] presented the displacement of a cervix cancer patient but did not correlate this to inner anatomy. Ploeger et al. [17] estimated the standard deviation of $\boldsymbol{\delta}_{BS}$, in the lateral direction to be

0.11 cm based on 22 prostate cancer patients comparing video image registrations to portal image registrations. This is in line with the estimated range of $\boldsymbol{\delta}_{BS}$ in this work. Displacements in the two other directions were, however, by technical reasons not investigated in their work.

Further investigations are needed to determine the magnitude of the deviation caused by insufficient total BSLS acquisition time per fraction. The risk of capturing a surface in an unrepresentative position due to breathing motion is decreased if the total scanning time is prolonged before averaging, i.e. more scans before averaging. A longer total scanning time is needed for patients with low breathing rate to capture all phases. Instead of the mean surface position, the full expiration phase might be a better choice to increase the reproducibility.

Measurements with an anthropomorphic pelvic phantom indicated a decreased deviation between the determined displacements of the BSLS system and the CBCT system if a higher resolution was used for the BSLS surfaces. The average deviation was 0.04 cm ($\pm$ 0.01 cm, 1 SD) for high resolution and 0.08 cm ($\pm$ 0.04 cm, 1 SD) for the resolution used in this study. The level of resolution might be even more crucial for patients with a deformed surface and fast gradient changes.

In our clinical routine, a deviation between skin-marks and BSLS registration outside specified tolerances always triggers a CBCT acquisition. This facilitates a fast and clear way to detect a sudden weight change of the patient or a tumor regression/progression. By using the BSLS and CBCT information, a decision can be made whether a new treatment planning CT is needed or not. Body contour changes during the treatment course can be handled through a combination of CBCT and optical methods. The correlation between the surface and the complex soft-tissue movements in the pelvic area was not investigated in this work since fluoroscopy, ultra sound or some other tracking method may be more suitable.

In the vertical direction, the standard deviation of ${}^{BSLSref}_{rstr}\Delta$ was smaller than for ${}^{BSLSref}_{full}\Delta$. This seems reasonable because the day-to-day variation in stomach size was partly eliminated from the restricted surfaces. The clinical benefit of using restricted surfaces instead of full surfaces is, however, doubtful because inner anatomy variations of bladder, rectum, etc. are an order of magnitude larger.

The main benefit of adding a BSLS scan to a set-up process is that it verifies the pose and position of the targeted area. If, for example a leg is misaligned it can be corrected before the treatment staff exits the treatment room and a good starting point for higher precision means is established. Some of these errors may affect the treatment volume indirectly, and it is sometimes hard to determine the cause of such errors only by viewing the limited volume covered by the EPI's or the CBCT images. Work is also ongoing to investigate the feasibility of the BSLS system for gated radiotherapy treatments.

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Supplementary material available online

Supplementary Appendix.