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Clinical evaluation of a commercial surface-imaging system for patient positioning in radiotherapy

Image-guided radiotherapy (IGRT) allows precise patient positioning in radiotherapy (RT), especially for intensity-modulated radiotherapy (IMRT) and stereotactic body radiotherapy (SBRT) where accurate positioning of the patient and the target is necessary because of the small margins around the clinical target volume (CTV) [1]. Furthermore, IGRT reduces the set-up error and interfractional motion and allows a reduction of the planning target volume (PTV). Two-dimensional (2D) megavoltage (MV) imaging with the therapy beam is a standard imaging technique, but it only provides patient positioning relative to bony structures and makes it difficult to align soft tissue target volumes such as the prostate. Additionally, because of the low detector efficiency for MV photons, the imaging dose is relatively high for the limited amount of information provided [2]. Ultrasound positioning systems allow the positioning of soft tissue target volumes without additional radiation dose but they are limited in their applications (depth of target volume, artifacts due to bones, not suitable when significant amounts of air are in the area of interest). A state-of-the-art imaging technique for IMRT is three-dimensional (3D) kilovoltage (kV) imaging or cone-beam computed tomography (CBCT). This technique enables the most accurate positioning with the least restrictions; moreover, the additional dose to the patient is relatively low albeit still relevant with 20–30 mGy for imaging of pelvic targets and 3–10 mGy for head-and-neck/thoracic targets [2, 3].

An alternative patient positioning strategy is surface scanning. A laser beam that is calibrated relative to the linac isocenter moves over the patient and a camera records the reflections on the patient surface. From this surface information and the information derived from the treatment planning CT, the system is able to calculate a shift vector between the planned and actual patient position in relation to the linac isocenter. Depending on the achievable accuracy, the system may offer the possibility to reduce the number of CBCTs for patient positioning, particularly in patients where imaging dose should be minimized as much as possible, such as children or young adults, and it may improve positioning accuracy on linear accelerators not equipped with CBCT. In addition, the system offers a surveillance option during the treatment of the patient to detect patient movements (intrafractional movement). Few data regarding the clinical potential of surface scanning systems have been published [4, 5, 6, 7], some only based on phantom measurements and for a limited number of anatomical sites.

We investigated the performance of the Sentinel system compared to the gold standard CBCT in a clinical routine environment for a variety of tumor sites.

Patients and methods

A total of 153 radiotherapy treatment fractions in 9 women and 12 men (head-and-neck, thoracic, and pelvic targets) were recorded within the framework of this clinical evaluation that was analyzed retrospectively with internal review board (IRB) approval. Subjects were randomly chosen from all patients routinely treated in one of the three treatment regions of interest. Patients treated for head-and-neck cancer were positioned/fixated by using a mask system (headSTEP, IT-V, Innsbruck, Austria). Patients with thoracic targets were positioned using a wingSTEP (IT-V) breast board to raise their arms above the body. Patients with pelvic targets had no special positioning devices other than knee support (knee-fix, IT-V). All patients were positioned supine and had no fiducial markers. The CBCT equipment was mounted on an Elekta Synergy accelerator (Elekta, Crawley, UK) orthogonal to the

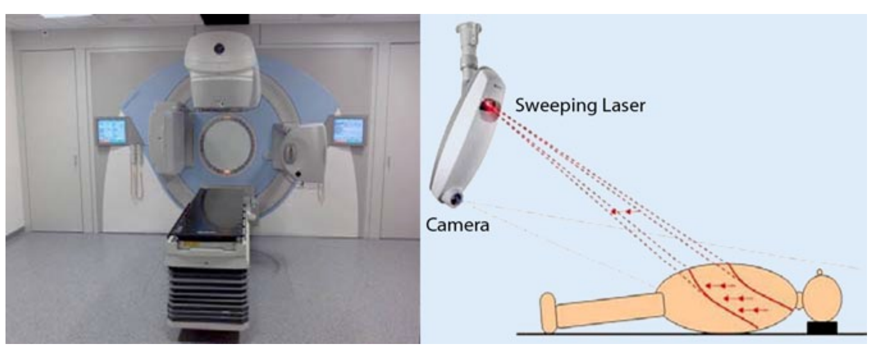

Fig. 1 ▲ *Left*: Elekta Synergy accelerator with CBCT (University Medical Center Mannheim). *Right*: C-Rad Sentinel. Modified from www.c-rad.se with kind permission of C-RAD AB, Sweden.

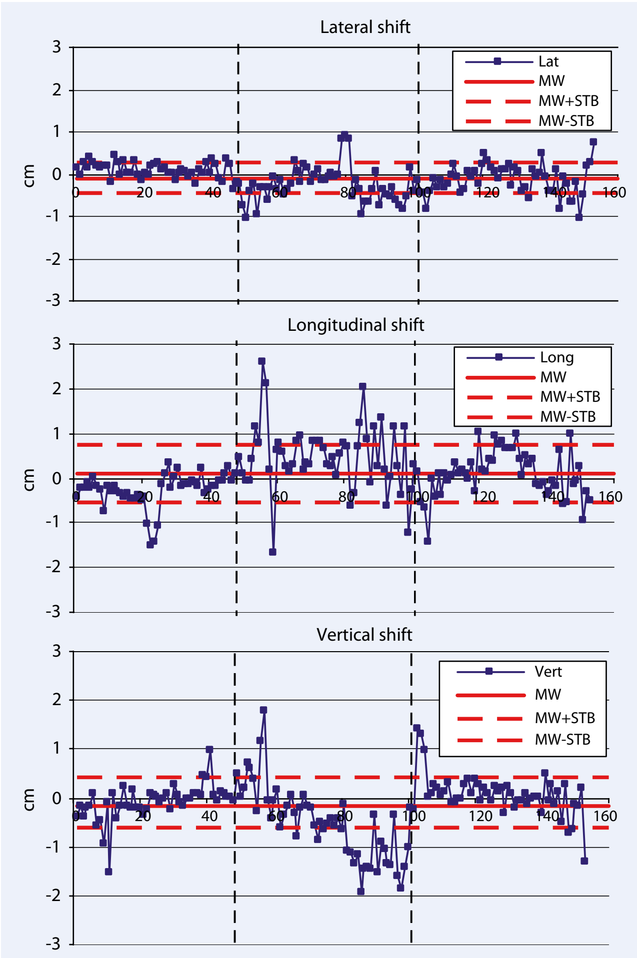

Fig. 2 ▲ Shift vector in centimeters for the 153 fractions for three translation directions (lateral, longitudinal, and vertical). First block, head-and-neck targets; second block, pelvic targets; third block, thoracic targets. (*MW* mean value, *STB* standard deviation)

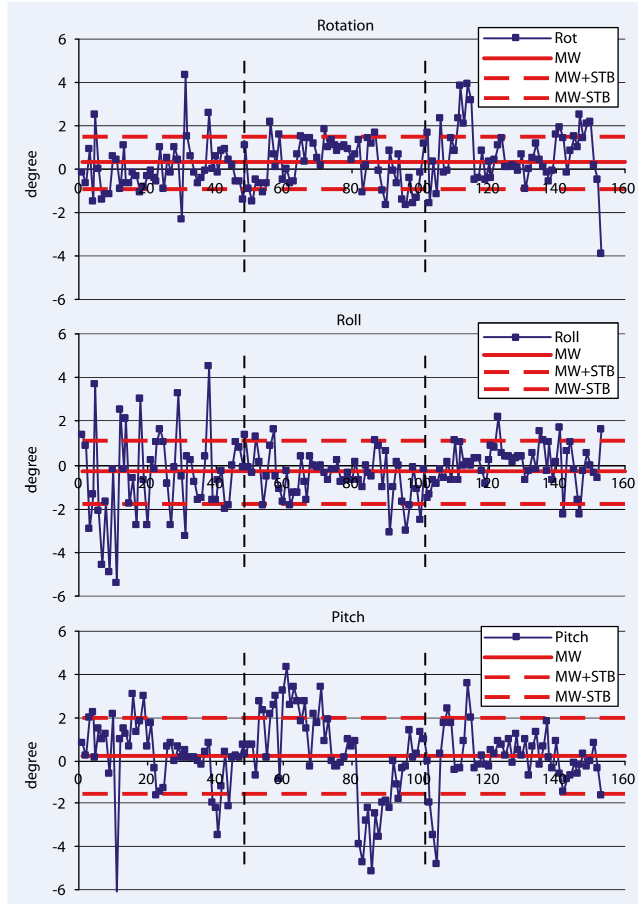

Fig. 3 ▲ Shift vector in degrees for the 153 fractions, three rotations (rotation, roll, and pitch). First block, head-and neck patients; second block, pelvis patients; third block, thoracic patients. (*MW* mean value, *STB* standard deviation)

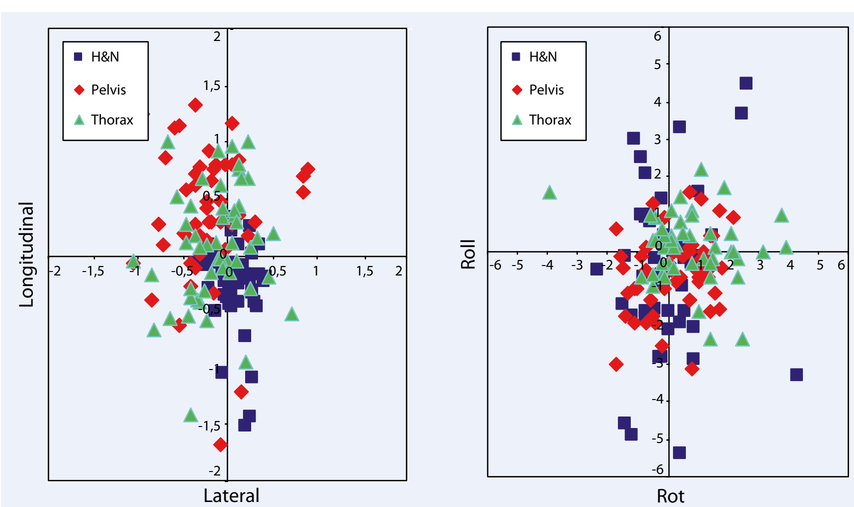

Fig. 4 ▲ *Left*: Longitudinal shift vs. lateral shift in centimeters for 153 datasets. *Right*: Roll vs. rotation in degrees for 153 datasets. (*Rot* rotation, *H&N* head and neck, *MW* mean value, *STB* standard deviation)

therapy beam (**Fig. 1**). The Sentinel optical scanner (C-RAD, Uppsala, Sweden) was mounted on the ceiling above the foot-end of the treatment couch and used a sweeping visible red line laser (690 nm), a camera (CMOS BCi4 LS camera with 1,280×1,024 pixels), and rigid matching software (**Fig. 1**). The maximal scan volume was 800×1,300×700 mm^3 with a measurement reproducibility of 0.2 mm. The time to scan a volume of 40-cm length amounted to 2 s. The rigid matching software uses an “iterative closest point algorithm” [8] to calculate multiple registration parameters (rotations and translations) relative to a predefined reference.

The clinical workflow was as follows. After the planning CT, the CT dataset was sent to the treatment planning system (TPS; Monaco 3.0, Elekta Software, St. Louis, USA) and a treatment plan was created. The treatment plan, the CT files, and the structure set including the reference contour were sent to the record-and-verify system (Mosaiq, Elekta Software, Henderson, USA) as well as to the Sentinel system. For comparison of positioning based on surface matching or CBCT matching (soft tissue or bone match depending on paradigm), the patients were first scanned with CBCT and shifted to the optimal isocenter position (based on target volume and not on patient surface) according to the planning CT. Afterwards, an optical scan using Sentinel was performed and the shift vector that would provide an optimal surface match was calculated. The following parameters were analyzed: three translation directions (lateral, longitudinal, and vertical) and three rotation axes (rotation = yaw, roll, and pitch). Ideally, the resulting shift vector should be zero because then the surface matching (Sentinel) yields the same results provided by soft tissue matching (CBCT).

Results

In general, there was a good agreement between the Sentinel and CBCT systems. ◘ **Figures. 2 and 3** show the resulting shift vectors separately for the three translation directions (◘ **Fig. 2**) and three rotational axes (◘ **Fig. 3**) including mean value ± standard deviation for all patients and separately for the three different target sites.

The recorded lateral shifts were very low, especially for the head-and-neck patients who were positioned using a mask fixation. All measured values stayed within a tolerance of 1 cm, with very few values exceeding 5 mm. The longitudinal shifts were larger, due to breathing-induced changes in the longitudinal patient profile. This effect is obvious by comparing the results in patients treated for head-and-neck lesions with the other target sites. For pelvic patients, the largest deviations were recorded because most patients use predominantly abdominal respiration when positioned supine, and this motion is in the scanning field. When analyzing all the results from ◘ **Fig. 2** it can be seen that only a few fractions had extraordinarily large shifts. The mean overall difference

Abstract · Zusammenfassung

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Clinical evaluation of a commercial surface-imaging system for patient positioning in radiotherapy

Abstract

Introduction. Laser scanning-based patient surface positioning and surveillance may complement image-guided radiotherapy (IGRT) as a nonradiation-based approach. We investigated the performance of an optical system compared to standard kilovoltage cone-beam computed tomography (CBCT) and its potential to reduce the number of daily CBCTs.

Patients and methods. We analyzed the patient positioning of 153 treatment fractions in 21 patients applied to three different treatment regions. Patients were first scanned with CBCT, shifted to the optimal isocenter position, and an optical scan was performed to verify the matching in relation to CBCT.

Results. For the head-and-neck region, the lateral/longitudinal/vertical/rotational/roll and pitch shift was 0.9±1.8 mm/–2.7±3.8 mm /–0.8±3.6 mm/0.0±1.1°/–0.5±2.1°/0.2±1.6°. For the thorax, the lateral/longitudinal/vertical/roll and pitch shift was –1.2±3.6 mm/ 0.8±5.1 mm/0.8±4.3 mm/0.6±1.4°/0.1±0.9°/ 0.3±1.0°. For the pelvis, the respective values were –2.5±4.1 mm/4.6±7.3 mm/–5.1 ±7.4 mm/0.3±1.1°/-0.5±1.0°/0.3±2.1°. In total, the recorded disagreement was –1.0 ±3.6 mm/1.0±6.3 mm/–1.8±5.9 mm/0.3 ±1.2°/–0.3±1.5°/0.2±1.7°.

Conclusion. This analysis showed good agreement between the optical scanner approach and CBCT. The optical system holds potential to ensure precise patient positioning and reduced CBCT frequency in tumor locations with fixed relation to surface structures.

Keywords

Image-guided radiotherapy · Optical surface laser scanner · Cone-beam computed tomography · Patient positioning · Tumor location

Klinische Bewertung eines kommerziellen Oberflächenbildgebungssystems zur Patientenpositionierung bei Strahlentherapie

Zusammenfassung

Einleitung. Die Abtastung der Patientenoberfläche mittels Laser zur Positionierung hat das Potenzial, die bildgesteuerte Strahlentherapie zu ergänzen. Wir untersuchten die Leistung eines optischen Systems im Vergleich zur normalen digitalen Volumentomographie („kV cone beam computed tomography", CBCT) und deren Potenzial, die Zahl der notwendigen Positionierungscomputertomographien zu reduzieren.

Material und Methoden. Wir untersuchten die Patientenpositionierung bei 153 Fraktionen an 21 Patienten (drei verschiedene Bestrahlungsregionen). Die Patienten wurden zuerst mit der CBCT positioniert und danach mit dem optischen System gescannt, um die Abweichung zur CBCT zu erfassen.

Ergebnisse. Für die Kopf-Hals-Region betrugen die Abweichungen in lateraler/longitudinaler/vertikaler/rotationaler/rollender/kippender Richtung 0,9±1,8 mm/–2,7±3,8 mm/ -0,8±3,6 mm/0,0±1,1°/–0,5±2,1°/0,2±1,6°. Für die Thoraxregion betrug die laterale/longitudinale/vertikale/rotationale/rollende/kippende Abweichung –1,2±3,6 mm/0,8 ±5,1 mm/0,8±4,3 mm/0,6±1,4°/0,1±0,9°/ 0,3±1,0°. Für die Beckenregion waren die entsprechenden Abweichungen –2,5±4,1 mm/ 4,6±7,3 mm/–5,1±7,4 mm/0,3±1,1°/–0,5 ±1,0°/0,3±2,1°. Die Abweichung über alle Fraktionen betrug –1,0±3,6 mm/1,0±6,3 mm/ –1,8±5,9 mm/0,3±1,2°/–0,3±1,5°/0,2±1,7°.

Fazit. Die Analyse zeigte eine gute Übereinstimmung zwischen dem optischen System und der CBCT. Das optische System hat das Potenzial zur präzisen Patientenpositionierung mit verminderter Anzahl von CBCT-Aufnahmen bei Tumorlokalisationen mit fester Relation zur Patientenoberfläche.

Schlüsselwörter

Bildgesteuerte Strahlentherapie · Optischer Oberflächenscanner · Digitale Volumentomographie · Patientenpositionierung · Tumorlokalisationen

Tab. 1 Mean shift vector including standard deviation in centimeters and degrees

cm/degrees	Head and neck	Pelvis	Thorax	Overall
Lateral	0.10±0.18	−0.26±0.41	−0.13±0.36	−0.10±0.37
Longitudinal	−0.27±0.38	0.46±0.73	0.09±0.52	0.11±0.64
Vertical	−0.08±0.36	−0.51±0.74	0.08±0.43	−0.18±0.60
Rotation	−0.1±1.1	0.3±1.1	0.6±1.4	0.3±1.2
Roll	−0.5±2.1	−0.5±1.0	0.1±0.9	−0.3±1.5
Pitch	0.2±1.6	0.3±2.1	0.3±1.0	0.2±1.7

for patients and sites, and therefore the systematic error, was minimal.

All rotations had a mean deviation of around 0° and stayed within 5°. The largest roll difference was found for patients with head-and-neck targets, which was caused by misalignments of the shoulders. After CBCT, there was no anatomical need to reposition the patient because the PTV was in the correct position and there was no irradiation going through the shoulders.

Fig. 4 shows the longitudinal shift plotted against the lateral shift and roll plotted against rotation in centimeters and degrees, respectively, for the three different scan regions.

This figures show that the longitudinal shift was larger than the lateral shift. Comparing roll and rotation, all data are equally distributed except the roll difference for head-and-neck targets as shown before.

Tab. 1 shows the mean shift vectors including standard deviations for the three different scanning regions and all 153 datasets. The largest overall deviations could be found for the pelvis. For all patients and fractions, the mean shift in all directions was below 2 mm and 0.3°. The recorded standard deviations were within 7 mm and 1.7°.

Discussion

The accuracy of the Sentinel surface scanning system regarding stability and reliability was shown earlier by Palotta et al. [4]. The group compared the performance of Sentinel with CBCT and portal imaging based on rigid phantoms. They explicitly mentioned, however, that their results were not meant to be an indication of the clinical accuracy. The clinical study of Moser et al.[9] analyzed the Galaxy scanning system (LAP Laser, Lüneburg, Germany) on a TomoTherapy unit (Tomotherapy, Madison, WI, USA) with megavoltage computed tomography (MVCT) based on 20 patients and 200 fractions. Similar to our study, they compared the deviations between the reference surface and the MVCT and found larger systematic shifts within 3–9 mm, which were explained by incomplete surface scans due to the single-camera system and breathing motion. In addition, they compared the deviation between an optical reference scan and daily optical scans and found no clinically relevant shifts. Gopan et al. [5] studied another surface scanning system (AlignRT), but focused mainly on head-and-neck targets. Our results for this scanning region are similar to theirs (rotation 0.8°–2.2° and translation 2.4–4.5 mm) with somewhat better agreement in our series that very likely has a different population and fixation system to start with. They found a larger discrepancy (rotation 1.9°–4.5° and translation 6.9–11.9 mm) for nonrigid registration of head-and-neck targets, which cannot be compared with our study since a nonrigid registration algorithm was not available for Sentinel at the time of the analysis. The group of Kauweloa et al.[6] used their surface tracking system (GateCT) for respiratory signal reconstruction in 4D-CT imaging based on phantom measurements. Their results are hardly comparable to our study, but the authors showed that their system provided consistent temporal/phase tracking. Placht et al.[7] developed a novel preregistration algorithm in conjunction with a time-of-flight (ToF) camera. On the basis of unspecified phantom measurements, they found a mean registration error for translations of 1.6±1.0 mm and for rotations of 0.07±0.05° similar to our clinical results. Our results show good agreements in the surface scanning method for patient positioning.

Although in this series target positioning was successfully achieved based on surface matching, several clinical issues may compromise the results and should therefore be carefully evaluated and controlled if a surface scanning system is to be used for patient positioning exclusively. Patients may lose weight during cancer therapy [10, 11], which affects the body surface and thus the position of the target volume relative to the body surface. In this case, a new surface reference for Sentinel can be set, e.g., weekly after a preceding verification with CBCT or ultrasound. Thus, a combination of CBCT and surface scanning may provide sufficiently precise positioning at low imaging doses. Portal imaging is inadequate in this situation because of its lack of soft tissue contrast, unless implanted target fiducials are used.

Another currently encountered issue is surface movement caused by breathing. In most targets, this movement does not dramatically affect the tumor position and standard image guidance (CBCT, portal images, or ultrasound) is adequate for positioning, except for small lung or hepatic lesions where "breath hold" or "gating" techniques are implemented [12, 13, 14]. The problem is that until recently breathing motion reduced the precision of surface scanning. This could be remedied by a nonrigid matching algorithm, algorithms taking into account 4D information, or algorithms that can differentiate between mobile and rigid body parts and then base their position on rigid parts only. Such approaches are currently being developed, implemented, and evaluated in the next generation of surface scanners.

Time is an important factor in radiotherapy. Multiple techniques were implemented to speed up the treatment time during irradiation, e.g., volumetric modulated arc therapy (VMAT), faster multileaf collimators (MLC), or flattening filter-free linear accelerators. Even if a positioning method is inherently more precise, this precision may be lost if the overall treatment process takes so long that patient/target motion becomes more probable. A standard CBCT takes 1–2 min for scanning of the patient and some more minutes to match the data, i.e., a total of 4–5 min for positioning. The Sentinel system needs only a few seconds to scan and match the actual position to the reference position and may speed up the process of image guidance in radiotherapy.

In situations where some centers refrain from frequent CBCT images (e.g., for children or younger women with breast cancer) despite its availability, supplementary use of a surface scanner will result in improved positioning compared to no IGRT without any drawbacks. Finally, particularly for long treatment procedures such as stereotactic body RT or particle treatments, the surveillance function of these systems may reduce intrafractional positioning insecurities.

Conclusion

This analysis found good agreement between the Sentinel surface scanner and CBCT in patient positioning for radiotherapy. Differences between the two techniques may be caused by changes in tumor-to-patient surface distance, changes in patient weight over the duration of treatment, or patient breathing. Under controlled circumstances, a combination of surface scanning with reduced frequency of CBCT (1–2 per week) and ultrasound image guidance may provide precise positioning with a low extra imaging radiation dose, and it may improve positioning precision in situations where CBCT is usually avoided or ultrasound is not feasible. In addition, surface scanning with Sentinel ensures monitoring of the patient during treatment, thereby minimizing intrafractional positioning errors.

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Conflict of interest. On behalf of all authors, the corresponding author states the following: Research agreements with C-Rad and Elekta Inc. regarding image guidance and patient positioning are in place.

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