Title
The Role of Optical Surface Imaging Systems in Radiation Therapy

Journal
Seminars in Radiation Oncology, 28(3)

ISSN
1053-4296

Authors
Hoisak, Jeremy DP
Pawlicki, Todd

Publication Date
2018-07-01

DOI
10.1016/j.semradonc.2018.02.003

Peer reviewed

ELSEVIER

Seminars in
RADIATION
ONCOLOGY

The Role of Optical Surface Imaging Systems in Radiation Therapy

Jeremy D.P. Hoisak, PhD, and Todd Pawlicki, PhD

Optical surface imaging is a nonradiographic, noninvasive technology for continuous localization of patients during radiation therapy. Surface-guided radiation therapy (SGRT) has been applied to many treatment sites including breast, intracranial, head and neck, and extremities. SGRT enables a reduction of initial setup variability, provides verification of immobilization continuously during treatment including at noncoplanar linac gantry angles, and provides dynamic surface information for use in gated and breath-hold treatment techniques, all of which can permit reductions in the margins required to account for target localization uncertainty. Ancillary benefits from surface imaging include the ability to use immobilization techniques that confer greater comfort to patients, a reduction in imaging dose through reduced radiographic localization requirements, and improvements to the speed, efficiency, and safety of clinical workflows. This review will describe the objectives of SGRT, review the commercially available surface imaging systems, and provide an overview of SGRT applications by treatment site. Limitations and future applications of surfacing imaging systems are also discussed.

Semin Radiat Oncol 28:185-193 © 2018 Elsevier Inc. All rights reserved.

Introduction

Innovation in radiation therapy technology has been motivated by the goal of increasing the dose delivered to the target while maintaining or minimizing dose to normal tissues. Modern linear accelerators equipped with multileaf collimators together with intensity-modulated radiation therapy (IMRT) have made it possible to deliver highly conformal radiation dose distributions around the target while sparing adjacent healthy tissues. This requires that the target be localized as accurately as possible to ensure the dose is delivered as intended. Localization uncertainty requires that the target includes a margin of surrounding healthy tissue called the Planning Target Volume (PTV) to ensure that the target will receive the intended dose of radiation, and there is a similar expansion around normal tissues called the Planning at Risk Volume (PRV) to ensure normal tissue sparing.[1,2]

Intrafraction localization uncertainty can arise during radiation delivery due to patient movement or from internal anatomical motion through physiological processes such as breathing. If radiation is delivered over multiple treatment fractions, interfraction localization uncertainty can be created by variations in patient position or posture, changes in target size or shape, and normal physiological variability such as bladder and bowel filling. To help reduce interfraction position variations and intrafraction motion, many devices have been developed to ensure reproducible patient setup between fractions and immobilization of the target during delivery. These include rigid body frames and cradles, positioning boards, head fixation frames, thermoplastic head and shoulder masks, plaster molds and vacuum bags that conform to the patient's body and help ensure a consistent posture from treatment to treatment.

The introduction of image-guidance into the treatment room using orthogonal kV x-rays and later, cone-beam computed tomography (CBCT), has further improved the ability to localize the target and allowed reduced margins.[3] However, as these imaging modalities are generally employed at the start of the treatment only to address interfraction positioning uncertainties, there remains intrafraction target localization uncertainty during radiation delivery. Imaging can be performed periodically throughout the treatment fraction, between fields or during delivery using cine MV imaging or kV fluoroscopy, but this comes with a cost in the form of

---

Department of Radiation Medicine and Applied Sciences, University of California San Diego, La Jolla, CA.

Conflicts of interest: None.

Address reprint requests to Jeremy D. P. Hoisak, PhD, 3855 Health Sciences Drive, #0843, La Jolla, CA 92093–0843. E-mail: jhoisak@ucsd.edu

https://doi.org/10.1016/j.semradonc.2018.02.003

additional radiation dose to the patient, or a longer overall treatment time. Conventional linac-mounted image-guidance systems have limited ability to image the patient at noncoplanar gantry angles, which are commonly used in stereotactic radiosurgery (SRS), and are increasingly finding application in stereotactic body radiation therapy (SBRT) for liver and lung.[4,5]

Continuous monitoring of patient position can reduce target localization uncertainty due to intrafraction motion, and can reduce interfraction positioning uncertainty by improving initial setup. This translates into reductions in the PTV size, dose to normal tissues, and associated side effects. Nonradiographic continuous localization technologies that do not use ionizing radiation have been developed specifically to aid in patient setup, reduce the need for imaging and attendant imaging dose, monitor patient position during treatment, and provide localization of the patient and target when using noncoplanar gantry angles.[6] Nonradiographic continuous localization technologies can be broadly classified as either marker-based or surface-based. Marker-based localization technologies either passively track a reflective marker with an imaging system operating in the infrared (IR) spectrum or actively track a radiofrequency (RF) beacon using a set of RF receivers. These systems use a number of markers placed directly on the patient's surface or on a frame or immobilization device that is rigidly attached to the patient's surface; RF emitting beacons can also be implanted within the body. Active and passive marker systems typically employ a small number of markers, inherently limiting their ability to fully describe a patient's position and posture. Advances in computing power and imaging technology now allow the mapping of many arbitrary points on the patient while simultaneously tracking their position over time. If appropriately distributed, these points comprise a 3D surface and can be considered an extension of a marker-based approach, with a corresponding improvement in the ability to relate a patient's current position and posture to a reference.

The aim of this review is to provide a summary of the various roles that surface imaging can perform in an effort to reduce interfraction and intrafraction localization uncertainty and limit target volume expansions necessary to account for those uncertainties. Currently, these roles include reducing initial setup variability, verifying immobilization continuously during treatment, and providing dynamic surface information for use in gated and breath-hold treatment techniques. Commercially available surface imaging systems will be briefly described followed by an overview of their application by treatment site. Limitations and future applications of surfacing imaging systems are also discussed.

Surface-Guided Radiation Therapy

Surface-guided radiation therapy (SGRT) describes a variety of radiation therapy techniques that employ optical surface imaging to reduce localization uncertainty during treatment delivery, which can in turn lead to reduced target margins and dose to normal tissues. SGRT achieves this by (1) reducing interfraction setup uncertainty, (2) monitoring intrafraction patient movement, and (3) enabling respiratory-correlated treatments using gating or breath-hold techniques designed to minimize internal target motion and reduce dose to normal tissues. By providing continuous localization, SGRT also permits the use of less invasive patient fixation than other immobilization technologies, and greater patient comfort and speed of setup.

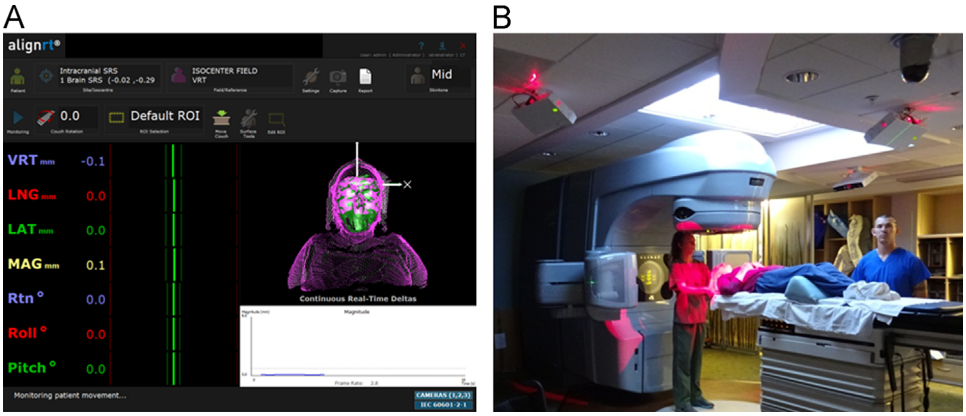
Commercially available optical surface imaging systems have been developed by vendors that are independent from current treatment delivery vendors. Although compatible with current gantry-based systems, this standalone nature also facilitates their use in support of treatment modalities where on-board imaging systems are either difficult to implement or have not yet been integrated. Surface imaging also has an important role in the treatment of pediatric patients where minimization of imaging dose is especially desirable.[7]

Commercially Available Surface Imaging Systems

This review identified several optical surface imaging systems that are currently available for clinical use. There also exist several open-source and off-the-shelf surface imaging solutions being employed clinically or in a research capacity.[8-10]

AlignRT (Vision RT, London, United Kingdom)

The AlignRT surface imaging system employs a combination of light projectors and optical cameras to generate a 3D map of a patient's topography. Projectors and high-definition cameras are mounted in pods on the ceiling of the treatment room, with typical installation having 3 pods to allow visualization of the patient in any position or gantry angle. An example of a treatment room installation of AlignRT is shown in Figure 1. The projectors emit white light that is colored red for patient comfort, as well as a checkerboard pattern to generate a texture pattern on the patient's surface. The optical cameras use these textural patterns to generate a 3D map of the patient's surface in real-time. This imaged surface is compared against a reference surface using a rigid registration algorithm. The reference surface can use the CT data-derived body contour calculated in the treatment planning system or captured in the treatment room at a given time point using the camera system. A user selects a region of interest (ROI) on the reference surface for the system to use for registration. AlignRT displays 3 axis displacements and 3 axis rotations as well as the root-mean-square (RMS) vector magnitude, i.e., 6 degrees of freedom (DOF), of all displacements on a display screen visible to radiation therapists in the treatment room. Tolerances for each axis can be set according to the treatment site or application. Resolution and refresh rate can also be set depending on treatment site and application. For example, tolerances and refresh rates are tighter for monitoring position in SRS cases vs whole breast. When any axis or the RMS vector magnitude is out of tolerance, the display switches from a green bar to a red bar. The performance of AlignRT has been widely studied in surface-guided SRS, breast, and other treatment sites.[11-15]



Intracranial SRS
1 Brain SRS (-0.02 ,-0.29
ISOCENTER FIELD
VRT
Mid
0.0
Default ROI
VRT mm -0.1
LNG mm 0.0
LAT mm 0.0
MAG mm 0.1
Rtn ° 0.0
Roll ° 0.0
Pitch ° 0.0
Monitoring patient movement...
CAMERAS (1,2,3)
IEC 60601-2-1

Figure 1 (A) AlignRT user interface showing reference surface (magenta) and live surface (green), along with displacements in 6 degrees of freedom and RMS magnitude displacement (B) in-room setup of AlignRT with ceiling-mounted cameras and light sources, and light projected onto the patient. (Color version of figure is available online.)

AlignRT can also operate in a mode called GateRT which tracks an optical surface of the patient's abdomen as a surrogate of breathing.[16] A camera pod must be mounted in the CT simulation room to image the patient's surface and generate the breathing signal for sorting 4D-CT acquisition. The surface is then monitored in the treatment room and can be interlocked to the treatment machine to trigger beam on/off when respiration is within predefined respiratory phases.

Catalyst (C-Rad, Upsalla, Sweden)

The Catalyst surface imaging system uses ceiling-mounted light emitters in the near-violet range to form a map of the patient's topography. The Catalyst-HD system is designed specifically for stereotactic applications and uses high-definition cameras. Catalyst performs real-time deformable registration using a finite element model to correlate the surface image with the reference image, and internal anatomy. The system also employs a red light source and a green light source to project calculated posture errors directly onto the patient's surface, facilitating therapist guidance in how to correct the patient's posture to match the planned treatment position (Fig. 2). The calculated displacement of the treatment isocenter is translated into 6 DOF shifts to align the patient to the final treatment position. The Catalyst system can also be used for gating at the time of simulation and treatment. To obtain a breathing signal, a separate subsystem in the CT simulation room called Sentinel uses a laser to measure the rise and fall of the patient's surface within an ROI located approximately at the xyphoid. The amplitude of this time-varying signal serves as a surrogate measure of the patient's respiratory cycle and is used to gate the CT image acquisition. Free-breathing, 4D-CT and breath-hold scans can then be acquired. The Catalyst system has been employed in several studies of surface-guided breast treatment.[17-20]

Identify (Humediq, Grunwald, Germany)

A recently available surface imaging system, the Identify system, employs 3 ceiling-mounted high-definition cameras to image the patient and map the patient's surface. The reference surface is derived from the CT data set, and is compared with an optical surface. Deviations from the reference are displayed as 6 DOF error bars along with a color overlay with a live video feed, providing therapists with an augmented reality scene to guide adjustments to the position and posture of the patient (Fig. 3). The system employs a 3D camera with a larger field of view to detect position-dependent accessories such as immobilization devices and guide their placement on the treatment couch. Identify has modules for breath coaching and gating in the CT simulation room as well as the treatment delivery room. This surface imaging system has only recently become available for clinical use, and peer-reviewed publications describing the system's performance were not available at the time of this writing.

Clinical SGRT Workflow

The previously described optical surface imaging systems use different mechanisms for imaging the patient's surface, determining the difference between actual patient position and a reference position, and relaying these differences back to the user for corrective action. However, the role of surface imaging in a typical treatment delivery workflow is largely similar

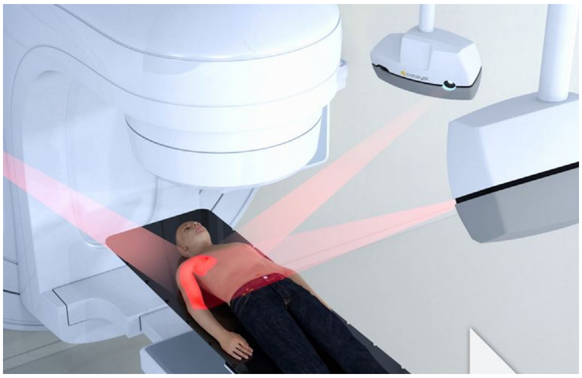
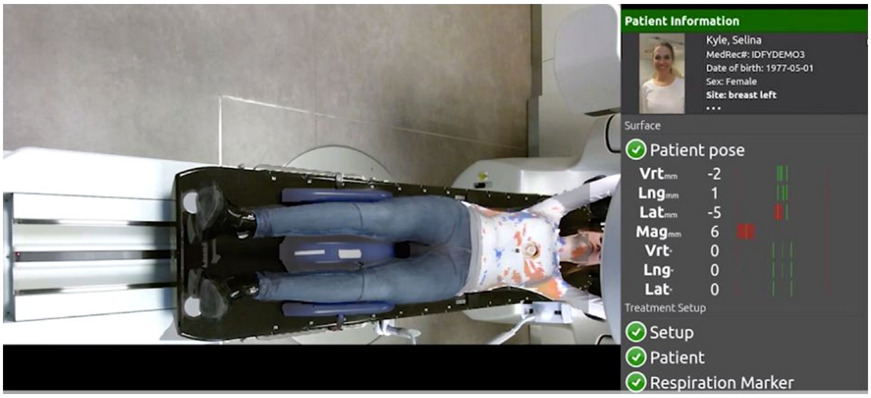


Figure 2 Computer rendering of the Catalyst surface imaging system using ceiling-mounted light source and camera pods. The Catalyst system can project regions-of-interest onto the patient's surface to assist with setup. (http://.c-rad.se/product/catalyst-2/). (Color version of figure is available online.)



Patient Information

Kyle, Selina
MedRec#: IDFYDEMO3
Date of birth: 1977-05-01
Sex: Female
Site: breast left
...

Surface

✓ Patient pose

Vrt_{mm} -2
Lng_{mm} 1
Lat_{mm} -5
Mag_{mm} 6
Vrt° 0
Lng° 0
Lat° 0

Treatment Setup

✓ Setup
✓ Patient
✓ Respiration Marker

Figure 3 An example of the user interface for the Humediq Identify surface imaging system. Displacements in 6 degrees of freedom and RMS magnitude displacement from the reference surface are shown on the right. On the left is a live video feed overlaid with surface displacements indicated by red or blue. The user can adjust the patient in real-time using this information. (http://www.humediq.com). (Color version of figure is available online.)

between different systems. The conventional radiation therapy patient setup technique uses marks on the patient's skin placed at the time of simulation to provide a reference point to align to the room lasers and position the treatment isocenter at the treatment machine's isocenter.

One example clinical workflow for SGRT is to complement the initial setup of the patient on the treatment couch with information obtained from a surface imaging system. The reference surface from the treatment planning system is used to verify whether patient position and posture matches the patient's position and posture at the time of simulation. Initial setup is followed by pretreatment imaging using planar orthogonal images to further verify patient and target position by aligning to bony anatomy, implanted marker seeds, or surgical clips to digitally reconstructed radiograph (DRR) reference images derived from the planning CT. Volumetric imaging with CBCT allows soft-tissue visualization and can be performed in place of, or as a complement to, planar orthogonal images if the treatment requires direct localization of the target. In general, however, SGRT is not used as a gold standard for patient setup. Therefore, shifts computed by the in-room radiographic imaging system are then remotely applied to the treatment couch to finalize patient position. The surface imaging system is used to acquire a new reference surface for monitoring the patient for the duration of the treatment fraction. If motion is observed at any time, treatment can be halted until the patient is back within the predefined tolerances for that site. The radiation therapists can reenter the room and adjust using surface imaging as guidance if posture or position remains outside of tolerance, or if necessary, repeat radiographic imaging followed by re-capture of a new reference surface.

The generation and real-time registration of a patient surface map are computationally intensive tasks, and with current computer processing hardware, there exists a trade-off between the resolution of the rendered surface, the dimensions of the region being monitored, and the refresh rate necessary to detect motion for a given application.[21] For example, intracranial treatment applications require a high-resolution surface to detect submillimeter motion, but lower refresh rates are acceptable. For breathing monitoring applications, a larger surface is required but this can be of lower resolution; conversely, faster refresh rates are needed to detect larger and faster surface movements.

Clinical Applications of SGRT

The role of SGRT has been explored in a variety of anatomical sites, according to the objectives outlined previously; that of reducing margins, improving comfort while maintaining margins, reducing imaging requirements while maintaining margins, and/or enabling breathing-correlated treatment techniques. The treatment sites and applications range from the simple to complex depending on which of these objectives SGRT is aiming to address.

Intracranial

Surface imaging has been proposed as a continuous localization method in intracranial SRS to achieve submillimeter localization of the patient through all treatment positions and permit the same margins as are used with invasive head frames, bite block systems, or other marker-based localization technologies.[22] With long treatment times, excessively restrictive immobilization devices can become counterproductive, in that uncomfortable patients may move or shift during treatment, necessitating periodic imaging or larger target margins. Furthermore, edentulous patients have poor immobilization with bite block systems. Cervino et al. describe an SGRT technique for radiosurgery that uses an open face mask and no frame or bite block.[11] In this approach, the patient is monitored continuously during treatment with surface imaging. Tests of a preclinical surface-based imaging system that was compared with an infrared marker block system for healthy volunteers and anthropomorphic phantoms showed an agreement to within 1 mm/ 1 degree between the two systems. Other comparisons of surface imaging with IR-marker-based systems have shown comparable agreement.[23] The open face style mask had sufficient immobilization and motion detection accuracy to permit the use of the same margins as with more invasive fixation schemes, but was more comfortable to the patient, potentially making them less likely to move. In a clinical study of 23 patients, initial setup with surface imaging was verified with CBCT, and average shifts to correct residual setup error were < 2 mm.[24] Pham et al. performed a retrospective study of 134 patients with brain metastases treated with SGRT.[25] There was no significant difference in outcome (local control and overall survival). Although patient comfort was not formally evaluated, the need for patient sedatives was uncommon, and some patients fell asleep during treatment, suggesting a greater degree of comfort than possible with more invasive immobilization schemes. SGRT also required significantly less time to perform than a conventional frame-based approach, with reported median total fraction times of 15 minutes.

The SGRT technique has subsequently been applied to the treatment of a variety of benign intracranial conditions, including trigeminal neuralgia,[26] and benign skull base tumors,[27] with comparable outcomes to conventional frame-based approaches. Clinical studies of SGRT report similar outcomes including toxicity compared with conventional approach. These applications highlight an added benefit of nonradiographic continuous localization technologies in the treatment of benign conditions or in the treatment of pediatric cases where it is desirable to limit imaging dose as much as possible. Continuous monitoring using surface imaging can also reduce or eliminate the need for anesthesia or larger margins or both to account for motion uncertainty in younger patients or patients where compliance with instructions or involuntary motion can be a challenge to accurate localization.[7] Some vendors provide a 6 DOF adjustable head mount, so that surface imaging-guided corrections to yaw, pitch and roll can be manually applied without requiring a full 6 DOF treatment couch.

Manger et al. performed a failure modes and effects analysis (FMEA) on the use of SGRT for radiosurgery to evaluate the overall safety of the approach.[28] Of the top 25 failure modes identified in the SGRT process, only one was directly related to the use of surface imaging. They concluded that surface imaging actually mitigated several risk factors related to linac-based radiosurgery in general. A fault-tree analysis identified quality assurance (QA) of the surface imaging system on the day of treatment as an effective mitigation strategy for the surface-imaging-related failure modes identified by the FMEA. In order to achieve submillimeter accuracy and ensure that the surface imaging system is calibrated to the treatment room isocenter, a comprehensive quality assurance program is essential. Paxton et al. evaluated methods for spatial calibration of the AlignRT system, using dedicated procedures for monthly QA and radiographic-to-surface isocenter calibration procedures.[29] The report of the American Association for Physicists in Medicine Task Group 147 on nonradiographic continuous localization technologies makes recommendations for comprehensive quality assurance of surface imaging systems.[30]

Breast and Chest Wall

The breast comprises a significant volume of soft-tissue, is highly deformable, and is therefore difficult to treat without employing generous margins. Another challenge is the relationship between breast surface topography and internal bony anatomy is variable, limiting the utility of MV and kV imaging at aligning the breast tissue. If imaging is only performed weekly, then there is potentially significant inter-fraction variability in patient setup. Nonradiographic continuous localization technologies such as surface imaging offer the ability to assess breast position, and breast shape in real-time, without requiring additional radiation. Surface imaging can also enable treatment techniques designed to minimize irradiation of normal tissues such as heart, lung, and liver.

Left-Side Whole Breast

Irradiation of the heart during radiation therapy for left-sided breast cancer can increase the risk of ischemic heart disease and coronary artery disease.[31] A focus of breast radiation treatment research has been on reducing dose to normal tissues and reduced late side effects. Late side effects decrease quality of life, and increase mortality through conditions such as ischemic heart disease, coronary artery disease, and secondary cancers.[31-33] The deep inspiration breath hold (DIBH) is a treatment technique that was developed to reduce the amount of heart within radiation treatment fields.[32,33,35] In DIBH, the patient is instructed to take a deep breath, and then hold their breath while the treatment beam is turned on. When treating left-sided breast cancer, the deep breath causes an excursion of the chest wall, and moves the heart out of the tangential treatment beams. A DIBH treatment can avoid irradiation of the heart and descending coronary artery in a way that does not require compromise on target volume (eg, from the use of an in-field heart block) or cause excess lung dose.

Surface imaging can be used to monitor the chest wall position during the DIBH.[15] With verbal or audio-visual coaching, it is possible for a patient to perform the DIBH voluntarily and reproducibly.[13,34] A reproducible deep inspiration chest wall excursion and stable chest wall position for the duration of the breath hold are important for ensuring dosimetric benefit from the DIBH technique.[36,37] To that end, surface imaging has been widely applied towards the guidance of DIBH. Shah et al. evaluated 50 patients undergoing radiation therapy for whole breast.[38] Patients were aligned daily using surface imaging, and shifts from skin marks were recorded, in comparison with MV port films. Although recorded displacements were not dosimetrically significant, they found that surface imaging would be valuable in reducing setup errors due to reliance on skin marks for setup only, and would require an increase in PTV margin if using the same setup technique for partial breast irradiation.

Accelerated Partial Breast Irradiation

Accelerated partial breast irradiation (APBI) is a hypofractionated technique used to treat the postsurgical cavities of select patients with early-stage breast cancer who have undergone lumpectomy. Compared to whole-breast radiation therapy, APBI employs relatively smaller target expansions around the tumor bed, between 1 and 2 cm of normal tissue to account for respiratory motion and setup errors.[39] Because breast is a deformable target relative to bony anatomy, surface imaging has been employed to improve setup.[40] Gierga et al. found that target registration error (TRE) of a surface imaging system compared to laser-based alignment, kV imaging of chest wall and kV imaging of surgical clips was on average, 3.2 mm.[41] This was using a gated surfacing imaging technique. When the surface imaging was ungated, TRE was 6.2 mm, suggesting that to maximize potential reductions in margin size through the use of surface imaging, gated acquisition is important if the motion is moving due to respiration.

Chest Wall IMRT

Chest wall IMRT with photons or protons have steep dose gradients with minimal flash compared with conventional 3D conformal beam arrangements, thus, accurate patient positioning is essential. Batin et al. investigated if surface imaging could reduce the need for radiographic imaging for guiding proton therapy of postmastectomy chest wall patients.[42] They found that surface imaging allowed more accurate positioning of chest wall patients, compared with radiograph-based techniques. The study also found that setup time substantially decreased, from 11 to 6 minutes, when using a surface imaging approach to setup.

Head and Neck

The use of SGRT for treating intracranial lesions has led to the application of SGRT to the treatment of head and neck cancers. The standard of care for the delivery of radiation for head and neck cancers is IMRT, with patients immobilized with a thermoplastic mask covering the head, neck, and shoulders. As SGRT requires direct visualization of the patient's skin surface, and should not be obscured by clothing, sheets, or immobilization, research into SGRT for head and neck has focused on the suitability of open-face masks for immobilizing patients. Initial research into open-faced masks was intended to explore their use for claustrophobic patients who had difficulty tolerating a full head/neck mask, and has led to their combination with surface imaging to monitor for residual patient motion in head and neck patients.[43,44] Li et al. evaluated the immobilization provided by open-faced masks by performing forced movements with volunteers and evaluating clinical performance with claustrophobic patients.[44] Head motion was less than 2 mm, and it was found that forced head motions in 6 DOF were within 1 mm/1 degree indicating that an open face mask offers comparable immobilization to closed face masks. Both study groups preferred the open face mask in terms of comfort and anxiety. Wiant et al. compared open and closed masks in a series of patients and evaluated registration errors with daily imaging.[43] Open masks were found to provide comparable immobilization to closed masks; however, they found no statistically significant difference in reported patient anxiety. An open face mask has the additional benefit of permitting more flexibility with mouth/jaw positioning aids and accessories such as tongue retractors or feeding tubes. Open masks may also potentially reduce skin toxicity from the bolus effect of the thermoplastic material against the patient.[45] Using surface imaging to correct head posture prior to pretreatment imaging may reduce pretreatment setup imaging requirements, reduce the need to reenter the room and adjust the patient, and reduce overall treatment times.

Thoracic/Abdominal/Pelvic

Surface imaging has several roles in the treatment of thoracic and abdominal sites. It can improve reproducibility of the treatment setup and help to identify posture errors within immobilization cradles which would otherwise be difficult to correct remotely by conventional treatment couches. Correcting posture errors before therapists leave the room to perform imaging and treatment can improve clinic efficiency and reduce imaging requirements. Surface imaging also provides a continuous localization capability during treatment, and can monitor intrafraction patient position during high dose or hypofractionated treatments, such as SBRT for lung,[46] liver, and spine. Surface imaging has also been used to reduce setup reproducibility in prostate treatments.[47]

In thoracic and abdominal treatments, the most significant component of intrafraction target localization uncertainty is often internal target motion or displacement, due to physiological processes such as breathing. If an optical surface imaging system is installed in the CT simulation room, a patient's skin surface can be measured in real-time, and the dynamic motion of the surface can provide a respiratory trace for 4D-CT studies, or guide inhalation or exhalation breath holds. Respiratory-correlated CT studies are important tools for designing the internal target volume (ITV) and PTV expansions during treatment planning.[2,48] In the treatment room, surface imaging-based respiratory monitoring can be used to gate the treatment machine depending on the patient's respiratory cycle.

Hughes et al. found that surface imaging provided a respiration surrogate with good correlation to spirometry, without the latter's tendency toward baseline drift.[49] Spadea et al. evaluated the GateCT system and found comparable results to the Varian Real-Time Position Management (RPM) (Varian Medical Systems, Palo Alto) 1D marker block system but observed some phase discrepancies, with potential for 4D-CT binning errors.[16] Schaerer et al. used surface imaging with a deformable registration to achieve multidimensional tracking of the abdominal surface.[50] A respiration surrogate based on a surface may enable a more accurate correlation model between the external and internal anatomy compared with a 1D marker block approach. Kauweloa et al. explored the feasibility of performing 4D-CT acquisitions using GateCT and found good temporal and phase based agreement with Varian RPM, but observed some drift in amplitude measurements.[51] The literature suggests that the use of surface imaging as a respiratory surrogate will continue to be an area of investigation into possible differences between phase and amplitude discrepancies. Other applications of thoracic and abdominal applications of optical surface imaging include the use of

DIBH in the treatment of mediastinal lymphomas[52] and exhalation breath-holds for treatment of liver and gastric cancers.

Extremities

Patients being treated for tumors of the extremities such as sarcoma present a challenging setup for external beam radiation therapy. Owing to their mobility, positioning a limb for treatment can be difficult, necessitating large margins. The limb must also be positioned in such a way that it can be effectively treated without excessively irradiating normal tissues of the body and adjacent limbs. Excess dose to normal tissues can inhibit wound healing if the radiation is delivered postsurgically, causes joint stiffness, lymphedema, or fibrosis. Immobilization of the limb can be achieved with custom devices, and facilitate reproducible setup, however, uncertainties remain. Surface imaging has a role in treatment of extremities and can be used as a nonradiographic alternative to imaging to verify setup of mobile limbs for treatment. However, current systems are limited in their ability to relate surface topography to internal or bony anatomy. Roll, pitch, and yaw of a target cannot be corrected with conventional treatment couches, and must be manually adjusted by a therapist by re-entering the treatment room if such an error is detected on pretreatment imaging. Surface imaging could potentially detect such errors while therapists are still in the treatment room, decreasing time spent on initial setup. Gierga et al. used surface imaging to evaluate setup uncertainty and intrafraction immobilization in patients undergoing radiation therapy for sarcoma.[53] Intrafraction motion was < 2.1 mm suggesting current immobilization techniques are adequate but the interfaction setup error could exceed typical PTV margins used for treating sarcoma, requiring daily image guidance. They conclude that surface imaging will continue to play a role in reducing image requirements by minimizing the need for repeat imaging to get the posture of the limb into the correct treatment position.

Limitations of Surface Imaging

There are several important limitations to current surface imaging technologies. Surface imaging requires that the patient's skin surface be visible to the system, thus the choice of immobilization technology must not obscure too much of the patient's surface, and becomes a trade-off between surface imaging ability and degree of immobilization. Similarly, poor reflectivity and reproducibility of items such as clothing, blankets, or sheets restrict their use with surface imaging. The surface imaging must not be obscured from imaging the patient by the gantry, imaging arms or other components in the treatment room.

A more fundamental limitation of the application of surface imaging toward target localization is that the relationship between external surface and internal anatomy is not always sufficient to fully localize the target. Thus, it is unlikely that surface imaging will fully replace in-room radiographic imaging systems in the near future, but rather will serve as a complement. Finally, for surface imaging systems and workflows that employ a CT-generated reference surface, it is important to recognize and understand the potential differences between patient surfaces reconstructed from a CT scan, and the surface imaged by an optical system. For example, artifacts in the CT reconstruction can produce reference surfaces that do not accurately describe the patient's visible topography. Reference surfaces should be reviewed before use as part of a surface imaging QA program.

Future Applications of Surface Imaging and Potential for Development

Surface imaging continues to find novel applications in radiation therapy. Based on the large number of studies that have evaluated surface imaging for improving initial patient setup, it is possible that skin marks and 3 point triangulation-based patient setup may be discontinued in favor of a purely SGRT-based approach to patient setup. Although it is unlikely that SGRT will supplant radiographic imaging for target localization (except possibly in the case of breast treatment), it may be possible to reduce or eliminate the need for radiographic setup imaging in some treatment sites, if external surfaces can be correlated to internal anatomy. However, the ability of surface imaging to infer internal target position based on a comparison of external topography to a reference surface requires additional research.

With increased computing power, it can be expected that higher resolution surfaces capturing more detailed information about patient topography will become available. In combination with recent developments in biometrics, surface imaging systems may be useful for enhanced patient identification through facial or other surface recognition. Similarly, improved rigid and deformable registration algorithms may permit automatic detection of patient weight loss or gain and/or tumor size change without requiring acquisition of a weekly CBCT. The ability of surface imaging systems to record position data continuously throughout treatment can be used to inform target margins by providing position uncertainty information acquired over a fraction or course of treatment. This could potentially allow a form of adaptive therapy in which a patient's own surface imaging-derived motion history is used to design reduced margins in later fractions of their treatment. Alternatively, the motion data could be used for population studies and validation of strategies for calculating target expansions in the presence of random and systematic errors.[54]

Conclusion

SGRT has been applied to many sites including brain, breast, head and neck, abdomen, and the extremities. Surface imaging can reduce interfraction and intrafraction target localization errors and allow reductions in target volume expansions designed to account for localization uncertainty. Surface imaging can also enable breathing correlated CT simulation and treatment delivery, facilitating reductions in margins to account for internal target motion, and sparing normal tissues. Additional benefits of surface imaging include the use of setup and immobilization techniques that confer greater comfort to patients, reduced need for imaging, and improvements to the efficiency and safety of clinical workflows.

References

1. International Commission on Radiation Units and Measurements ICRU Report 50. Prescribing, recording, and reporting photon beam therapy. Bethesda, MD: ICRU, 1993
2. International Commission on Radiation Units and Measurements ICRU Report 62. Prescribing, recording, and reporting photon beam therapy (Supplement to ICRU Report 50). Bethesda, MD: ICRU, 1999
3. Jaffray DA, Siewerdsen JH, Wong JW, et al: Flat-panel cone-beam computed tomography for image-guided radiation therapy. Int J Radiat Oncol Biol Phys 53(5):1337-1349, 2002
4. Dong P, Lee P, Ruan D, et al: 4π non-coplanar liver SBRT: A novel delivery technique. Int J Radiat Oncol Biol Phys 85(5):1360-1366, 2013
5. Sheng K, Dong P, Lee P, et al: 4π non-coplanar SBRT for centrally located or larger lung tumors. Int J Radiat Oncol Biol Phys 87(2):S122, 2013
6. D'Ambrosio DJ, Bayouth J, Chetty IJ, et al: Continuous localization technologies for radiotherapy delivery: Report of the American Society for Radiation Oncology Emerging Technology Committee. Pract Radiat Oncol 2(2):145-150, 2012
7. Rwigema JC, Lamiman K, Reznik RS, et al: Palliative radiation therapy for superior vena cava syndrome in metastatic Wilms tumor using 10XFFF and 3D surface imaging to avoid anesthesia in a pediatric patient—a teaching case. Adv Radiat Oncol 2(1):101, 2017
8. Lindl BL, Müller RG, Lang S, et al: TOPOS: A new topometric patient positioning and tracking system for radiation therapy based on structured white light [n/a, 042701]. Med Phys 40. http://dx.doi.org/10.1118/1.4794927
9. Gilles M, Fayad H, Miglierini P, et al: Patient positioning in radiotherapy based on surface imaging using time of flight cameras. Med Phys 43:4833-4841, 2016. http://dx.doi.org/10.1118/1.4959536
10. Fattori G, Seregni M, Pella A, et al: Real-time optical tracking for motion compensated irradiation with scanned particle beams at CNAO. Nucl Instrum Methods Phys Res A 827:39-45, 2016
11. Cerviño LI, Pawlicki T, Lawson JD, et al: Frame-less and mask-less cranial stereotactic radiosurgery: a feasibility study. Phys Med Biol 55(7):1863, 2010
12. Wiant DB, Wentworth S, Maurer JM, et al: Surface imaging-based analysis of intrafraction motion for breast radiotherapy patients. J Appl Clin Med Phys 15(6):147-159, 2014
13. Betgen A, Alderliesten T, Sonke JJ, et al: Assessment of set-up variability during deep inspiration breath hold radiotherapy for breast cancer patients by 3D-surface imaging. Radiother Oncol 106(2):225-230, 2013
14. Gopan O, Wu Q: Evaluation of the accuracy of a 3D surface imaging system for patient setup in head and neck cancer radiotherapy. Int J Radiat Oncol Biol Phys 84(2):547-552, 2012
15. Schöffel PJ, Harms W, Sroka-Perez G, et al: Accuracy of a commercial optical 3D surface imaging system for realignment of patients for radiotherapy of the thorax. Phys Med Biol 52(13):3949, 2007
16. Spadea MF, Baroni G, Gierga DP, et al: Evaluation and commissioning of a surface based system for respiratory sensing in 4D CT. J Appl Clin Med Phys 12(1):162-169, 2011
17. Walter F, Freislederer P, Belka C, et al: Evaluation of daily patient positioning for radiotherapy with a commercial 3D surface-imaging system (Catalyst™). Radiat Oncol 11(1):154, 2016
18. Stieler F, Wenz F, Shi M, et al: A novel surface imaging system for patient positioning and surveillance during radiotherapy. Strahlenther Onkol 189 (11):938-944, 2013
19. Crop F, Pasquier D, Baczkiewic A, et al: Surface imaging, laser positioning or volumetric imaging for breast cancer with nodal involvement treated by helical TomoTherapy. J Appl Clin Med Phys 17(5):1-2, 2016
20. Schönecker S, Walter F, Freislederer P, et al: Treatment planning and evaluation of gated radiotherapy in left-sided breast cancer patients using the Catalyst$^{\text{TM}}$/Sentinel$^{\text{TM}}$ system for deep inspiration breath-hold (DIBH). Radiat Oncol 11(1):143, 2016
21. Soufi M, Arimura H: Surface-imaging-based patient positioning in radiation therapy. Image-Based Comput Assist Radiat Ther 237-270, 2017
22. Wagner TH, Meeks SL, Bova FJ, et al: Optical tracking technology in stereotactic radiation therapy. Med Dosim 32(2):111-120, 2007
23. Wiersma RD, Tomarken SL, Grelewicz Z, et al: Spatial and temporal performance of 3D optical surface imaging for real-time head position tracking. Med Phys 40(11), 2013
24. Cerviño LI, Detorie N, Taylor M, et al: Initial clinical experience with a frameless and maskless stereotactic radiosurgery treatment. Pract Radiat Oncol 2(1):54-62, 2012
25. Pham NL, Reddy PV, Murphy JD, et al: Frameless, real-time, surface imaging-guided radiosurgery: update on clinical outcomes for brain metastases. Transl Cancer Res 3(4):351-357, 2014
26. Paravati AJ, Manger R, Nguyen JD, et al: Initial clinical experience with surface image guided (SIG) radiosurgery for trigeminal neuralgia. Transl Cancer Res 3(4):333-337, 2014
27. Lau SK, Patel K, Kim T, et al: Clinical efficacy and safety of surface imaging guided radiosurgery (SIG-RS) in the treatment of benign skull base tumors. J Neurooncol 132(2):307-312, 2017
28. Manger RP, Paxton AB, Pawlicki T, et al: Failure mode and effects analysis and fault tree analysis of surface image guided cranial radiosurgery. Med Phys 42(5):2449-2461, 2015
29. Paxton AB, Manger RP, Pawlicki T, et al: Evaluation of a surface imaging system's isocenter calibration methods. J Appl Clin Med Phys 18 (2):85-91, 2017
30. Willoughby T, Lehmann J, Bencomo JA, et al: Quality assurance for nonradiographic radiotherapy localization and positioning systems: Report of task group 147. Med Phys 39:1728-1747, 2012. http://dx.doi.org/10.1118/1.3681967
31. Darby SC, Ewertz M, McGale P, et al: Risk of ischemic heart disease in women after radiotherapy for breast cancer. N Engl J Med 368 (11):987-998, 2013
32. Boda-Heggemann J, Knopf AC, Simeonova-Chergou A, et al: Deep inspiration breath hold—based radiation therapy: a clinical review. Int J Radiat Oncol Biol Phys 94(3):478-492, 2016
33. Sayan M, E Hopkins W, Heimann R: Deep Inspiration Breath-hold (DIBH) Technique to Reduce Cardiac Radiation Dose in the Management of Breast Cancer. Curr Cancer Ther Rev 12(1):2-14, 2016
34. Cervino LI, Gupta S, Rose MA, et al: Using surface imaging and visual coaching to improve the reproducibility and stability of deep-inspiration breath hold for left-breast-cancer radiotherapy. Phys Med Biol 54 (22):6853, 2009
35. Sixel KE, Aznar MC, Ung YC: Deep inspiration breath hold to reduce irradiated heart volume in breast cancer patients. Int J Radiat Oncol Biol Phys 49(1):199-204, 2001
36. Wiant D, Wentworth S, Liu H, et al: How important is a reproducible breath hold for deep inspiration breath hold breast radiation therapy? Int J Radiat Oncol Biol Phys 93(4):901-907, 2015
37. Padilla L, Kang H, Washington M, et al: Assessment of interfractional variation of the breast surface following conventional patient positioning for whole-breast radiotherapy. J Appl Clin Med Phys 15(5):177-189, 2014
38. Shah AP, Dvorak T, Curry MS, et al: Clinical evaluation of interfractional variations for whole breast radiotherapy using 3-dimensional surface imaging. Pract Radiat Oncol 3(1):16-25, 2013
39. Smith BD, Arthur DW, Buchholz TA, et al: Accelerated partial breast irradiation consensus statement from the American Society for Radiation Oncology (ASTRO). Int J Radiat Oncol Biol Phys 74(4):987-1001, 2009
40. MacDonald SM, Gierga DP, Napolitano B, et al: APBI 3D Conformal External Beam: The MGH Technique. Accelerated Partial Breast Irradiation:315-326, 2009
41. Gierga DP, Riboldi M, Turcotte JC, et al: Comparison of target registration errors for multiple image-guided techniques in accelerated partial breast irradiation. Int J Radiat Oncol Biol Phys 70(4):1239-1246, 2008

42. Batin E, Depauw N, MacDonald S, et al: Can surface imaging improve the patient setup for proton postmastectomy chest wall irradiation? Pract Radiat Oncol 6(6):e235-e241, 2016
43. Wiant D, Squire S, Liu H, et al: A prospective evaluation of open face masks for head and neck radiation therapy. Pract Radiat Oncol 6(6): e259-e267, 2016
44. Li G, Lovelock DM, Mechalakos J, et al: Migration from full-head mask to "open-face" mask for immobilization of patients with head and neck cancer. J Appl Clin Med Phys 14(5):243-254, 2013
45. Sharp L, Lewin F, Johansson H, et al: Randomized trial on two types of thermoplastic masks for patient immobilization during radiation therapy for head-and-neck cancer. Int J Radiat Oncol Biol Phys 61(1):250-256, 2005
46. Alderliesten T, Sonke JJ, Betgen A, et al: 3D surface imaging for monitoring intrafraction motion in frameless stereotactic body radiotherapy of lung cancer. Radiother Oncol 105(2):155-160, 2012
47. Krengli M, Gaiano S, Mones E, et al: Reproducibility of patient setup by surface image registration system in conformal radiotherapy of prostate cancer. Radiat Oncol 4(1):9, 2009
48. Keall PJ, Mageras GS, Balter JM, et al: The management of respiratory motion in radiation oncology report of AAPM Task Group 76. Med Phys 33(10):3874-3900, 2006
49. Hughes S, McClelland J, Tarte S, et al: Assessment of two novel ventilatory surrogates for use in the delivery of gated/tracked radiotherapy for non-small cell lung cancer. Radiother Oncol 91(3):336-341, 2009
50. Schaerer J, Fassi A, Riboldi M, et al: Multi-dimensional respiratory motion tracking from markerless optical surface imaging based on deformable mesh registration. Phys Med Biol 57(2):357, 2011
51. Kauweloa KI, Ruan D, Park JC, et al: GateCT™ surface tracking system for respiratory signal reconstruction in 4DCT imaging. Med Phys 39 (1):492-502, 2012
52. Aznar MC, Maraldo MV, Schut DA, et al: Minimizing late effects for patients with mediastinal Hodgkin lymphoma: Deep inspiration breath-hold, IMRT, or both? Int J Radiat Oncol Biol Phys 92(1):169-174, 2015
53. Gierga DP, Turcotte JC, Tong LW, et al: Analysis of setup uncertainties for extremity sarcoma patients using surface imaging. Pract Radiat Oncol 4 (4):261-266, 2014
54. Van Herk M: Errors and margins in radiotherapy. Seminars in radiation oncology, Vol. 14. WB Saunders, 52-64, 2004