Applications of surface guided imaging in radiotherapy: A literature review

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***Abstract*—Surface-guided radiotherapy (SGRT) has evolved into a promising method that offers continuous real-time feedback and remarkable sub-millimeter spatial accuracy in three dimensions, while ensuring patients do not receive any extra radiation. In recent times, SGRT has been a promising tool, capable of assuring patient safety, shortening treatment duration, and refining the precision of treatment setup in diverse radiotherapy processes. In studies comparing gated surface-guided imaging with laser-based alignment, x-ray imaging of the chest wall, and x-ray imaging of surgical clips, SGRT demonstrated a target registration error of just 3.2 mm. In patients undergoing partial breast irradiation, SGRT significantly reduced the average setup time by approximately one minute per treatment fraction when compared to the traditional 3-point localization method. Another notable feature of SGRT is its ability to actively monitor and accurately position the patient's surface, allowing for adjustments to be made and the treatment beam to be paused if deviations from the reference position occur.**

This review aims to provide an overview of the diverse clinical applications of SGRT in brain, thoracic, abdominal, and breast tumor indications. The evaluation of SGRT as a complementary tool to traditional image-guided cone-beam computed tomography and four-dimensional computed tomography will also be discussed.

Despite its benefits, SGRT has certain limitations such as the visibility of the patient's skin surface and the relationship between the external surface and internal anatomy. Additionally, SGRT requires adequate clinical workflow and quality assurance regulations to ensure safe clinical use and treatment accuracy.

Overall, this review covers the current and potential future applications of SGRT in radiotherapy and emphasizes the importance of safe and accurate implementation of this imaging modality.

***Index Terms*—Surface-guided radiotherapy, cone-beam computed tomography, four-dimensional computed tomography, stereotactic radiosurgery, whole-brain radiotherapy, Deep-Inspiration-Breath-hold and accelerated partial breast irradiation.**

1. INTRODUCTION

Surface-guided radiotherapy (SGRT) is a modality that uses real-time 3D patient surface imaging to guide radiotherapy [1]. SGRT involves optical surface scanning for patient positioning, intra-fraction motion monitoring, and respiratory gating techniques [2]. SGRT systems typically use a combination of a projector and one or more camera units to generate a real-time 3D surface of the patient relative to a reference surface at the treatment isocenter position. This information is used to calculate necessary patient position corrections in translational and rotational directions. The beam can be held if there are deviations from the reference position on the patient's surface, as determined by the planning CT set-up, or if the calculated isocentric deviations exceed a specified threshold.

The use of SGRT has increased due to its potential for a more accurate target irradiation while sparing normal tissue [3]. SGRT enables continuous monitoring of patient positioning, which improves patient safety and comfort, standardizes workflows with higher precision and reproducibility [4, 5]. SGRT also has the advantage of reducing fraction duration and minimizing imaging dose as it provides in-room online information of the complete surface and position of the patient [1, 6]. SGRT is particularly useful for superficial tumors around the isocenter where surface deviations can act as a surrogate for tumor motion and provides more accurate positioning compared to traditional 3-point-lasers [7]. Daily imaging with ionizing radiation remains mandatory for deeper located tumors, however SGRT is able to reduce the time required for deformable surface registration and prevent the need for excessive imaging [8]. SGRT has proven to be an important addition to the radiation therapy process regarding patient positioning and monitoring with high spatial and temporal resolution. The main advantages of SGRT are visualized in Table 1.

SGRT has been applied in brain tumors using whole-brain radiation therapy (WBRT) or stereotactic radiosurgery (SRS) for accurate patient positioning and shorter fraction durations. Other applications of SGRT has been implemented on deeper located tumors, such as thoracic and abdominal tumors. Moreover, SGRT shows promising applications in gated radiotherapy delivery of tumor locations close to the skin surface, such as in breast cancer, using deep-inspiration-breath-hold (DIBH) and accelerated partial breast irradiation (APBI) [9, 10]. Additionally, SGRT has been used in specialized techniques such as surface-guided our-dimensional computed tomography (4D-CT) [11].

This review evaluates the differences between image-guided cone-beam computed tomography (CBCT) and SGRT, and also provides a summary of the clinical use of SGRT, recent research findings and potential future applications. Moreover, this review will discuss the benefits and limitations of SGRT.

Table 1: Advantages of SGRT

Source	Advantage
[1, 2, 6]	No imaging dose
	Real-time 3D volumetric imaging
	Sub-millimeter spatial resolution
	Large field-of-view
	Reducing fraction duration
[12–14]	Improved patient position accuracy & efficiency
	Alternative to tattoos

2. COMMERCIALLY AVAILABLE SGRT SYSTEMS

This section describes several optical surface imaging systems that are currently available for clinical use [8].

2.1. AlignRT

The AlignRT system, developed by Vision RT in London, UK, combines multiple light projectors with optical cameras to create a 3D representation of a patient's surface topography. Comprising three pods situated on the treatment room ceiling, each equipped with high-end cameras and projectors, this system enables visualization of the patient from various positions and gantry angles. By emitting colored light and a checkerboard pattern, the projectors create a textured pattern on the patient's skin. The optical cameras utilize these patterns to create an instantaneous 3D representation of the patient's surface, which is then compared to a reference surface by implementing complex rigid registration.

CT data can be used to calculate body contours for the patient's reference surface, this surface can also be obtained by the imaging system camera. On top of this patient reference surface, the radiation therapists can specify specific regions of interest (ROI), which will be used to register the surfaces. AlignRT presents three-axis rotations, three-axis displacements, and the root-mean-square vector magnitude of all movements, encompassing the six degrees of freedom (6DOF). Radiation therapists can access this information on a computer, which is connected to the imaging system. The tolerances for each axis can be adjusted according to the specific requirements of the treatment site or application, offering a tailored approach. Moreover, the resolution and refresh rate of the system can be modified to match the needs of the treatment site and application. The refresh rate determines the frequency at which real-time surface registration is performed, allowing for the continuous visualization of the live surface area.

Additionally, AlignRT can be used in GateRT mode, which tracks the patient's breathing using an optical surface of the abdomen as a surrogate [15]. This is implemented by using the 4D-CT acquisition sorting approach. In order to facilitate the sorting of 4D-CT acquisition, it is necessary to install a camera pod within the CT simulation room. This camera pod serves the purpose of capturing the patient's surface and generating the breathing signal. Subsequently, the system can continuously monitor the patient's surface within the treatment room. By establishing an interlock with the treatment machine, the system can accurately determine predefined respiratory phases and effectively trigger the beam on/off accordingly.

2.2. Catalyst

The Catalyst surface imaging system, developed by C-Rad in Upsala, Sweden, utilizes light emitters in the near-violet optical range mounted on the ceiling. This system generates a comprehensive map of the patient's topography. Originally designed for stereotactic radiotherapy, the Catalyst-HD system also employs high-end cameras. Using a finite element model, the Catalyst surface imaging system enables accurate and dynamic alignment between the patient's surface, reference image, and internal structures, using a real-time deformable registration based technique.

Moreover, the Catalyst system incorporates the use of red and green light, which are utilized to project patient positional mismatches in real-time onto the surface of the patient. This innovative feature empowers therapists to effectively guide patients in correcting their posture, ensuring alignment with the predefined treatment position. By accurately calculating the displacement of the treatment isocenter, the system determines precise shifts in all 6DOF for final alignment of the patient position.

Additionally, the Catalyst system offers gating capabilities for both simulation and treatment procedures. A separate subsystem known as Sentinel is employed in the CT acquisition to obtain a breathing signal. This subsystem utilizes a laser to measure the upward and downward movement of the patient's surface within a predefined ROI situated near the sternum. The magnitude of this signal, which varies over time, functions as a reliable measure of the patient's breathing cycle. It is utilized to gate the acquisition of CT images, facilitating the capture of scans under different conditions, including free-breathing, 4D-CT, and breath-hold scans.

2.3. Identify

The Identify system, developed by Humediq in Grunwald, Germany, which utilizes three high-end cameras mounted on the ceiling to capture and generate a detailed 3D map of the patient's surface. The reference surface, which is calculated from the CT data, is continuously brought in comparison to the optical surface using an augmented reality display. This display provides therapists with valuable visual information, including 6DOF error blocks, a colored surface overlay, and real-time video feedback. This comprehensive feedback assists therapists in making precise adjustments to the patient's position and posture during treatment.

Furthermore, the Identify system is equipped with a 3D camera featuring a wider field of view. This camera facilitates the detection and guidance of position-dependent objects, for example immobilization devices, ensuring their accurate placement during treatment.

The Identify system encompasses dedicated modules for breath coaching and gating in both the CT acquisitions and treatment rooms. These modules enable therapists to provide guidance and support to patients during their breathing cycles and implement gating techniques as necessary to enhance treatment accuracy.

3. IMAGE-GUIDED CBCT VERSUS SGRT

Image-guided radiotherapy (IGRT) is a therapeutic approach that involves the use of imaging techniques for anatomical and functional localization as well as response assessment during treatment [16]. The use of IGRT has made it possible to reduce the size of the margins, minimizing risk of toxicity from the treatment, while still maintaining adequate dose to the planned target volume [17]. Although, the acquisition of planar kilovoltage images or the most commonly used IGRT method, the on-board cone-beam computed tomography (CBCT), usually results in additional dose to the patient. Due to its widespread availability on a large number of treatment units, CBCT has become the established standard-of-care for the positioning of tumors located deep in the patient. Figure 1 visualizes the principle of image-guided CBCT [18].

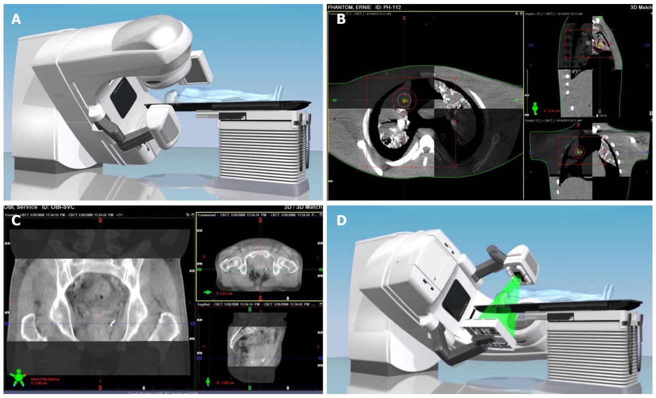

Fig. 1: Cone-beam computed tomography. A: CBCT device; B: Chest view; C: Pelvic view; D: Image-guided radiotherapy [18].

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There are various techniques to minimize the radiation exposure to patients during the imaging procedures of CBCT. One approach is to reduce the number of frames acquired or to decrease the current-time parameters for an acquisition in kilovoltage imaging. Studies have explored the efficacy of these techniques by reducing the amount of imaging, varying the start/stop angles, shortening the scan-time, and replacing high-dose protocols with low-dose protocols [19, 20].

Roxby et al. proposed an alternative approach that suggests the use of a copper filter in the imaging beam [21]. This method effectively increases the half-value layer of the beam, resulting in a reduction in the delivered dose. It is essential to consider that while such dose reductions can be achieved, there is a possibility of compromising the quality of the resulting image. Therefore, striking a balance between minimizing radiation exposure and ensuring sufficient image quality is crucial to enable accurate diagnosis and effective treatment.

When feasible, non-ionizing imaging techniques like trans-abdominal 3D ultrasound and MRI are employed for IGRT [16]. These techniques offer notable advantages over CBCT, primarily due to their characteristic for real-time imaging and superior soft tissue contrast, particularly in the case of MRI. By providing enhanced visualization of anatomical structures, they contribute to more accurate and precise treatment guidance during radiation therapy.

Despite the clear advantages of 3D volumetric imaging, SGRT can serve as a valuable complementary tool for IGRT. SGRT offers real-time imaging and can be easily added to most treatment units, improving accuracy, safety, and efficacy for all radiotherapy patients. To achieve high accuracy, SGRT requires a reliable correlation between the target and the patient surface. For deeper located organs such as the prostate, other imaging techniques like ultrasound imaging and MRI applications, such as the MR-linac, are generally more accurate to enable soft-tissue contrast [22, 23]. However, SGRT and the MR-linac are the only modalities that offer imaging without dose, real-time feedback, sub-millimeter spatial resolution in 3D, and the largest field-of-view available in radiotherapy [1]. These characteristics enable SGRT to verify immobilization accuracy, correct the patient's posture, track the respiratory state, and provide intra-fraction monitoring. Such applications of SGRT could be beneficial in most radiotherapy approaches, regardless of whether another complementary IGRT modality will be used for anatomical localization.

4. CLINICAL APPLICATIONS

The conventional approach for marking patients during CT simulation to ensure reference and alignment on the treatment machine involves the use of 3-point localization, commonly achieved through tattoos. Findings from Jimenez et al. report the discomfort of patients towards the application of tattoos, citing potential pain, adverse effects on body image, religious or cultural beliefs, or psychological distress stemming from a permanent reminder of their cancer diagnosis [13]. SGRT has emerged as a potential alternative to tattoos, although certain clinics still employ tattoos as a backup or for extra safety measures.

SGRT provides a notable advantage over 3-point localization by offering rotational 3D maps of the patient's position and topography [24, 25]. This capability enables corrective action to be taken before verification imaging or treatment. In contrast, markers and 2D x-ray imaging primarily correct along planes perpendicular to the imaging direction, which do not provide accurate indicators of rotations or deformations in the setup of the patient. Therefore, SGRT offers enhanced visualization and guidance for setup prior to treatment, placing greater emphasis on proactive measures rather than reactive ones after imaging procedures.

4.1. *Clinical workflow*

According to Hoisak et al., one SGRT clinical workflow involves utilizing a surface imaging system as a complementary element to the original setup of the patient [8]. The treatment planning system (TPS) creates the patient's reference surface used to confirm the alignment of the patient's position and posture with their simulated position. Pre-treatment imaging involves planar orthogonal images used for the alignment of bone structures, surgical clips, markers, and reference images obtained by the planning CT. CBCT may be used in addition to or as an alternative to planar orthogonal images when immediate target localization is required. It is important to note that SGRT is not considered the golden standard for patient setup.

The shifts determined by the in-room imaging system are implemented remotely to adjust the position of the treatment couch, ensuring the patient's precise alignment. Subsequently, an updated reference surface is obtained through the surface imaging system, enabling continuous monitoring of the patient throughout the treatment session. In the event that any movement surpasses the predefined tolerances for the specific treatment area, the treatment can be temporarily halted until the patient returns within the acceptable range. To correct any posture or position deviations that persist beyond the tolerance limits, radiotherapists can re-enter the room and are able to make adjustments according to the surface imaging reference. Alternatively, they may opt to repeat this procedure to update reference surface until satisfied.

4.2. *Patient positioning*

The study by Haraldsson et al. have demonstrated that SGRT yields comparable or even enhanced accuracy in patient positioning when compared to the traditional 3-point localization method [12]. The level of accuracy achieved through SGRT, however, varies depending on the specific anatomical site being treated. For treatments targeting the head and neck region, SGRT has shown minimal shifts in comparison to CBCT due to additional immobilization techniques and minimal impact from respiratory motion. The expanded field-of-view provided by SGRT allows for effective correction of arm positioning, thereby improving the patient posture. Conversely, in the abdomen and pelvis regions, both 3-point localization and SGRT tend to exhibit decreased accuracy in patient positioning [12, 24].

For breast cancer patients, SGRT has been shown to be helpful for whole breast [6, 25] and partial breast irradiation [13], as the surface serves as a reliable surrogate for the target area. To implement SGRT, an optical surface scanning system is employed. It generates a 3D representation of the patient's external surface, extracted from the TPS. This 3D map is then compared with a real-time scan of the patient's surface obtained while they are positioned on the treatment couch. This technique, known as surface-based setup, enhances the amount of patient setup information compared to the traditional 3-point localization method that relies solely on three skin marks. By utilizing the entire skin surface of the patient, the surface-based setup enables more comprehensive alignment and positioning, contributing to improved accuracy during treatment. Figure 2 captures the visual representation of the optical surface scanning system to align the patient for treatment.

Apart from enhancing accuracy, SGRT has the potential to enhance positioning efficiency in comparison to conventional laser- or x-ray-based methods [14]. Findings from studies conducted by Jimenez et al. and Batin et al. demonstrate that SGRT offers time-saving benefits during patient positioning for treatment using traditional linear accelerators (LINACs) and proton therapy [13, 14]. Specifically, for patients experiencing partial breast irradiation, SGRT has been shown to decrease the average setup time by approximately 1 minute per fraction duration when compared to the traditional 3-point localization method.

According to recent studies, the use of surface imaging for breast cancer patient setup has shown to reduce positioning errors in skin and clip alignment compared to laser alignment [10, 13]. Surface imaging not only provides accurate isocenter positioning, but also guidance for correcting patient posture, resulting in improved breast position [6]. However, the accuracy of surface-guided patient setup may be affected by various factors, such as patient motion, camera shadowing, selection of the region-of-interest, absence of anatomical gradients, and anatomical changes throughout treatment [6, 25].

Recent studies have highlighted a limited correlation between the displacement of the patient's external surface and the displacement of internal targets during treatment [24, 26]. In the case of targets located in the abdomen, considerable shifts till 3 cm have been observed, while shifts near to 2 cm have been noted for targets in the pelvis and lower extremities. Despite this observed lack of correlation, surface imaging has been shown to have comparable preciseness in laser alignment and has been deemed helpful for initializing patient setup and as a supplementary tool to conventional imaging methods. It is important to note that while there may be a limited correlation between surface movement and internal target movement, this does not diminish the utility of SGRT. Instead, SGRT provides complementary information for image guidance.

4.3. *Brain tumor indications*

Whole-brain radiotherapy (WBRT) is the recommended treatment for patients with three or more brain metastases, but it can cause long-term adverse effects and a decrease in quality of life [27]. Stereotactic radiosurgery (SRS) is recommended for patients with limited metastases. Recent technological advancements state that frameless SRS is a more patient-friendly option, enabling precise positioning during treatment [28]. This advancement not only improves patient comfort but also eliminates the need for dummy runs before treatment delivery, significantly reducing the total treatment time per fraction.

To enhance treatment quality and minimize complications, a 6DOF correction technique can be employed. This technique utilizes on-board CBCT imaging in combination with a thermoplastic mask to achieve smaller treatment margins. By treating multiple lesions with a single isocenter, the technique optimizes treatment accuracy [29]. Non-coplanar couch angles can be incorporated into the treatment planning process to spare normal brain tissue, with up to 5 non-coplanar arcs based on 4 fixed angular couch positions, as shown in figure 3.

To maximize the effectiveness of SGRT in patients with brain tumors, the use of open-face masks or the absence of masks is necessary [8]. A study conducted by Dekker et al.

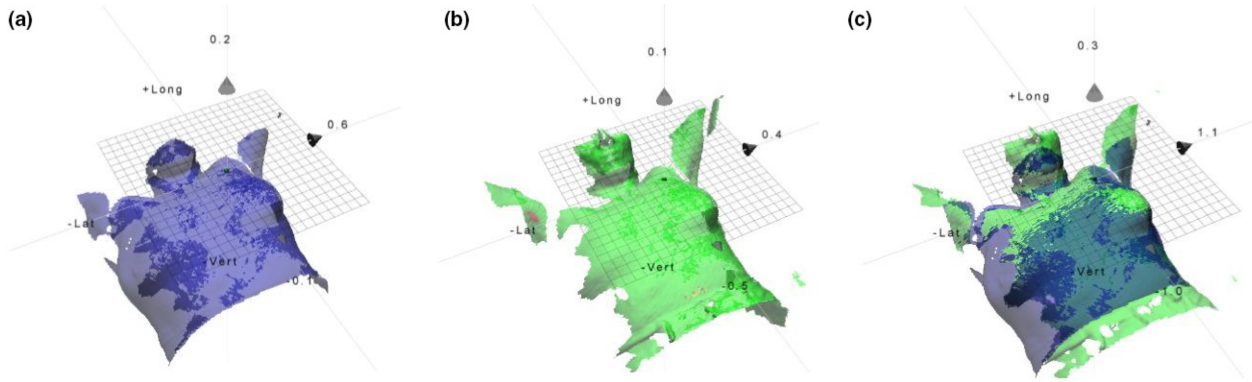

Fig. 2: a) The surface of reference (represented in blue) is generated based on the planned isocenter from the TPS. b) The surface of the live patient (represented in green) is captured using the optical surface scanning system. c) The live surface and reference are matched using a deformable algorithm and a couch-shift [6].

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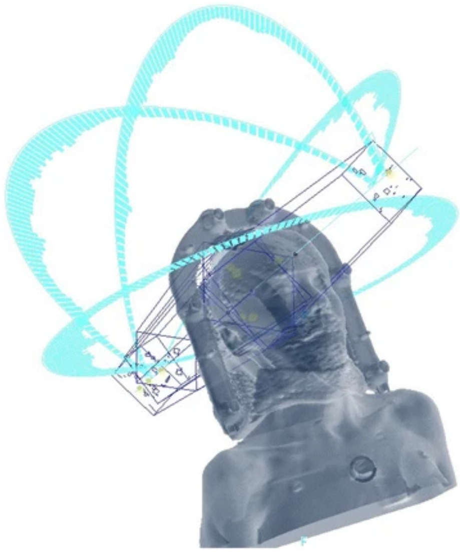

Fig. 3: The beam arrangement for SRS using 5 non-coplanar 180°-arcs at 4 different angular configurations of the couch [28]

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assessed the clinical feasibility of delivering WBRT to 30 palliative brain tumor patients excluding immobilization masks and using a SGRT system with only a single camera [30]. The results of this study reported a success rate of 93%, showing that the absence of thermoplastic masks in radiation therapy was feasible. Moreover, the study found that the motion of the isocenter was within an average range of 1.1 mm. The SGRT system was also integrated with the Linac, allowing for automated beam shut-off in the event that patients exceeded displacements outside of the given range.

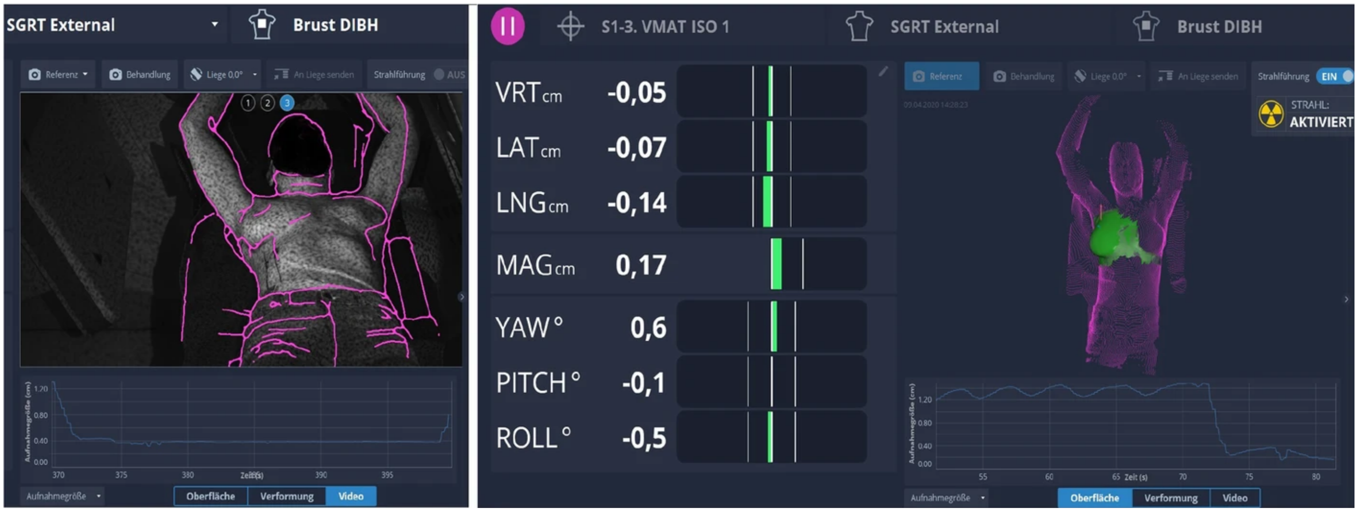
Regular verification of the radiation isocenter is crucial for maintaining accuracy during the treatment of non-coplanar couch angles. It is essential to assess the alignment between the radiation isocenter and various gantry, collimator, and couch angles, as well as to evaluate the performance of the SGRT system. This meticulous process is necessary to prevent any complications that may arise during the delivery of treatment with the walkout of the couch. Conducting routine checks to ensure accurate information regarding the radiation isocenter for different angles is fundamental to guarantee the effectiveness of the SGRT system.

4.4. Thoracic and abdominal tumor indications

Patients undergoing treatment thoracic and abdominal tumors can benefit from the use of surface imaging [8]. One key benefit is its ability to enhance the reproducibility of treatment setup, ensuring consistent and precise patient positioning. Moreover, surface imaging aids in the identification of posture errors that may occur within immobilization inconsistencies, which can be difficult to rectify using conventional treatment couches. By detecting these errors, surface imaging improves the overall efficiency of the clinic and minimizes the need for additional imaging procedures. Therapists can promptly correct posture errors before leaving the room for imaging and treatment, optimizing workflow and saving time.

Moreover, SGRT offers real-time target localization throughout the entire treatment process. This is particularly beneficial during high-dose or hypofractionated treatments, such as stereotactic body radiotherapy for lung, liver, and spine. By continuously monitoring the patient's position during treatment, surface imaging ensures that the patient remains accurately aligned. This ongoing monitoring plays a crucial role in promoting precise and effective radiation delivery, ultimately enhancing treatment outcomes.

Accurately localizing internal targets during treatment is primarily affected by the motion or displacement of these targets. To address this, optical surface imaging systems can be placed in the treatment room to capture the real-time data of the patient's skin surface. This dynamic surface imaging technique gives access to valuable information, such as respiratory traces, for 4D-CT studies or can be used to guide patients during breath holds. Furthermore, in the



VRT cm -0,05
LAT cm -0,07
LNG cm -0,14
MAG cm 0,17
YAW ° 0,6
PITCH ° -0,1
ROLL ° -0,5

Fig. 4: The placement of a patient for DIBH is shown in the left image, where the reference surface (in purple) and the live surface data are utilized. The right image visualizes the monitoring of DIBH during treatment, highlighting the ROI (in green), and displaying the breathing curve at the bottom [2].

treatment room, surface imaging-based respiratory monitoring can be employed to synchronize the treatment machine with the patient's respiratory cycle, ensuring precise targeting and delivery of radiation.

4.5. *Deep-Inspiration-Breath-hold*

Respiratory-induced organ motion is recognized as the primary source of intrafractional motion in radiation therapy for tumors or lesions affected by respiration [10]. Addressing this challenge, respiratory-based gated radiotherapy techniques have been developed to mitigate this uncertainty. These techniques include Deep-Inspiration-Breath-hold (DIBH), where patients take a maximum inspiration and hold their breath, as well as shallow breath-hold techniques with moderate inspiration [9]. Both approaches effectively minimize tumor motion, enabling a reduction in the dose delivered to the heart while maintaining comparable planning target volume (PTV) coverage. These techniques play a crucial role in enhancing the accuracy of radiation therapy and reducing the potential risks associated with organ motion during treatment.

The SGRT system used for patient positioning and monitoring is shown in figure 4. This system can be used to monitor breath-hold levels, however it can only monitor the patient surface as a surrogate for tumor motion.

4.6. *Accelerated partial breast irradiation*

Accelerated partial breast irradiation (APBI) is a radiotherapy technique utilized for patients having post-surgical cavities after lumpectomy [8]. This method involves targeting tiny regions surrounding the tumor, typically ranging from 1 to 2 cm of healthy tissue. This range has been accepted to include possible setup errors and patient's respiratory motion. By utilizing APBI instead of whole-breast radiation therapy, the treatment volume is reduced, thereby minimizing radiation exposure to healthy tissue surrounding the area [31]. This focused approach aims to optimize treatment outcomes while reducing potential side effects on unaffected regions of the breast.

To enhance the accuracy of treatment setup in APBI, surface imaging has been employed due to the deformable nature of breast tissue. Gierga et al. conducted a study that demonstrated the effectiveness of surface imaging for target registration in APBI [32]. Their findings indicated that a gated surface imaging approach resulted in a target registration error of 3.2 mm, which outperformed other methods such as laser-based alignment and kV imaging. However, when the surface imaging in APBI treatment setups was conducted without gating, the target registration error increased to 6.2 mm. This emphasizes the crucial role of gated acquisition in maximizing the potential reduction in margin size when utilizing surface imaging, especially in the presence of respiratory-induced motion.

Furthermore, the integration of SGRT with 2D X-ray and the use of surgical clips has shown to be precise in patient alignment and setup verification method, eliminating the requirement for skin-based tattoos [13]. If the post-surgical cavities are present without surgical clips SGRT can still be beneficial, especially when there is minimal variation of less than 10% in these areas [33].

4.7. *Surface-guided 4D-CT*

The use of surface guidance for four-dimensional computed tomography (4D-CT) and fraction delivery has been found to demonstrate promising temporal consistency and accuracy when compared to the Varian RPM system for tracking displacements [34, 35]. Kauweloa et al. reported that when using surface-guided 4D-CT, the tracking of the mean-position resulted in higher uncertainty as the amplitude of the respiratory motion decreased [34]. This indicates that SGRT could be more promising in phase-sorting than used for amplitude-sorting, when using 4D-CT acquisitions. Additionally, SGRT has shown promising outcomes in monitoring and managing respiratory motion, as evidenced by its strong correlation with x-ray imaging-based internal target position monitoring [36].

5. FUTURE APPLICATIONS

Surface imaging has exhibited promising potential in the field of radiation therapy, raising the possibility of replacing conventional patient setup methods. Recent research indicates that skin marks and patient setup methods reliant on 3-point localization could potentially be substituted with a purely surface-guided radiotherapy (SGRT) approach [13]. While SGRT may not entirely replace x-ray imaging for target localization, it has the potential to minimize or eliminate the need for x-ray setup imaging in specific treatment areas if a correlation can be established between external surfaces and internal structures. In most cases, SGRT is expected to be utilized as a complementary component. Nevertheless, further research is necessary to assess the accuracy and effectiveness of surface imaging in deducing the internal target position by comparing external topography to a reference surface.

5.1. *Biometric patient identification*

Advancements in computing power lead the way for higher-resolution surface imaging, enabling the capture of more detailed patient topography. Beyond patient setup, clinics are implementing biometric patient identification systems that utilize body surface or facial recognition to optimize workflows and enhance patient safety [37]. With improved rigid and deformable registration algorithms, automatic detection of weight variances or changes in tumor size can be achieved without the need for weekly CBCT scans [2]. The continuous position data acquired through surface imaging offers valuable information about position uncertainty, which can be helpful in determining target margins and potentially facilitate adaptive therapy. Moreover, this motion data can contribute to population studies and validate strategies for calculating target expansions in the presence of random and systematic errors.

5.2. *Scene mapping*

SGRT is characterized by its non-ionizing nature that offers a larger FOV than other IGRT systems. This expanded FOV allows SGRT to capture a comprehensive 3D surface image of the treatment room, facilitating the generation of additional 3D information through scene mapping techniques [1]. Moreover, the FOV of SGRT proves advantageous when addressing the limitations of CT scanning. CT scanners possess a restricted FOV, which can result in truncated or inaccurately reconstructed external structures. In such cases, SGRT can complement the missing information by importing the surface scan into the treatment planning system, provided an interface for such importation exists. This integration of SGRT data can help enhance the overall accuracy and completeness of treatment planning and delivery.

SGRT presents a distinctive approach for Total Body Irradiation (TBI) that eliminates the need for CT scanning [1]. In conventional TBI treatment planning, patient dimensions are manually measured at a few locations to generate a treatment plan. However, SGRT offers the advantage of acquiring continuous contour measurements using optical cameras, which can be converted into a DICOM structure. Importing these accurate and reproducible measurements into a TPS enables more precise dose calculations for TBI. Furthermore, SGRT allows for continuous monitoring of the patient's overall position throughout the treatment session, which can extend for an hour or more, particularly when higher doses are prescribed or when lung block placement necessitates multiple iterations. For TBI treatments implemented at an extended distance, additional optical cameras placed strategically to avoid occlusion by the scatter shield are required. SGRT also demonstrates potential for isocentric TBI treatments, such as intensity-modulated total marrow irradiation, which typically involve multiple isocenters on a LINAC [38]. Presently, there is no imaging method available to correct the positioning of the entire patient, and the verification of isocenters is performed through an iterative and time-consuming process.

5.3. *Augmented reality*

Augmented reality (AR) combines virtual objects with the real-world environment, resulting in an enhanced perception of both realms [1]. The integration of AR has the potential to significantly improve treatment accuracy, enhance patient safety, and optimize workflow efficiency. One notable application of AR is the ability to superimpose virtual representations of immobilization devices onto patients during treatment setup, effectively mitigating the risk of human error. An example of this can be seen in Figure 5, where an SGRT system projects colors onto patients to provide guidance during setup. Moreover, AR can be utilized to display relevant information derived from DICOM data, such as the cross section between the beam and the patient's reference surface, facilitating the verification of accurate treatment field positioning. Additionally, AR can project target volume contours and structures onto the patient's surface, providing clinicians with additional visual guidance during setup. AR holds great promise in the field of radiation therapy by leveraging advanced visualization techniques to enhance treatment precision and improve overall patient care.

5.4. *Adaptive radiotherapy*

SGRT holds significant potential in adaptive planning, particularly in the context of particle therapy, where subtle changes in patient anatomy and position, like weight fluctuations or inflammation, can have a profound impact on dosimetry due to the sensitivity of particle range to these alterations [2, 39]. The utilization of SGRT in particle therapy is expected to expand, encompassing aspects such as machine-specific and patient-specific quality assurance (QA). In proton therapy systems, maintaining mechanical and radiation isocentricity is crucial, often relying on complex algorithms to adjust the

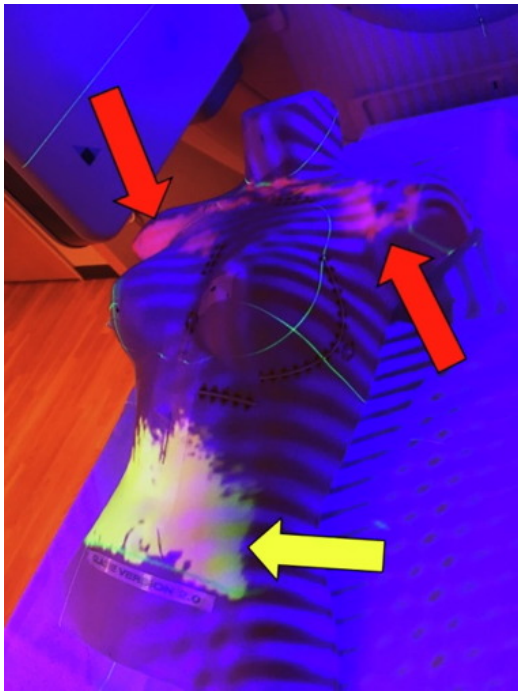


Fig. 5: AR based visualisation using a color map projected onto the phantom. The arrows point to red and yellow areas indicating placement mismatches [1].

couch position to compensate for gantry sagging, which varies for different treatment angles due to the substantial weight of the gantry. An SGRT system with precise calibration, in combination with an adequate QA plan, can serve as a valuable additional verification method for confirming the position of the couch. Furthermore, in the context of photon beam radiotherapy, it can autonomously validate the accuracy of gantry and couch positions. By incorporating SGRT into these QA processes, an additional layer of assurance can be established to enhance treatment precision and safety in particle and photon therapies alike.

The advancement of specialized treatment systems for adaptive radiotherapy (ART), like the MR-linacs, gives SGRT the opportunity to state a key limitation in ART workflows: the time-consuming nature of adaptive planning [1, 40]. The fundamental principle of ART involves generating a treatment plan on the same day when adaptation is required. This process involves multiple steps, including system quality assurance and updating the contouring, evaluation and optimization, during which the patient must remain in the treatment position for an extended duration. SGRT offers a suitable technique to monitor and track the patient's position in real-time, without exposing the patient to additional imaging dose. In some adaptive treatment systems, there may be limitations on the degrees of freedom for the couch configuration, restricting the applicability of adjustments in all directions. By employing precise patient positioning through SGRT, the frequency of re-positioning can be reduced, minimizing the use of complex ART interventions to events where actual fluctuations in internal anatomy occur.

6. LIMITATIONS

SGRT systems have certain limitations that must be taken into consideration. One of the main limitations is that the patient's skin surface must be visible for the surface imaging system to work effectively [8]. This implies that when selecting an immobilization technology, it is crucial to find a suitable balance between the ability to capture surface images effectively and the level of immobilization provided. Furthermore, it is important to consider the impact of items like pieces of cloth with low reflectivity and poor reproducibility, as they can negatively affect the accuracy of surface imaging. Additionally, the surface imaging system should not be obstructed by equipment such as imaging arms, the gantry itself, or other objects within the room.

Real-time generation and registration of a patient surface map pose significant computational demands [41]. With the current capabilities of computer processing hardware, there exists a trade-off among the resolution of the displayed surface, the size of the monitored region, and the refresh rate necessary to detect motion in a given application. For example, in intracranial treatment scenarios, a high-resolution surface is essential for precise detection of submillimeter motion, although lower refresh rates are acceptable. Conversely, breathing monitoring applications require a larger surface, which can have a lower resolution, but faster refresh rates are necessary to ensure accurate tracking of larger and faster surface displacements.

Furthermore, despite the capability of clinical systems to acquire real-time images for reconstructing 3D surfaces [1], most systems only offer a simplified quantitative output in the form of a 6 DOF translational/rotational shift. This simplified output aims to facilitate user interpretation by resembling the output of CBCT systems and presents one correction recommendation at a time. However, by condensing the 3D data into a set of integers, important information is lost in the process. Users are aware that relying solely on a single set of registration parameters to summarize a patient's condition is insufficient, and inconsistencies between CBCT and SGRT outputs can undermine confidence in the system. Thus, it is vital to find a delicate equilibrium between the imperative of avoiding information overload and the capacity to leverage the abundant data gathered through SGRT.

Additionally, it is important to acknowledge that surface imaging has a limitation in that the correlation between the external surface and internal structures may not be sufficient for precise target localization [8]. Hence, in-room x-ray imaging systems are still necessary for accurate target localization, while surface imaging can still serve as a complementary tool. Lastly, when implementing surface imaging systems that utilize a CT-based reference surface, it is crucial to be aware of the potential disparities between the CT-generated patient surface and the surface images created by the optical systems. To ensure accuracy, reference surfaces should be thoroughly reviewed necessary for a demanding surface imaging quality assurance (QA) program.

6.1. Quality assurance

The implementation of SGRT in radiotherapy workflows introduces new challenges that need an adequate QA program including risk management to ensure safe clinical use [42]. According to international guidelines, it is recommended to conduct a risk assessment analysis for novel techniques or changes in workflow. This analysis aims to identify potential failure events and their underlying causes, encompassing various aspects such as action thresholds, technical parameters, documentation, protocols, and decision-making processes. [43]. The clinical implementation of SGRT may add new sources of risk, such as mechanical failures, inefficient workflows, or insufficient training [4, 44]. Risk analysis is a department-specific process, and certain sources of risk may present challenges in terms of identification and mitigation.

Despite the encountered challenges, the integration of SGRT with the linear accelerator provides an additional layer of safety in the clinical setting [11]. SGRT has the potential to lower the amount of human errors and decision-making, enhance the detection of failure events, and promote workflow standardization [44]. The latest SGRT systems offer improved frame rates, enabling treatment during free-breathing. However, this necessitates the inclusion of gating response times, gating window, and linear accelerator configurations in the QA program [45].

7. DISCUSSION

SGRT is an imaging technique that utilizes real-time 3D surface imaging to guide radiotherapy procedures. By employing optical surface scanning, SGRT enables accurate patient positioning, intra-fraction motion monitoring, and the implementation of respiratory gating techniques. This modality has garnered significant attention due to its potential to deliver more precise radiation to the target while minimizing damage to healthy tissue. SGRT offers several advantages, including real-time online information of the entire patient surface within the treatment room, continuous monitoring of patient positioning, workflow standardization, and reduced treatment time per fraction. It serves as a valuable complementary tool to conventional image-guided CBCT and can be seamlessly integrated into most radiotherapy treatment units. The implementation of SGRT enhances the overall accuracy, safety, and effectiveness of radiotherapy for all patients.

SGRT provides comparable or improved accuracy to 3-point localization for patient positioning, with accuracy varying based on the anatomical site. SGRT has an extended field-of-view that enables correction of patient position, leading to improved treatment posture. It also increases positioning efficiency compared to traditional laser- or x-ray-based methods, saving time when positioning patients for treatment.

However, SGRT approaches have certain limitations that must be taken into consideration. The patient's skin surface must be visible to the system for surface imaging to work effectively, and the system must not be obstructed by the gantry or other components in the treatment room. Furthermore, the relationship between the external surface and internal anatomy may not always be sufficient to fully localize the target. Therefore, in-room radiographic imaging systems are still necessary for target localization, and surface imaging will serve as a complement.

Personally, I would recommend the use of SGRT due to its ability to provide imaging without dose, real-time feedback, and high spatial resolution in 3D. It can also be integrated with other radiation techniques, such as linear accelerators, to function as a complementary tool to ensure patient comfort and safety. Nevertheless, it should be noted that acquiring these systems can be expensive. For instance, the AlignRT system costs between £150,000 to £225,000 (excluding VAT) [46], in addition to the yearly service charge of £20,000. Furthermore, SGRT systems must adhere to valid QA regulations to ensure risk management and treatment accuracy.

Nevertheless, the MR-linac offers comparable advantages to SGRT without relying on continuous visibility of the patient surface. The planning system associated with the MR-linac is recognized for being time-consuming, but it offers enhanced accuracy in identifying soft-tissue contrast compared to SGRT. It should be noted, that MR-linacs have a considerably higher price range, costing millions of dollars, and are considerably more expensive than SGRT systems.

For future applications, SGRT could be a promising complementary tool in combination with novel radiation techniques to increase patient safety and comfort.

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