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AAPM task group report 302: Surface-guided radiotherapy

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Abstract

The clinical use of surface imaging has increased dramatically, with demonstrated utility for initial patient positioning, real-time motion monitoring, and beam gating in a variety of anatomical sites. The Therapy Physics Subcommittee and the Imaging for Treatment Verification Working Group of the American Association of Physicists in Medicine commissioned Task Group 302 to review the current clinical uses of surface imaging and emerging clinical applications. The specific charge of this task group was to provide technical guidelines for clinical indications of use for general positioning, breast deep-inspiration breath hold treatment, and frameless stereotactic radiosurgery. Additionally, the task group was charged with providing commissioning and on-going quality assurance (QA) requirements for surface-guided radiation therapy (SGRT) as part of a comprehensive QA program including risk assessment. Workflow considerations for other anatomic sites and for computed tomography simulation, including motion management, are also discussed. Finally, developing clinical applications, such as stereotactic body radiotherapy (SBRT) or proton radiotherapy, are presented. The recommendations made in this report, which are summarized at the end of the report, are applicable to all video-based SGRT systems available at the time of writing.

KEYWORDS
deep inspiration breath hold, frameless radiosurgery, risk assessment, surface guided radiotherapy

1 | INTRODUCTION

Surface imaging has been readily adopted by the radiotherapy (RT) community as a unique tool in the image-guided radiation therapy (IGRT) toolbox. Surface imaging reconstructs the three-dimensional (3D) surface of the patient in real time using optical imaging without the need for external markers. Its main advantage is that it is nonionizing. Since surface imaging does not add dose to the patient, it can, therefore, be used on a daily basis for initial positioning, continuous monitoring of intrafractional motion, and interfacing with linac control systems to interrupt the radiation beam when thresholds of motion are exceeded.

1.1 | Purpose and rationale

The use of surface guided radiation therapy (SGRT) has rapidly increased since the publication of AAPM Report TG-147 for various indications, including frameless stereotactic radiosurgery (SRS), deep-inspiration breath hold (DIBH) for breast radiation therapy treatment, initial positioning of extremities or breast, and general treatment surveillance. In 2016, when this task group was initiated, there were about 800 installations in clinical use worldwide. By December 2019, this number had increased to almost 2000. As more clinics acquire SGRT and incorporate it into their daily routine, recommendations on acceptance, commissioning, clinical implementation, and clinical applications are needed. To date, there are no specific consensus recommendations for the clinical implementation and best practice of SGRT. In this task group report, we review currently available commercial SGRT systems and provide guidance on the technical aspects of clinical use based on published experience and consensus opinion. A summary for acceptance, commissioning, and on-going quality assurance (QA) specific to SGRT, as well as an example of risk assessment for an SGRT program, are provided to help to standardize implementation. While AAPM TG-147[1] introduced the general concepts related to clinical use and QA of nonradiographic IGRT systems, including SGRT, this report provides specific details about the clinical utility and applications of this technology. In addition, the QA recommendations are framed from the perspective of risk analysis, with guidance on how to incorporate risk assessment using TG-100[2] techniques into an SGRT program. Finally, a discussion of emerging clinical applications of SGRT is provided along with associated QA implications.

1.2 | Goals

While surface imaging may provide high spatial and temporal accuracy for surface tracking on a phantom, clinical conditions may affect the accuracy of an SGRT system. The goal of this report is to provide the medical physics community with a foundational understanding of SGRT that is needed to successfully implement this technology for a variety of clinical applications. Considerations, such as the effect of patient positioning or immobilization and how to troubleshoot technical challenges, such as the effect of image quality degradation on SGRT results, are discussed to help users avoid common pitfalls that may impact SGRT results. The charges of the Task Group were to:

1. Review the current use of nonionizing surface imaging functionality and commercially available systems.
2. Summarize commissioning and on-going quality assurance (QA) requirements of surface image-guided systems, including implementation of risk or hazard assessment of surface-guided radiotherapy as a part of a total quality management program (e.g., TG-100).
3. Provide clinically relevant technical guidelines that include recommendations for the use of SGRT for general patient positioning, deep-inspiration breath hold (DIBH) for breast cancer, and frameless brain stereotactic radiosurgery (SRS) including potential pitfalls to avoid when implementing this technology.
4. Discuss emerging clinical applications of SGRT and associated QA implications based on the evaluation of technology and risk assessment.

1.3 | Scope

This report discusses QA specific to SGRT and clinical implementation for three common clinical tasks: general positioning of patients, DIBH breast cancer treatment, and frameless SRS. The QA recommendations expand and complement the purpose of TG-147, which provided a review of QA guidelines for all nonradiographic modalities including surface imaging. The report addresses workflow issues specific to SGRT that are independent of its commercial implementations.

Disclaimer: The recommendations of this task group should not be used to establish regulations. These recommendations are guidelines for Qualified Medical Physicists (QMPs) and others to use and appropriately interpret for their individual institution and clinical setting. Each institution may have site-specific or state-mandated needs and requirements which may modify its usage of these recommendations.

1.4 | Limitations of this report

Although published data have been used to develop the recommendations in the report, a complete literature review is beyond its scope. A comprehensive review

of the literature can be found in AAPM 2018 Summer School Chapters 12 and 13[3,4] and other resources.[5–7] While in-house systems will be mentioned if published, results pertaining to these systems have not been included in the report, as there has not been sufficient validation by the community. *Because SGRT is an evolving technology, commercial systems that have received FDA approval as of December 2017 are included in the report. Systems that received FDA approval within 2 years of the initiation of this report (i.e., 2018–2019) may be mentioned but are out of the current scope for the reasons stated above*. Vendor acceptance and commissioning tests are not included although they might be similar to some of the recommendations provided in this report. Clinical accuracy cannot be quantified in this report because it depends on the specific implementation of SGRT. As such, the QMP is responsible for providing guidance to the clinical (i.e., physicians) and treatment (i.e., radiation technologists) teams, about the performance of the system. This will require the QMP to interpret the recommendations in this report to select those that are applicable to their particular SGRT system and workflow. Because the technology is evolving and the workflow choices affect overall clinical accuracy, the QMP must continuously assess the performance and communicate any changes to the clinical and treatment teams.

2 | BACKGROUND

SGRT systems use optical imaging to register real-time (i.e., >1 frame/s) 3D surfaces of a patient to a reference surface. Because the reference surface is defined relative to the treatment isocenter, the algorithms calculate the translations and rotations in 6 degrees-of-freedom (6DOF) necessary to correct the patient's position in real time. For anatomical sites in which the patient's surface is a good surrogate for the RT target, such as breast and the brain, surface imaging has been rapidly integrated into clinical practice due to its high temporal and spatial accuracy.[3–5,8] In general, SGRT is used in conjunction with radiographic 2D or 3D imaging modalities, with increasing frequency especially for deep-seated targets.[8] Since the accuracy of SGRT depends on both the hardware or software specifications, in addition to the clinical considerations listed in Section 4, the technical evolution of SGRT systems into current commercial products is reviewed.

2.1 | Evolution of SGRT systems

SGRT evolved during the pre-IGRT era when there was a need to triangulate the patient in 3D in the treatment room for daily positioning. Early systems paired the ability to perform 3D localization from 2D images[1,3] with noninvasive video- and laser-based technology. The imaging principle used is stereophotogrammetry, which utilizes 2D images and the known spatial geometry at which they were acquired to triangulate the 3D coordinates of the imaged object.[9] To succeed, object features must be visible on multiple 2D images that have been acquired at various geometries. In certain commercial SGRT systems, the image features are generated when a structured light pattern is projected onto the patient's surface and the reflected light is subsequently detected in the 2D image. The distortion of the structured light pattern by the 3D objects allows for its reconstruction. In other commercial SGRT systems, 3D lasers are used to scan the patient's surface and the deformation of the laser line can be used to reconstruct the object.[10] Here, the early predecessors to SGRT systems and in-house systems as well as current commercial systems are summarized.

2.1.1 | Predecessors to SGRT systems

The need for reliable, real-time positioning prompted the clinical use of video positioning by early investigators. A 2D video cancellation system was proposed at the University of Arizona in 1979.[11] Such a system was clinically implemented at the University of Chicago for initial positioning and motion monitoring of head and neck patients, reducing setup errors to 1–3 mm as quantified by MV imaging.[12,13] Ploeger et al. combined the use of real-time video images with a reference surface rendered from a CT simulation scan in prostate patients and demonstrated an improvement in lateral patient positioning compared to lasers alone.[14]

2.1.2 | In-house SGRT systems

Following this promising early experience with real-time imaging, a number of surface imaging systems were developed in-house. Some were developed using stereoscopic cameras and applied to breast cancer RT[15,16] or frameless SRS[17] while others utilized scanning lasers that could reconstruct the surface by measuring the reflected light and transforming this into a depth measurement using appropriate calibration.[18] More recently, the availability of motion-detecting depth cameras for video gaming systems (e.g., Microsoft Kinect) incited a renewed interest in the development of in-house systems for patient positioning,[19] motion monitoring,[19] collision avoidance,[20–22] and biometric applications.[23,24]

2.1.3 | Commercial systems

As of 2019, there are three commercial vendors providing clinical SGRT solutions (see Table 1). Note that the Vision RT technology, AlignRT, was rebranded as

TABLE 1 General overview of commercially available SGRT systems as of October 2019

System (Vendor)	Treatment unit[#] hardware	CT Simulator system (vendor)	Patient identification	Patient biofeedback	Patient positioning Corrections
AlignRT (Vision RT)	1 to 3 cameras units (~90° apart)	GateCT (Vision RT)	Infrared facial recognition	Visual (Real-time coach)	6D
Catalyst (C-RAD)	1 to 3 cameras units (120° apart)	Sentinel* 4DCT (C-RAD)	Facial recognition	Audio & visual (Goggles)	6D
IDENTIFY (Varian)	3 cameras units (~90° apart)	IDENTIFY CT (Varian)	Palm reader	Visual coaching module	6D

[#]Each unit may contain more than one camera.
*Uses laser scanning technology.

Optical Surface Monitoring System (OSMS) and was sold by Varian as an integrated solution with their TrueBeam linacs from 2012 to 2019. In August of 2018, Varian acquired HumediQ, whose technology will be sold as an integrated solution with their linacs in place of OSMS beginning in 2019.

2.1.4 | Emerging commercial systems

The landscape of surface imaging solutions is expected to continue to change rapidly as demand for the technology increases. This may be due in part to the low entry cost associated with developing in-house solutions. Recently, a breath hold coaching solution has entered the market following FDA approval in 2018: BreatheWell (Opus Medical, Eveleigh NSW, Australia). This system is in use at several US institutions. In 2019, Brainlab incorporated thermal imaging with optical imaging for motion tracking and FDA clearance is pending as of October 2019.

2.2 | Summary of surface imaging theory and applications

Optical imaging systems use various technologies to reconstruct 3D surfaces: laser scanning,[18] time-of-flight,[25] stereovision,[9] and structured light imaging.[26] Current commercial SGRT monitoring systems project either a pseudo-random speckled light pattern, which relies on stereophotogrammetry as summarized in AAPM TG-147 and Section 2.1, or a known structured light pattern to reconstruct the camera-detected images into a 3D surface.[1] Stereovision employs two cameras to reconstruct the 3D surface using an *unknown* speckled light pattern to aid the triangulation process. A single camera is sufficient to reconstruct a *known* structured light pattern. In practice, multiple camera units are utilized for SGRT systems to maximize the field-of-view (FOV), reduce the effects of self-occlusion by the patient, and to include more features and surface gradients to improve the registration accuracy. This surface is then registered to a reference surface in 6DOF, enabling calculation of three translational and three rotational shifts required to match the two surfaces. SGRT systems use either a rigid or deformable algorithm for registration.[3] Rigid algorithms perform an iterative closest-point match between the two surfaces and are typically restricted to a user-defined region-of-interest (ROI). While deformable algorithms use the entire surface area for registration, the location of the isocenter is given more weight and a depth correction is performed to provide the final registration result.[27] Ideally, the entire imaging/reconstruction/registration chain occurs at a sufficiently fast frame rate to enable real-time imaging. Commercial systems postprocess the images acquired to achieve real-time imaging. As such, the frame rates are lower than those native to the camera hardware. In addition, they use proprietary algorithms for registering the real-time surface to the reference. Thus, the technical specifications of each system vary, as summarized in Section 2.2.1. The impact of both the technical specifications and registration algorithm used by each vendor on overall accuracy should be understood by the QMP, particularly when it comes to identifying the potential clinical limitations.

2.2.1 | Tables summarizing imaging hardware, algorithms, and technical specifications

General details of commercial systems are provided in Tables 1, 2, and 3. Single camera installations may be used in either CT simulator rooms or in treatment rooms, particularly for closed-bore treatment units.[28] Compared to multicamera systems, single-camera systems have a smaller FOV and are more susceptible to self-occlusion by the patient. Thus, for noncoplanar treatment, a multicamera system should be used. Some commercial SGRT systems offer a long FOV to enable other capabilities such as orthopedic alignment. The data in Tables 2 and 3 only include the specifications of the SGRT tracking capabilities. Since the SGRT market is rapidly changing, this information is provided as of June 2019 only for

TABLE 2 Performance overview of commercially available SGRT monitoring systems as of October 2019

System (Vendor)	Optical technology	Camera size (W × H × D); Weight	Field-of-view* (Lat × Long × Vert)	Camera resolution	Frame rate	Positioning accuracy#	Registration algorithm
AlignRT (Vision RT)	Stereovision using a speckle pattern	430 × 66 × 186 mm; 4.5 kg	650 × 1000 × 350 mm^3	2048 × 2048 px (4MP)	4-24 fps	<1.0 mm <1.0°	Rigid
Catalyst (C-RAD)	Structured light imaging	620 × 390 × 280 mm; 16 kg	1100 × 1400 × 2400 mm^3	640 × 480 px (0.3 MP)	8-24 fps	<1.0 mm <1.0°	Deformable[27]
IDENTIFY (Varian)	Stereovision using a speckle pattern	500 × 80 × 182 mm; 3.3 kg	500 × 500 × 400 mm^3	1280 × 1024 px (1.3 MP)	10 fps	<1.0 mm <1.0°	Rigid

*FOV is specified for three-camera systems for SGRT tracking functionality only and defined relative to couch coordinates at the nominal position (Lat = Lateral, Long = Longitudinal, Vert = Vertical).
#Assessed in-phantom.
fps, frames per second; px, pixel.

TABLE 3 Overview of the interface capabilities with known vendors of commercially available SGRT monitoring systems as of October 2019

	CT Simulator interfaces		Photon treatment unit interfaces		Proton treatment unit interfaces	
System (Vendor)	Capability^	Vendor	Capability	Vendor	Capability	Vendor
AlignRT (Vision RT)	Prospective & retrospective acquisition	Philips Siemens GE Cannon	Automatic patient selection, beam-hold ability, couch shift ability	Varian (TrueBeam/C-series) Elekta Siemens#	Beam hold	IBA Hitachi
Catalyst (C-RAD)	Prospective & retrospective acquisition*	Philips Siemens GE Cannon	Automatic patient selection, beam-hold ability, couch shift ability	Varian (TrueBeam/C-Series) Elekta Siemens#	Beam hold	IBA Mevion
IDENTIFY (Varian)	Prospective & retrospective acquisition through marker-based tracking**	Philips Siemens GE	Automatic patient selection and record of treatment/simulation session from/to OIS	OIS-based: Varian (ARIA) Elekta (MOSAIQ)	Works in Progress	Works in Progress

^See Section 4.5 for more details.
#Couch shift not available.
*Supported by Sentinel SGRT system (C-RAD).
**Supported by Respiratory Gating for Scanners (RGSC).
OIS, Oncology Information System.

vendors with FDA-approved products as of 2017 (see Section 1.4). Due to the rapidly changing technological landscape, the latest information should be gathered directly from the vendors.

2.2.2 | Limitations of imaging and registration capabilities

SGRT systems have certain technical limitations such as a finite FOV and an inability to image very dark skin tones. There are also registration accuracy limitations which could manifest as the target-to-surface displacement increases (e.g., deep-seated tumors) or when the real-time surface is significantly deformed compared to the reference (e.g., breast swelling). Some of these limitations are a function of the hardware (e.g., number and location of cameras) and are not modifiable. Other limitations would only manifest intermittently for certain patients and treatment tasks. The QMPs play an important role in reducing the static limitations as much as possible while serving as a resource for troubleshooting the limitations that may manifest intermittently.

While the nominal FOV is listed in Table 2, it is possible to select alternate positions for the in-room cameras to shift the center of the FOV. In general, the FOV should be optimized to accommodate current and future clinical applications and should be measured during acceptance with input from the QMP. Furthermore, the nominal FOV does not account for the effects of camera occlusion by the treatment head or imaging panels, which can render large areas of the surface invisible in selected clinical situations. While some SGRT systems attempt to alert the user when a significant proportion of the tracked region is missing, these alerts should not

be relied upon exclusively. It is the responsibility of the QMPs to be able to identify these cases.

Rendering of a 3D surface requires that the projected light pattern is reflected from the patient's surface and is detectable by the cameras. To account for the wide range of skin tones encountered in the clinic, SGRT systems have settings related to specific inherent camera properties such as the exposure, integration time, or camera gain.[3] In some SGRT systems, the user can select from a few settings predefined by the vendor, whereas for other systems, these settings can be manipulated directly by the QMP. When camera hardware limitations are encountered and the reflected light signal can no longer be amplified enough to be detected (i.e., the exposure time limit has been reached), which occurs for very dark skin tones, the surface rendered will have missing regions that cannot be reconstructed. Thus, the QMP should be involved in determining these exposure settings during acceptance and as warranted during clinical use of the system based upon knowledge of the institution-specific patient population. Note that, in some cases, the camera apertures can be physically adjusted by a field service engineer to minimize this effect, and it is the responsibility of the QMP to discuss this with the SGRT system vendor. Moreover, the QMP must be prepared to identify this issue in a clinical setting and to proceed with appropriate troubleshooting steps (see Section 4.7.2). Mitigation strategies include enabling per-patient customization of these settings, alerting the user to missing regions, and potentially combining thermal imaging with surface imaging as implemented in the Brainlab ExacTrac Dynamic system.

Because SGRT relies on tracking the patient's surface, the accuracy for inferring the location of the internal target is degraded when the surface is not a good surrogate for the target, or when the surface is not visible to the cameras. The reliability of the surface for target position must be determined by the QMP and clinical or treatment teams because the validity of the surface as a surrogate is task-dependent as well as patient-specific. For a detailed discussion of these surrogacy issues across anatomic sites, see Al-Hallaq et al.[4] As such, the QMP and clinical/treatment teams should be trained to identify situations in which this surrogacy is invalidated (e.g., significant anatomical changes, such as breast swelling, or when internal motion is not correlated to the surface). Since the QMP will generally be involved in troubleshooting (see Section 4.7.5), it is important for the QMP to liaise with the vendor's clinical service team if limitations to the equipment or algorithms are discovered and to convey this to the treatment team. In general, it is prudent to build clinical experience in sites in which the surface is a good surrogate for the target (e.g., breast or brain). The clinical and treatment teams must also be prepared to modify immobilization or account for other devices that may obstruct the patient's surface (see Sections 4.6.1 and 4.6.2). Finally, the QMP and clinical/treatment teams should be prepared to recognize when the registration accuracy has been compromised due to significant deformation of the surface (see Section 4.7.2). Different registration algorithms (e.g., deformable versus rigid) may behave differently in this regard.

3 | COMMISSIONING AND QA IMPLICATIONS FOR SGRT

3.1 | Brief summary of TG-147 recommendations for SGRT

The AAPM Task Group 147[1] was formed to review nonradiographic technologies used for localization and tracking in RT and to provide recommendations about QA, acceptance, and commissioning of such systems. Nonradiographic technologies reviewed in TG-147 include radiofrequency, infrared, laser, and video-based patient localization and monitoring systems, and therefore, apply to SGRT. TG-147 reiterates the goal of a combined accuracy of less than 2 mm, following TG-142,[30] or 1 mm whenever SRS/stereotactic body RT (SBRT) procedures are planned.

According to TG-147, accuracy checks of the linac should follow TG-142 and the vendor's acceptance test for the treatment delivery system. For any subsystem (lasers, light field, etc.) that is used to define the isocenter of the peripheral system, its accuracy should be established before installation of the nonradiographic system and checked at the recommended TG-142 frequency as a minimum or more frequently if determined necessary by the QMP. The main recommendations of TG-147, which directly apply to SGRT, are summarized below:

- *Acceptance*: Localization accuracy and reproducibility should be checked following vendor guidelines and TG-142. Safe operation and proper functionality of the treatment unit interface should be demonstrated. See Table 4.
- *Commissioning*: Data transfer between simulation, planning, and treatment delivery systems should be checked. The localization FOV should be measured, end-to-end tests in a phantom should be performed, and dose measurements with and without the localization system should be acquired to verify that delivered dose is within 1% and localization is within 1 mm. Stability of the camera system (e.g., thermal drift when cameras are first enabled) and reproducibility tests (e.g., once system has achieved stability) should be performed. Localization accuracy, both static and dynamic (e.g., for real-time tracking), and temporal response tests should be performed. See Table 4.

TABLE 4 Summary of tests outlined in Section III.B. of AAPM's Task Group 147 for commissioning an SGRT system

Test category	Description	Tolerance
Interface with peripheral systems	• Integrity of data transferred from CT simulation, TPS, R&V systems for a variety of patient orientations to test coordinate systems • Confirm isocenter coordinate transfers accurately into SGRT system using a phantom • Beam delivery functionality (with/without gating) • CT triggering functionality for prospective/retrospective gating • Couch shift functionality	Passing/functional
Spatial drift and reproducibility	• Characterize warm-up period necessary prior to clinical use • Localization accuracy for a 90-min period or until stability is achieved[48]	• NA • ≤2 mm over 1 h; ≤1 mm after stabilizing
Static localization accuracy	• Localization accuracy of offset phantom over a reasonable clinical range (i.e., ±100 mm range from isocenter)	≤2 mm ≤1 mm for SRS/SBRT
Dynamic localization accuracy	• 4D spatial localization accuracy • Frame rate characterization for clinically reasonable scenarios • Latency threshold (may depend on clinical workflow)	• per TG-142 • per spec. • within 100 ms of expected value
Camera system characteristics	• Camera exposure settings are appropriate for a variety of skin tones • Measure localization FOV • Characterization of camera occlusion for variety of clinical scenarios (e.g., couch/gantry angles)	• NA • per spec. • NA
Imaging	• Isocenter coincidence with all imaging modalities that will be used in complement with SGRT	≤2 mm ≤1 mm for SRS/SBRT
End-to-end	• Characterization of localization and monitoring accuracy from CT to dose delivery including beam hold if available • Winston-Lutz including SGRT for SRS applications	• ≤1% dose change; ≤2% dose change for beam hold • <1 mm
Standard Operating Procedures	• Should include training guidelines for new personnel (either new to the department or new to the technology) • Should include intended use of the SGRT system, case-types, etc. • Should be updated as experience and technology evolves	Existing/Available

FOV, field-of-view; R&V, record and verify; SRS, stereotactic radiosurgery; SBRT, stereotactic body radiotherapy; TPS, treatment planning system.
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- *Periodic quality assurance*: In addition to vendor recommended tests, TG-147 recommends the following tests: safety and static localization (daily); safety and static localization using a hidden target test (monthly), dynamic localization accuracy (monthly); safety, system integrity, camera stability, extended system performance, positioning accuracy, evaluation of gating or tracking capabilities, data transfer (annually). See Table 5. As recommended by TG-147, these tests should be performed by or under the supervision of a QMP. For example, daily tests are often performed by a radiation therapists and reviewed by a QMP. If any test fails, the QMP should be informed before the system is used clinically.

3.2 | Phantom selection for SGRT

Surface image quality depends on the surface to be imaged. For that reason, a critical component of the QA of SGRT systems is the selection of phantoms to be used for these tests. While other characteristics for RT phantoms, such as dosimetric capabilities, are still applicable, the characteristics that make phantoms accurately trackable with SGRT will be discussed.

3.2.1 | Color, texture, and reflectivity

SGRT systems function best with opaque/matte, light-colored surfaces that can reflect the projected light pattern. While some systems allow the user to change the exposure time to be able to capture surface information for bodies/phantoms of varying skin tone, lighter-colored phantoms yield the best monitoring results during QA. In addition, if the surface is shiny, it might create numerous reflections of the projected light pattern that will reduce the tracking accuracy. If a phantom or device is only available with dark or shiny surfaces, a paint coat or light-colored tape could be added to the surface. Styrofoam material (such as foam with expanded polystyrene beads) might not be appropriate for use with SGRT because it has an abundance of texture and the projected pattern might not be clearly identifiable. However, smooth foam that is used for the creation of block

TABLE 5 Summary of routine QA tests to be performed daily, monthly, annually as specified in Table II of AAPM's Task Group 147[1]

Frequency	Test category	Methods	Accuracy
Daily	Safety	Check interlocks and clear FOV for all mounted cameras	Pass
	Static localization	Daily QA phantom positioned at isocenter and can track movement to isocenter from offset	2 mm
Monthly (in addition to daily tests):	Safety	Machine interface: gating termination, couch motion communication	Functional
	Static localization	Localization test based on radiographic analysis (i.e., hidden target)	2 mm 1 mm for SRS/SBRT
	Dynamic localization	Motion table or manual couch motion of monthly phantom by known distances	2 mm or less as per manufacturer spec.
Annually (in addition to all monthly tests)	Safety	Test/reset buttons, backup power supply, and emergency-off switches	Pass
		System mounting brackets (all cameras are secure)	Pass
	Integrity	Check camera settings if accessible	Unchanged from previous
	Stability (drift/reproducibility)	Drift measurement (over at least 1 h)	<2 mm over 1 h
		Reproducibility of localization	<1 mm after stabilizing
	Static localization (extensive)	Complete end-to-end test (including data transfer check of localization accuracy, etc.)	<2 mm from isocenter <1 mm for SRS/SBRT
		Translation and rotation auto correct over a clinical range of motion	<2 mm from isocenter
	Dynamic (gating system)	Using a motion phantom/check of gating system radiation dosimetry accuracy.	< 2% (per TG-142)
	Data transfer	From all systems in use	Functional

FOV, field-of-view; SRS, stereotactic radiosurgery; SBRT, stereotactic body radiotherapy.

molds in many RT departments can be utilized as an inexpensive 3D surface phantom using carefully defined alignment marks.[31]

While the recommendation is to use light-colored phantoms as they yield the best monitoring results during routine QA, the effect of surface color on localization accuracy should be assessed by testing both light- and dark-toned phantoms when possible. This is particularly important for institutions where a larger proportion of patients with darker skin tones are treated.

3.2.2 | Effects on localization displacement accuracy tests

As recommended by TG-147, the localization displacement accuracy needs to be verified for any localization system over a range of displacements that covers all expected positional shifts. The main phantom property required for testing localization accuracy, in addition to the already mentioned color and reflectivity characteristics, is sufficient topography for the SGRT system. When a phantom lacks topography, as is the case for a flat board, the system cannot accurately discern position or motion. For this reason, many phantoms mimic anatomical surfaces such as the head, leg, or breast. Some phantoms that have been used for routine QA are shown in Figure 1. In the case of a cubic phantom, an ROI with enough topography, such as a corner, should be selected.

For real-time monitoring applications, such as SRS, DIBH, and SBRT, and particularly for those cases in which the beam will be automatically turned off when the SGRT parameters are out of tolerance, the user should perform additional QA with a dynamic phantom. This phantom should be used for localization accuracy tests, to check that the system latency is below a clinically applicable threshold, and to perform gating tests per TG-142. Existing motion phantoms might need to be modified to provide sufficient topography for SGRT QA.[32,33] For example, a commercial or handmade phantom satisfying the guidelines outlined above can be placed on a moving platform to generate a cyclical pattern to be tracked by the SGRT system.

3.2.3 | Other considerations of commissioning and end-to-end testing

In addition to the phantom properties mentioned above, additional properties to help characterize SGRT during end-to-end testing, are necessary including (1)

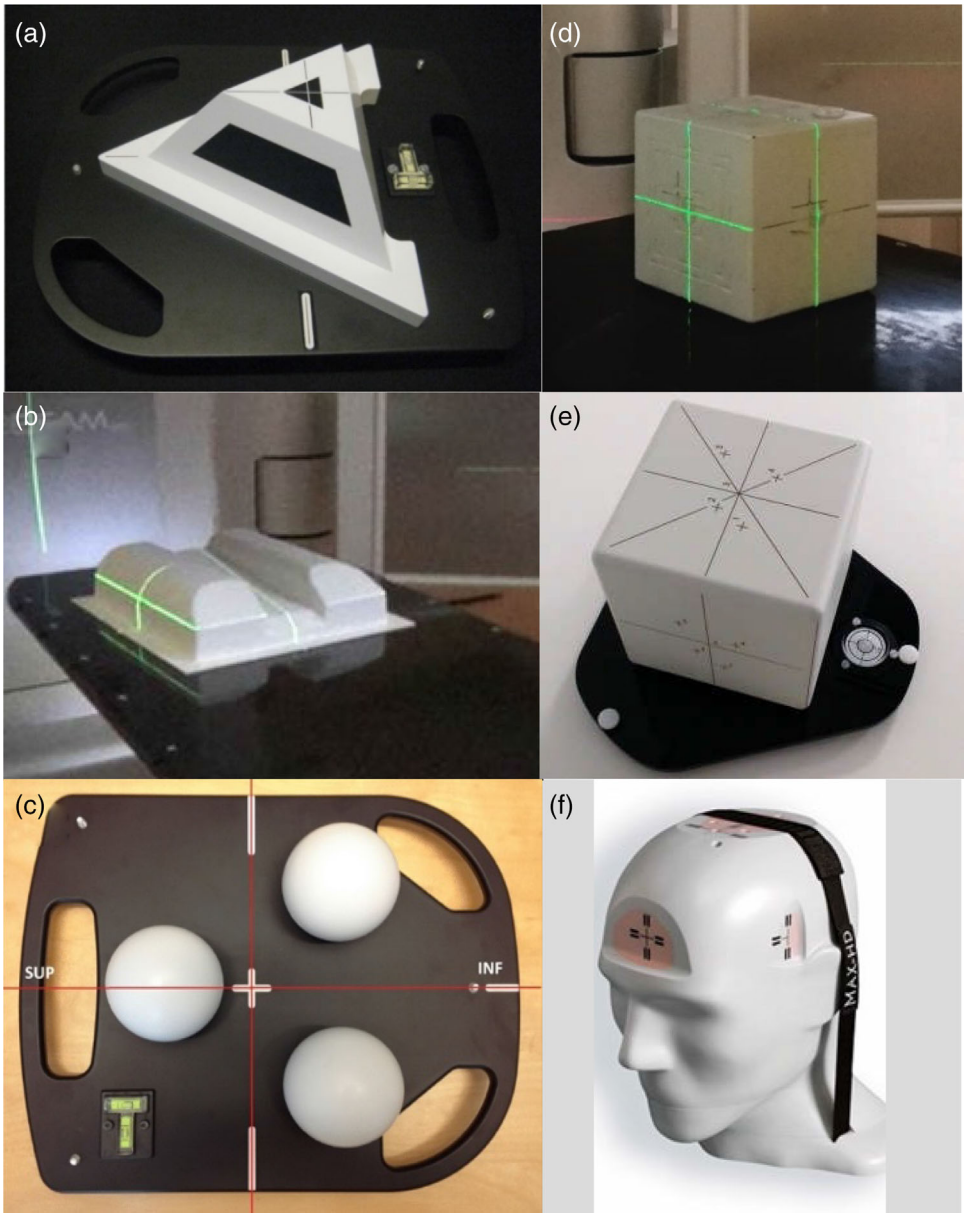

FIGURE 1 Examples of phantoms used for QA of SGRT systems: (A) Triangle phantom for daily check of the isocenter position relative the room lasers (C-rad); (B) Leg phantom (Vision RT); (C) Sphere phantom for daily check of the isocenter position relative to the room lasers (C-rad); (D) Penta-Guide Penta1 (QUASAR); (E) Cube 2.0 phantoms for routine QA and calibration of the isocenter using kV or MV imaging (Vision RT); and (F) MAX-HD SRS anthropomorphic phantom (IMT)

fixed interior fiducials for intercomparison with other IGRT modalities and (2) external fiducials to define and verify the skin contour thresholds chosen in the treatment planning system (TPS) to generate a Digital Imaging and Communications in Medicine (DICOM) reference surface for SGRT. To comply with TG-147 recommendations, some users might wish to combine a phantom with SGRT and dosimetric capabilities. However, most users perform cross-validation of SGRT against other IGRT systems that have undergone dosimetric verification. Additionally, budget considerations should be taken into account when selecting phantoms. A very comprehensive phantom with anatomy, embedded fiducials, motion, and dosimetric capabilities may exceed the budget of many clinics and may provide little advantage over other phantoms that could already provide the necessary information for the intended use.

Some phantoms will resemble the anatomy for a specific use, such as the face, leg, or breast, etc. Before testing the tracking accuracy of the SGRT system, one should evaluate the effect on surface generation and registration frequency using different ROIs with these phantoms, namely the frame rate. The system's response typically slows down as the ROI size

increases. Therefore, during commissioning and at the time of end-to-end testing, the user needs to evaluate which ROI size is the best compromise for tracking accuracy and system response for the given application.

Some SGRT systems come with a calibration plate provided by the vendor. This plate is to be used to calibrate the position of the camera system at isocenter with respect to the machine isocenter. It has been shown, however, that minor misalignments of the calibration plate with the machine isocenter can lead to erroneously predicted offsets when the couch is rotated, and that additional calibration with a phantom using MV portal imaging reduces the error.[34]

Calibration of most multiple-camera SGRT systems is a two-step process whereby the cameras are calibrated to one another and then the camera system is calibrated to the mechanical isocenter of the treatment unit. This approach implies that the mechanical isocenter is coincident with the radiation isocenter of the treatment unit, which is typically verified through a Winston–Lutz test or equivalent. Ultimately, the most accurate approach would be to calibrate the SGRT camera system directly to the radiation isocenter of the treatment unit since this circumvents any inaccuracies in the linkage between the mechanical and radiation isocenter.

3.3 | Incorporating SGRT into existing QA program including other imaging modalities

3.3.1 | Comprehensive end-to-end test to verify isocenter coincidence

End-to-end testing to verify coincidence of SGRT with other imaging modalities, such as kV or MV X-ray or cone beam CT (CBCT), and the treatment isocenter should be performed during commissioning and acceptance and after any major upgrade.[1] For clinical applications that require higher accuracy, such as SRS, this test should be performed periodically as guided by analyses such as TG-100[2] or statistical process control.[34] In such cases, SGRT can be incorporated into the Winston–Luz testing for SRS/SRT treatment.[34]

3.3.2 | Implications of temporal accuracy/latency for dynamic radiation delivery

The temporal accuracy/latency for dynamic radiation delivery (i.e., beam hold) and integration with the treatment unit, when available, may affect dosimetric accuracy.[36] Per TG-142, the SGRT system delay should be evaluated for the specific application and deemed appropriate before treatment. While direct measurement of the latency time may be challenging,[37] SGRT latency time should be confirmed to be below a clinically appropriate threshold (e.g., <1 s for breast DIBH treatment). For free-breathing (FB) gated treatment, TG-76 recommends that the total time latency be as short as possible, and not to exceed 0.5 s in any case, as prediction models cannot perform well above this time.

3.4 | QA issues unique to SGRT

3.4.1 | Effect of reference surface selection on QA test results

There can be implications of utilizing a DICOM reference surface generated from a treatment planning CT dataset versus a reference surface acquired by the SGRT system when evaluating its performance during routine QA. As camera technology and software algorithms are constantly evolving (for both SGRT and TPSs), it is necessary for the QMP to evaluate the impact of reference surface type on system latency, localization, and end-to-end testing at the time of commissioning as well as following significant software or hardware upgrades. Note that, for any given workflow, a particular type of reference surface may be most appropriate, and that it is the responsibility of the QMP to aid in the evaluation of the surface type and to guide the reference selection based on those test results when developing treatment procedures (see Section 4.1).

A systematic bias in alignment has been observed in some SGRT systems with the use of DICOM surface structures generated from CT imaging within a TPS.[38] CT voxel size and an imprecise transformation from the scanner coordinate system to the SGRT system may impact the positioning accuracy.[39] Also, the scan speed and respiratory phase affect the reference surface (see Section 3.4.3). In addition, discrepancies in surface localization may occur when image thresholding based on Hounsfield units (HU) is used for surface segmentation from the CT data. It has also been suggested that an SGRT system's intramodality registration of a captured surface to a reference surface generated by the SGRT system is likely to produce optimal accuracy, as data structure and resolution can be matched between datasets.[40–42] As SGRT technology continues to progress and higher resolution cameras can distinguish small features without excessive calculation time, small discrepancies between reference surface types may become detectable. Alternatively, as vendors work toward more seamless integration with third-party TPSs, inconsistencies may become less perceptible.

The differences in system behavior at each institution between an SGRT-generated reference surface and

TABLE 6 Advantages and disadvantages of various reference surfaces and region-of-interest sizes

		Advantages	Drawbacks
Reference Surface Type	DICOM	• Represents the treatment plan position from CT & can detect changes from it (i.e., systematic and random errors)[28]	• Conversion of HU to surface may result in bias of surface position • May contain artifacts resulting from objects on patient's surface at CT sim • Quality may be degraded by breathing motion • FOV limited to CT data
	Camera-acquired	• Large FOV • Can be acquired at a known respiratory phase	• May not match CT sim position exactly leading to systematic bias
ROI size	Large	• Represents the overall posture of patient • More likely to encompass sufficient topography for accurate registration • Less susceptible to camera obstruction	• Slower monitoring rate compared to smaller ROIs • May be less sensitive to local anatomical changes
	Small	• More likely to be representative of treatment area • Faster monitoring rate compared to large ROIs • May be more sensitive to local anatomical changes	• Less likely to encompass sufficient topography thereby resulting in reduced registration accuracy • More susceptible to camera obstruction

FOV, field-of view; HU, Hounsfield unit; ROI, region-of-interest.

those generated by a TPS from DICOM images should be investigated thoroughly to identify any systematic bias that may be introduced upon clinical use. This evaluation can be accomplished by performing end-to-end tests using a DICOM surface, quantifying the ground truth of alignment accuracy using a co-calibrated IGRT modality, and comparing to the residual shifts resulting from monitoring the phantom compared to a camera-acquired reference surface. In general, the discrepancy expected from the use of these two surface types should be <1 mm. While the use of an SGRT-captured reference surface, as opposed to a DICOM-extracted surface, excludes the ability to perform an absolute setup test (i.e., to quantify systematic errors) as shown in Table 6, it allows tracking data to be more accurately evaluated. Finally, both types of reference surface (e.g., DICOM and camera-acquired) can be generated and used for a side-by-side comparison of the monitoring speed, provided that the same ROI is monitored.

To provide an accurate representation of the patient's surface from a CT scan, care must be taken when creating the DICOM surface in the TPS using HU thresholding. Accuracy can be assured empirically. A phantom can be used to determine the HU threshold that leads to the most veridic representation of the phantom's geometric surface and physical scale. For example, various HU values can be used to create corresponding DICOM surfaces that can then be used to position the phantom with SGRT. The optimal HU value range is that which minimizes any positioning error when using a camera-acquired surface of the phantom.

3.4.2 | Effect of region-of-interest selection on QA results

ROI selection for QA purposes should reflect that which is used in clinical procedures, as the size and location will impact the response of the system (see Section 4.2). Phantom QA geometry should mimic the relevant clinical workflow to the maximum extent possible. For a given treatment procedure, the range of possible ROI sizes and shapes should be evaluated at the time of commissioning to assess the impact on system latency, localization accuracy, and end-to-end workflow assessment. Because a poorly defined ROI can reduce the accuracy of SGRT tracking, an important aspect of QA is for the QMP to check the ROI selection process. Competency of the team responsible for ROI delineation should be assured on a regular basis (e.g., annually) as well as following any process changes (e.g., when new staff members are hired or when skills may have diminished following a period of infrequent use of the technology, as mentioned in Section 4.7.5).

3.4.3 | Assessing the impact of image quality on system performance

Issues with image quality can affect system performance when utilizing a DICOM reference surface generated from CT simulation images and when using the SGRT system to capture a reference surface.

When generating a DICOM surface structure, the scan conditions can have a significant impact on the

quality of the reference surface. It is reported that even light breathing during CT scanning can lead to motion artifacts resulting in a rippling pattern on the surface of the patient when the image acquisition time is long with respect to the breathing cycle.[40–43] Breast motion during respiration was found to be on the order of 2 to 3 mm by Baroni et al.[44] Modern CT scanners with larger numbers of detector rows can mitigate this issue with scanning speeds faster than a respiratory cycle.[36] If faster CT scanning is not available, the image quality and accordingly, the localization accuracy for the generated DICOM surface may be degraded. Slice thickness and increment can also impact DICOM surface segmentation due to partial volume effects. If the slice thickness and/or increment of a scan are large, the resolution of the CT data may not correspond to that of the SGRT system, leading to poor registration accuracy. Imaging artifacts can also impact the segmentation of the patient's surface. Metal artifacts from contouring aids placed on the patient, such as wires and BBs, can alter the surface contour. Metal artifacts from inside the body, such as those from prosthetic implants or tissue expander ports, can greatly affect the ability to accurately delineate the patient's surface. Another consideration for CT surface segmentation is the impact of minimally attenuating items outside the patient body such as coverings placed for patient modesty, immobilization and positioning devices, and padding used for patient comfort. The proximity of these blankets, towels, rags, and devices can affect the HU thresholding of the relevant surface. The QMP should verify that a DICOM surface of sufficient quality for the clinical task has been accurately imported into the SGRT system.

While the use of a reference surface captured by the SGRT system avoids many of the pitfalls of CT surface segmentation, it also presents additional challenges. For SGRT systems that are sensitive to ambient room lighting conditions, care must be taken when capturing a reference surface to ensure room lighting is consistent with initial system configuration and falls within the range of acceptable conditions per the vendor-specific guidelines. Also, the reflective properties of the target structure need to be assessed. For phantoms, the ideal properties have been discussed in Section 3.2.1. For patient surface captures, considerations relating to bolus use are addressed in Section 4.6.1 while those pertaining to skin tone are addressed in Section 4.7.2. As has been discussed in Section 2.2.2, the exposure and gain settings may require adjustment for differences between light and dark skin tones.[45] Prior to capturing a surface, a clear line of sight to all relevant anatomy must be ensured. This includes limiting obstruction of the cameras by the treatment unit, IGRT panels, immobilization, and coverings for modesty and comfort. Postural obstruction, also known as self-occlusion, of the camera can also be problematic for SGRT capture quality. For example, the nose or chestwall tissue expanders can shadow relevant distal anatomy. As such, all captured images should be inspected for holes in the surface data that may significantly impact the system response, either due to a deficit of topography or due to scarcity of surface for creating an appropriate ROI. A reference surface captured by the SGRT system could lead to systematic errors (see Table 6), if the patient's position is not confirmed by another IGRT modality.

3.4.4 | Impact of camera occlusion from gantry head and imaging arms

The rationale for the use of multiple cameras in SGRT systems is to visualize as much relevant surface as possible throughout the entire treatment, including non-coplanar angles at which a camera system may become occluded, in order to provide more localization information. Obstruction of a camera system can occur as a result of the treatment unit components or the patient's own posture or accessories. SGRT has been known to underperform when the gantry head and kV imaging arms occlude the cameras, particularly at nonzero couch angles. The user should perform tracking accuracy tests with couch rotations and gantry occlusion to become familiar with the system and be able to decouple tracking accuracy from the intrinsic couch walk out. For more recent systems with advanced camera optimization, Wiant et al. recently studied the loss of tracking accuracy for a head phantom at 72 different couch and gantry configurations.[46] It was shown that the accuracy was minimally affected, with less than 0.2 mm tracking changes introduced during camera occlusion. Often, the effects of camera obstruction on tracking accuracy can be mitigated, or reduced, by modifying the tracking ROI. This should be investigated during system QA.

At the time of commissioning and end-to-end tests, the QMP should simulate typical camera obstructions in the treatment room while repeating system accuracy tests for applicable clinical scenarios. It is advisable to document the geometries that may lead to obstructions as well as the potential impact on the effective use of SGRT across anatomical sites and treatment techniques. Strategies should be developed to mitigate any deficit in accuracy observed as a result of obstruction, and the treatment team should be provided with troubleshooting procedures if obstruction occurs. One strategy is to return the gantry to an unobstructed geometry (if possible) and verify that positioning is within acceptable tolerances; however, this can result in an undesirable extension of the treatment time. A second option is to utilize a complementary IGRT technology to eliminate the misleading result. A proactive approach has been suggested to quantify system performance, in which patient-specific phantom QA is performed in the treatment geometry under ideal conditions (no deformation or motion).[47]

Once the user has characterized accuracy, the vendor should be contacted if accuracy is not within prespecified tolerances (≤1 mm for SRS). The QMP should communicate procedures to the clinical and treatment teams regarding how to proceed if this situation is encountered.

3.5 | Effects of deformable versus rigid registration on QA results

The validation of surface image registration needs to be integrated into initial commissioning and a continual QA program. Some commercial systems offer rigid registration and some offer deformable registration (see Table 2). The QA recommendations discussed throughout this report are straightforward to implement and interpret for rigid registration algorithms. However, there are additional considerations for deformable registration algorithms.

As of the writing of this report, in systems with deformable image registration capabilities, the algorithm defaults to a rigid algorithm for QA routines, since the phantoms are assumed to be rigid objects. Thus, the QA process will not be sensitive to deformations. However, in the clinical mode of those systems, the deformable algorithm is employed for patient positioning, monitoring, and gating for all patients. For SRS treatment, the algorithm in these systems is semi-deformable, where rigid structures in the face are used for the calculation of the position, and the deformable algorithm detects structures that have deformed (e.g., eyelashes, cheeks) and excludes them from the calculation. Currently, there are no known phantoms to enable rigorous testing of deformable algorithms. However, the QMP should be involved to identify clinical situations in which deformable algorithms may have reached their limits (e.g. large deformations) and when the assumption of a rigid body has been violated. Users should be familiar with all software tools available to them within the SGRT system to assess the algorithm's goodness-of-fit (e.g., tools to analyze surface discrepancy and/or deformation maps) and be ready to use this information to guide their decisions. Identification of such clinical situations becomes easier with experience, as discussed in Section 4.7.2.

4 | CURRENT CLINICAL APPLICATIONS WITH WORKFLOW RECOMMENDATIONS

SGRT systems function by registering the real-time surface to a reference and comparing the alignment differences to a user-defined threshold; some systems focus the registration to a limited ROI. Thus, the system's performance will depend in large part on the type of reference surface used (i.e., converted from DICOM CT data or camera-acquired) and the selected ROI and thresholds. While it is not possible to deconvolve the effects of each of these parameters on system performance, understanding the interplay provides valuable insight for troubleshooting in clinical situations. Analogously to PTV margins, selection of these parameters is at the discretion of individual clinics and it is recommended that they be continuously assessed and updated.[4]

4.1 | Types of reference surfaces and implications for registration and positioning accuracy

Reference surfaces can be generated using two methods: (1) by converting the external contour from the CT simulation scan to a surface (i.e., DICOM) or (2) by capturing a reference surface with the system cameras. The decision to use either a DICOM or a camera-acquired surface is task-dependent and should be guided with an understanding of the advantages and drawbacks of each surface type (see Table 6). When using a DICOM surface, systematic errors from the CT-simulated position can be quantified in addition to the random errors. As defined by van Herk,[48] systematic errors lead to deviations in the dose distribution relative to the target while random errors blur the dose distribution. More detail regarding the reference surface selection is provided in Sections 4.4 and 4.6.

4.2 | Region-of-interest selection and implications for registration accuracy and temporal resolution

In some SGRT systems, the registration is constrained to an ROI, whose size and shape can affect both registration accuracy and efficiency of real-time monitoring. The ideal ROI should represent the treatment area and contain salient topographic landmarks (i.e., distinct hills and valleys) to ensure a unique registration solution.[3,4] In contrast, a flat or symmetric surface (e.g., a small, narrow ROI on a flat abdomen) may not be uniquely registered leading to inaccuracies in the reported translations or rotations. Inclusion of anatomy outside of the treatment area to break the symmetry (e.g., rib cage or pelvic bones outside of the abdomen) may be necessary to ensure accurate registration. However, the ROI size is limited because of reduction in temporal resolution with increasing ROI area.[48] Table 6 lists additional advantages or drawbacks to consider when selecting an ROI. In other SGRT systems, no ROI selection is necessary as the entire visible surface can be utilized for real-time registration using a deformable algorithm that prioritizes data from the real-time surface that is closest to the treatment isocenter.[3]

Currently, there is no algorithm for automatic ROI selection or for prediction of the accuracy associated with the chosen ROIs.[49] These should be determined by the QMP and clinical or treatment teams and may need to be altered on a patient-by-patient basis (see Sections 4.7.2 and 4.7.3). More detail regarding the association between ROI selection and SGRT accuracy for various anatomic sites is discussed in the literature and is summarized by Al-Hallaq et al.[4]

4.3 | Beam-hold threshold selection

Thresholds can be used to gate the beam or alert the treatment team when the patient's surface does not match the reference within a predefined tolerance or threshold. This tolerance is specific to the anatomical site or patient. For example, larger thresholds may be utilized if the intention is to monitor both systematic and random errors (i.e., when using a reference surface acquired during CT simulation)[38] or if large physiologic motion is anticipated (e.g., FB chest) versus tighter thresholds when less motion is expected or only random errors are monitored (i.e., when using a reference surface acquired at a time point other than CT simulation). Analogously to PTV margins, these values can initially be selected from the literature as reviewed by Al-Hallaq et al.[4] For example, Stanley et al. compared coincidence of SGRT and CBCT in over 6000 treatment fractions in four anatomical sites excluding brain and found a range of mean discrepancies in the order of 5–6 mm,[50] which can be used to guide selection of a reasonable threshold for many treatment sites if CBCT will be used as the ground truth for final setup (see Section 4.4.2 for alternatives to CBCT as the ground truth for setup). Alternatively, clinics may use SGRT to collect data on the reproducibility of patient positioning in their clinic and use these values to customize thresholds. For example, if >90% of breast patients are within a 5-mm translational threshold, this value may be selected as the translational threshold. For breast DIBH treatments, a 2–3^{o} rotational and 3–5 mm translational threshold in each dimension are typically achievable when using a DICOM reference surface (see Section 4.6.1). It is recommended that institutions investigate further if this is not attainable and also update their tolerances as necessary on an annual basis based on analysis of setup reproducibility in their clinic. A similar process should be applied to all treatment sites treated with SGRT.

4.4 | Workflow considerations for general positioning and monitoring

SGRT offers two advantages compared to traditional three-point laser-based localization for initial positioning: increased positioning accuracy and efficiency.[50,51] SGRT has also been used for intrafraction monitoring in clinical workflows for which the patient's surface and treatment target are highly correlated: (1) when the target is at, or close to, the patient's surface (e.g., breast) and (2) when the surface is rigid and has prominent topographic features (e.g., face, head, extremity). Considerations for SGRT workflows in head and neck and brain, breast, and extremities will be presented in the next section including an overview of the evolving role of immobilization devices.

4.4.1 | Head and neck and brain

Two main challenges were encountered in the initial phase of implementing SGRT for head and neck: (1) obstruction of the patient's surface by traditional closed full-face immobilization masks and (2) influence on registration accuracy from routine physiologic processes, such as swallowing and blinking. To address these concerns, studies were performed to determine if an open-face mask could provide positioning accuracy comparable to a closed-face mask. These studies demonstrated comparable positioning accuracy for open- and closed-faced masks for the spine, mandible, and brain[48,52,53] and under forced intentional movements.[52] The accuracy was typically assessed using volumetric X-ray imaging[53] if the patient's surface was occluded by the closed mask. These studies also showed that an ROI, including prominent bony landmarks but that is robust to facial expression, should be used for SGRT.[49,52] In addition, as the accuracy of SGRT systems varies as a function of couch rotations, additional QA may be necessary for treatment that include couch rotations (see Section 4.6.2). In head and neck cancer patients, weight loss, variability in shoulder immobilization, and deflection of the treatment couch can cause deformations that reduce the accuracy of SGRT registration algorithms,[27] especially in the neck.[54–56] As such, the treatment team should be prepared to identify the cause and troubleshoot the resultant effects on SGRT accuracy.

4.4.2 | Breast and chestwall

It has been proposed that SGRT could serve as a replacement for skin marks or MV portal imaging for positioning breast patients.[50,57] In the case of highly conformal treatment, such as partial breast irradiation, SGRT has been shown to be a better surrogate of the clips in the lumpectomy cavity, as detected by kV imaging, than skin marks.[40,41,43] One challenge encountered in this treatment site is the frequent mismatch between the alignment of bony landmarks versus breast surface, which may obscure the ground truth, thus, making

it difficult to troubleshoot positioning errors.[58] This discrepancy could result from either a true discrepancy in patient positioning or anatomical changes (i.e., swelling of the seroma cavity or lymphedema). Use of SGRT for whole-breast RT (WBRT) has led several institutions to alter various aspects of their workflow, including improving their immobilization,[59] transitioning to kV orthogonal imaging for initial positioning to reduce intraobserver subjectivity,[58] and shortening the total treatment times to minimize intrafraction motion.[51] Others have reported that SGRT serves as a good real-time quality control tool to monitor patient motion, anatomical changes, and accurate positioning particularly of the arm or chin.[60] While the dosimetric benefit of such workflow or quality improvements is not expected to be large, as WBRT delivered with tangential fields is fairly robust to positioning errors,[61,62] they have allowed new users of SGRT to gain experience with the system before attempting to use it for motion management (i.e., DIBH) and enabling tattoo-less treatment as mentioned above.[57] A general treatment workflow during FB is provided in Appendix A. Special attention to the following workflow items is recommended for successful implementation of SGRT for WBRT:

- Consider using a DICOM reference surface to detect both systematic and random errors during initial positioning.
- Utilize two separate metrics for patient positioning: the entire patient's surface including the arm and chin may be used to correct the overall posture[59] while a specific ROI of the breast area may be used to fine tune the patient's position and detect anatomical deformation (see Sections 4.7.2 and 4.7.3).
- Thresholds should be selected to include motion during FB which adds another 2–3 mm.[44]
- More frequent verification with X-ray films may be necessary initially to build trust of the SGRT system's accuracy.
- Identify a quantitative ground truth metric of patient positioning. For example, on-board imaging (OBI) landmark matching may prove more useful than visual inspection of MV portal films, which is prone to inter-subject interpretation variability.[28,58]

4.4.3 | Extremities

SGRT has the potential to replace skin marks for positioning of extremities as long as care is taken to select an ROI that contains sufficient curvature to ensure unambiguous registration.[50,63] Gierga et al. showed that SGRT reduced interfraction errors to less than 10 mm, minimizing the need for repeat X-ray imaging; intrafraction errors were typically not affected, as they were minimal in this anatomical site.[63]

4.4.4 | The role of immobilization

As the use of SGRT for real-time monitoring increases, the role of immobilization may evolve from active (e.g., movement restriction) to passive (e.g., assistance in maintaining a comfortable position) immobilization. For example, Cerviño et al. demonstrated that it is possible to forgo the mask altogether for frameless SRS guided by surface imaging[64] and Wiersma et al. demonstrated that it may be possible to correct the patient position in real time using a robotic stage and feedback from surface imaging.[48,65] Reduction of active immobilization was initially implemented for SRS but has been applied to other sites, such as head and neck and breast, without the use of tattoos or skin marks.[57] Clinical implementation of such surface-guided real-time positioning correction could tip the scales to favor passive rather than active immobilization.

4.5 | Workflow considerations for CT simulation and motion management

Some SGRT systems can be incorporated into the CT simulation workflow to enable both retrospective and prospective gating for respiratory motion management. These SGRT systems typically consist of a single camera installation in the CT simulator room that can interface with various commercially available CT simulators (see Tables 1 and 3). The SGRT camera is used to track a small ROI on the patient in real time such that a patient-specific respiratory pattern may be generated by tracking the temporal excursion of the selected ROI typically only in the anterior–posterior dimension.[66] This surface ROI is typically kept small (e.g. $\leq 30 \times 30$ mm^2) to provide a fast sampling rate.[67]

Because several factors influence the accuracy and reproducibility of the respiratory pattern, steps should be taken to select a robust ROI. These steps include selecting an ROI that is not located on a highly sloped surface, does not become obstructed as the patient travels through the CT bore, does not have abrupt motion perturbations during respiration, and is reproducible during a respiratory cycle. Care should be taken as ROI occlusion could occur due to a number of factors such as patient anatomy (e.g., large belly occluding the thorax), immobilization devices (e.g., abdominal compression devices), or by the CT simulator as the patient enters the CT bore.[67,68] The selected ROI must be tracked not only at the imaging plane but also as the surface ROI moves dynamically into the bore during CT acquisition. The methodology to provide the spatial tracking feedback during the dynamic CT simulation process is performed uniquely by each SGRT vendor.

Implementation and support for retrospective and prospective gating does vary across both CT and SGRT

systems and may change as the vendor product evolves. The QMP is responsible for guiding the safe implementation of these CT techniques in the clinic according to the most recent AAPM guidance.

4.5.1 | Retrospective gating (4DCT)

An SGRT system interfaced with a CT simulator can be used to acquire a retrospective respiratory breathing pattern for sorting of 4DCT datasets.[68–70] Although a number of alternative devices exist to acquire 4DCT datasets, there are advantages in using a SGRT system for this task, namely (a) placement of an external device on the patient to track motion is unnecessary,[69] (b) the tracking of ROI may be moved about the patient's surface to virtually determine the optimal location for a reproducible respiratory pattern, (c) the surface ROI does not interfere with the use of other devices such as abdominal compression belts, and (d) small surface displacements can be detected with high sensitivity in 3D.[48,66] One key consideration when amplitude-based sorting methods are used with SGRT is that the absolute amplitude position of breathing patterns may be influenced by couch sag as the patient is cantilevered past the CT imaging plane.[68] To account for this, couch sag should be well characterized using a couch calibration profile to describe the vertical displacement of the couch at various longitudinal positions both with and without a mass loaded onto the couch to mimic a patient load.[69] This could potentially be accomplished with SGRT systems as described in Section 6.2.3.

4.5.2 | Prospective gating

For prospective gating, SGRT systems have typically been used to acquire CT data during DIBH by triggering the scanner using a surface ROI that produces a reproducible respiratory pattern.[66] For CT-based systems that track motion in the anterior–posterior direction only, a flat surface, such as an area above the xiphoid process, should be used to reproducibly track the respiratory signal. The position of the end-expiration phase in FB is defined as the baseline, and is automatically tracked by the system.[71] The patient is guided by audio or visual coaching to a reproducible DIBH position. The DIBH amplitude and gating window is manually determined in the software. Similar to retrospective gating applications, a small ROI is tracked (e.g. $\leq 30 \times 30$ mm^2) to improve the temporal sampling rate. In this case, the influence of couch sag can again influence the breathing pattern in such a way as to mimic the release of a breath hold.[72] Additionally, SGRT systems could potentially be used for prospective gating during a quiet respiratory cycle (e.g., end-exhale) if the associated triggering delay does not introduce any phase-based sorting errors.[70]

4.6 | Workflows for motion gating and tracking

The power of noninvasive real-time surface imaging has been harnessed for motion tracking and management with beam-hold capability (i.e., beam gating). As a result, SGRT has facilitated two clinical applications: (1) voluntary DIBH[73] treatment for breast cancer and (2) frameless SRS.[8] In both of these applications, the patient's surface serves as a surrogate for the target without the need for any additional markers. Additionally, SGRT systems can be used to gate the beam either manually or automatically thereby halting treatment when the patient moves out of the specified tolerance. In the case of frameless SRS, the main advantages introduced by SGRT are the increased comfort resulting from use of an open-face mask and the real-time monitoring capability.[52] Also, the frameless SRS workflow provides a more flexible timeframe from simulation to treatment to accommodate the planning and QA process. In the case of voluntary DIBH for breast cancer, there are also two main advantages. The first is increased patient comfort during breath hold without the need for an invasive breathing-control apparatus.[73] The second is improved dosimetry as DIBH has been shown to significantly reduce the dose to the heart and lungs.[74]

4.6.1 | Respiratory gating at deep-inspiration breath hold (DIBH) for breast cancer

The delivered dose accuracy of DIBH using surface imaging has proven to be clinically acceptable for both left- and right-sided breast cancer irradiation.[37,71,75–77] A general workflow of DIBH guided by surface imaging can be found in Appendix B. General recommendations of TG-76 for motion management of DIBH regarding patient selection, education, and coaching are directly applicable and should be followed.[35] Workflow details specific to breast cancer patients that were not explicitly discussed in TG-76 include:

- *Patient selection and education*: The majority of breast cancer patients can perform voluntary breath hold.[37,78] The registration accuracy of SGRT may be compromised for postmastectomy patients without reconstruction, particularly in the longitudinal direction, or for patients with more pendulous breast tissue. Where applicable, a careful choice of ROI can often remediate these problems (see Section 4.2). Since the patient's surface must be exposed for SGRT, patient education and cooperation are necessary.
- *CT simulation*: Because SGRT tracks the surface for motion management, a reproducible correlation between the surface displacement and the breath hold pattern is important. Some tips to increase this reproducibility include: instructing patients to breathe

through the nose and to expand the chest, maintain a reproducible and sustainable inhalation level that may not necessarily be at maximum inspiration, and avoid arching of the back and other postural changes. The amplitude of the chest at mid-sternum over several breath holds may be used to assess the reproducibility, ideally using SGRT, which can assess reproducibility in 3D, but alternatives such as the Varian Real-time Position Management box can be used. If a patient's breath hold amplitude varies despite coaching, duplicate DIBH scans may be acquired to assess reproducibility of the surface. A FB scan may also be acquired to enable dosimetric evaluations and comparisons of anatomical displacements of organs-at-risk to determine if DIBH is warranted.[78] Occasionally, the FB scan can be used for replanning, if the patient experiences challenges on DIBH treatment.[35]

- *Setup and treatment*: To minimize patient discomfort and reduce fatigue, the patient should initially be positioned utilizing a FB surface. This provides an opportunity to ensure postural alignment of anatomy that moves independently of the target volume such as the chin, shoulder, and elbow. The FB surface can also be used to verify the correct magnitude of inspiration when transitioning from FB to DIBH surfaces to aid in distinguishing positioning errors from breath hold reproducibility issues (see Section 4.7.1). The DIBH surface can subsequently be used to position within acceptable thresholds (i.e., 3–5 mm, 2–3°), providing coaching as needed.

Verification of heart position

While the patient's surface is a good surrogate for the breast tissue or target, it cannot directly provide information regarding the position of the heart during DIBH. Thus, an alternate imaging modality capable of visualizing internal anatomy is required. The following X-ray-based imaging modalities can be employed to verify the heart position: fluoroscopy[79]; MV cine[79,80]; MV portal films[79,81]; or CBCT.[79,82] As each has different advantages or disadvantages, the selection of which to use is left to the discretion of the treating physician(s). Reconciling the SGRT registration results with those from internal imaging may be challenging in some instances and is discussed in Section 4.7.4. The frequency with which to utilize an internal imaging modality for breast cancer patients varies, but should be performed regularly.[8]

Treatment with bolus

By definition, the use of bolus obscures the patient's surface. Typically, acquisition of a new reference surface with bolus will be required at each treatment and its accuracy should be confirmed as is done with any new reference surface (see Section 3.4.3). Conventional bolus with a reflective surface may not be rendered adequately with SGRT as described in Section 3.2.1, and therefore, use of a nonreflective, conformal bolus is recommended. Otherwise, conventional bolus can be rendered nonreflective by covering it with opaque paper tape or a matte finish spray paint. Ideally, the bolus should be placed at the same location on the patient's surface each day to match the captured reference with bolus. However, this might not be achievable for all patients such as those with a reconstructed breast, particularly if the bolus needs to be secured with tape. Skin marks or the light field could aid in increasing the placement reproducibility and efficiency of bolus placement for subsequent treatment. Because breast cancer patients are typically not filmed daily, it is important to verify the patient's position despite the bolus which obscures the surface. For treatment units with low-energy MV imaging beams (i.e., 2 MV), the bolus placement may be verified using portal imaging prior to treatment.[81] Alternatively, the patient's position may also be compared to the nonbolus reference surface using SGRT prior to the placement of bolus. For example, nonbolus fields (e.g., supraclavicular) could be treated prior to the bolus fields, as there is evidence[37,79] which shows that patients can reproduce their breath hold to ≤3 mm on any single day and, thus, are expected to continue to do so once the bolus is added and a fraction-specific reference surface is acquired for use with bolus on a daily basis. See Appendix C, for a DIBH workflow including the use of bolus. Experience treating nonbolus patients will aid the treatment team to gain confidence with treatment requiring bolus. As bolus material and design vary by vendor, the QMP should assess the impact of the bolus on surface tracking prior to clinical use.

Treatment with matching fields

Treatment of supraclavicular nodes is typically achieved using anterior or posterior oblique fields whose divergence is matched to tangential breast fields, most commonly accomplished using a single shared isocenter located at the junction between the breast and the supraclavicular fields (i.e., "the matchline"). Similarly to FB treatment, setup at the matchline during DIBH is of concern due to potential overlap of the fields.[83] However, it has been shown that treating matched fields is acceptable for DIBH guided by SGRT.[37,77] When treating during DIBH, very little movement occurs at the apex of the lung (i.e., at or above the matchline), making this location robust to variations in the level of inspiration. In addition, SGRT accuracy is typically highest at or near the isocenter,[48,77] which is advantageous for treating matched fields sharing a common isocenter. Kügele et al. showed that a mono-isocentric setup with SGRT to treat the breast and nodes during DIBH was more accurate than multiple isocenters, that is, one in the breast and one for the nodes.[77] Furthermore, Xiao et al. observed that the variability of the matchline between

breath holds is of the order of 1.5-2.2 mm, which is comparable to that during spirometric-controlled DIBH.[38]

Treatment fields with wedges

As mentioned in TG-76, patient discomfort increases with prolonged length of breath hold and multiple breath holds.[36] The use of physical or virtual wedges may increase beam delivery time. If this time exceeds the length of the patient's breath hold (e.g. 20–40 s), it is advisable to manually split the beam such that each resulting beam can be delivered in a single breath hold per the recommendation of TG-76.[36] Elimination of wedges in favor of field-in-field (FIF) techniques per TG-76 should be considered. In general, care should be taken to minimize the required number of breath holds required to complete a treatment while also accounting for additional breath holds required for filming. In practice, eight to ten treatment beams are well tolerated by the majority of breast patients with healthy lung function.

Dynamic beam delivery

Treatment fields utilizing dynamic delivery have been successfully used for DIBH guided by SGRT including FIF tangent beams[38,81] and multiple intensity-modulated beams or volumetric modulated arc therapy (VMAT) arcs to cover more extensive nodal targets.[28] TG-76 guidelines should be followed to: split beams with high MU when possible, minimize the number of segments for FIF beams, and stitch delivery of intensity-modulated or VMAT plans across multiple breath holds. Appropriate commissioning and routine QA is necessary to ensure deliverability of arcs that are manually held and resumed.[36] During VMAT, surface monitoring may be compromised due to occlusion of cameras at certain gantry angles. Tests on a phantom may be performed to determine appropriate ROIs or arc angles that would minimize such interruptions. In general, selection of larger ROIs that cross midline may be necessary to minimize the effects of gantry occlusion of the cameras. Acquisition of CBCT may similarly obstruct SGRT cameras and should be evaluated in a similar manner as that described in this section for VMAT.

Role of immobilization devices for DIBH

Immobilization facilitates patient positioning reproducibility and treatment efficiency. The accuracy of the breast surface is closely coupled to the immobilization accuracy, which should be well characterized at each clinic for FB patients prior to implementing DIBH. In fact, the use of SGRT to monitor WBRT patients has led multiple institutions to alter their immobilization due to its high sensitivity to positioning accuracy.[58,59] Also, SGRT has demonstrated that accuracy of breast surface positioning decreases with increased treatment time.[51] Immobilization accuracy is especially important, as successful implementation of DIBH using SGRT relies on the ability to decouple positioning accuracy from other errors, as discussed in Section 4.7.

4.6.2 | Motion tracking during SRS

Shortly after surface imaging was introduced in RT, its potential use for motion tracking during SRS and stereotactic RT (SRT) was investigated, with the first cases treated soon after its initial clinical implementation. Since doses employed in SRS and SRT are in the ablative range, accurate setup and motion monitoring are key to implement this treatment technique. SRS has been traditionally performed using a frame system (fixed to the patient's skull) for immobilization and positioning. The frame has several drawbacks: it is uncomfortable to the patient, it is impractical for multiple-fraction treatment, it may cause stress and infection, it should be placed by the neurosurgeon, and, most importantly, it does not guarantee complete immobilization.[84] In SGRT for SRS, an open-faced mask is used for immobilization instead, so that the contours of the patient's face, typically the area around the eyes and nose, are visible to the SGRT system. The goal of SGRT in SRS is not to completely immobilize the patient, but to monitor intrafraction motion to determine when to compensate and adjust the patient's position as needed (i.e., by repositioning the patient following reimaging).

Multiple institutions have evaluated the accuracy of SGRT systems for SRS. They have shown submillimeter accuracy of the system with various treatment parameters, including couch rotations and the utilization of different ROIs for intrafraction motion tracking (i.e. forehead, nose, eyes, and part of the temporal bones).[85–87] The clinical workflow for surface imaging-guided SRS and SRT has been described in Cerviño et al.[64] and Li et al.,[88] and an example of such workflow is shown in Appendix D. Below is a description of the relevant SGRT-related procedures within the RT planning and treatment steps:

- *Simulation*: the selected immobilization should allow the SGRT system to visualize the selected tracking ROI. Examples of such immobilization devices are open masks or open head molds.[46,64,88] The simulation process is the same as for any other SRS technique and should follow the recommendations in the AAPM Practice Guideline 9.a for SRS-SBRT.[89] During and/or before simulation, the patient's ability to hold steady during treatment should be assessed (e.g., patient motion should not exceed a 1 mm tolerance limit, the patient does not have tremors that will surpass tolerances, the patient understands and complies with directions, etc.).
- *Planning*: the use of SGRT does not affect SRS and SRT treatment planning procedures. Once the plan is finalized, the body contour and the plan (isocenter and couch rotations) have to be exported from the TPS and imported into the SGRT system. For SRS, the "Intracranial SRS" tracking option, or equivalent, should be selected within the SGRT software, as it typically results in the use of higher resolution

surface grids than used for other treatment techniques and may also apply a different registration algorithm (e.g., the C-rad algorithm is less deformable for SRS than for other treatment sites). Since the body contour is used as the initial reference surface during patient setup, care should be taken when contouring, paying particular attention to the nose area if CT artifacts are present. ROI definition for SRS and SRT should contain the forehead, nose, and temporal bones. When including the eyes, it has been found that, for some patients, SGRT systems may yield large movements as the patient blinks when eyelashes are included in the tracked anatomy. In these cases, removing the eyes from the ROI is appropriate as long as the area tracked does not become too small to provide enough topography for accurate monitoring results. At the same time, the maximum ROI size should allow for a frame rate of at least three to five frames per second.

- *Setup*: It is a multistep process. First, the SGRT system is turned on and the patient is positioned using the DICOM external contour from the treatment plan as the reference surface in the SGRT system. Once SGRT tolerances are met, that is, the real-time surface and the reference surface do not differ more than the prespecified thresholds (usually 1 mm for translations and 1° for rotations), another internal imaging modality, commonly CBCT, is used as the ground truth for final setup. *At the time of this writing, radiographic images (e.g., kV images or CBCT) should always be used for the final adjustments of the patient position following the standard of practice*. Use of a 6DOF couch, although not needed, facilitates the setup. As soon as shifts are applied, a new reference surface at the new position is acquired with the SGRT system and used for treatment monitoring during the remainder of the treatment fraction. Depending on the version and software, the ROI might need to be redrawn if it is not automatically transferred from the original reference image to the treatment reference image. If the system automatically propagates the ROI, the propagated ROI should be checked for integrity and consistency with the originally defined ROI. Patient motion should be monitored with surface imaging during the time from CBCT imaging and the application of final shifts to SGRT reference image acquisition. If interval patient movement exceeds tolerances during this time, a new CBCT (or X-ray-based internal imaging, according to the clinical protocol) should be acquired. The presence requirements of a QMP should follow relevant guidelines.
- *Treatment*: Treatment delivery occurs with continuous monitoring of the patient employing SGRT based on the post-CBCT reference surface. Deviations from the reference surface are not to exceed prespecified tolerances. These tolerances, usually ≤1 mm for translations and ≤1° for rotations, should be determined based on institutional practice and equipment performance (tolerances can vary depending on planning margins used for treatment, delivery technique, known treatment couch walk-out values, SGRT calibration procedures, etc.). As the couch moves to different planned treatment angles, the couch angle, which should have been directly imported from the plan, needs to be updated in the SGRT system as needed. This action will rotate the reference surface and compare it to the real-time surface. Whenever tolerances are exceeded, the QMP should determine whether this is due to patient motion, camera occlusion, or extreme couch rotation affecting ROI visualization by the SGRT system and make adequate recommendations to the clinical or treatment teams on how to proceed. One way to check if the detected patient motion is real or due to camera occlusion by the gantry is to rotate the gantry to a position where there is no camera occlusion to determine if the SGRT image remains out of tolerance. Similarly, to determine if the motion detected at a nonzero couch rotation is real, the couch can be returned to the nominal position (e.g., 0°) to observe if the SGRT image is still out of tolerance. When the discrepancy between the reference and real-time images is due to patient motion, the patient's position may need to be readjusted. New internal images (i.e., CBCT or X-ray-based) are recommended to confirm the correct treatment position, and a new surface image for intrafraction monitoring should be recaptured after final adjustment.

Selection of mask for immobilization and surface visualization

Initial implementations of surface imaging in SRS considered the use of custom patient-specific head molds with no mask,[64,90] allowing for the whole patient's face to be visualized by the SGRT system. This initial feasibility study evaluated its use in four volunteers, and no motion outside of tolerances was observed during a 20-min period. The trend for subsequent implementations, however, has been to use an open thermoplastic mask to immobilize patients while allowing visualization of the forehead, nose, temporal bones, and eyes. The customization of a mask is a much simpler process than the creation of the head mold. A recent study evaluated the use of eight different commercial open masks and observed that all of them yield the same accuracy and immobilization.[91] However, these masks have room for patient motion that, although small, can exceed clinical thresholds.[85] Therefore, setting up tolerances in the SGRT system that highlight when the patient's head moves outside allowed limits with respect to the reference position is imperative to ensure the accuracy of the treatment.

In addition to minimal immobilization, comfort criteria are used when selecting masks. Li et al. compared two different systems: a head mold with open mask and a head mold with a mouthpiece.[85] They observed that the open mask outperformed the mouthpiece in terms

of patient comfort and clinical workflow, without sacrificing immobilization performance. Because patients can move within thermoplastic immobilization devices and pinned head frames can slip,[92] a reasonable strategy is to focus on making the patient comfortable while delivering the treatment as quickly as possible. In this scenario, the immobilization is used to remind the patient of the correct head position, not necessarily to rigidly keep their head from moving, while real-time surface monitoring of the patient's head allows the treatment to proceed safely and accurately by correcting the position throughout treatment as necessary.

Patient monitoring considerations pertaining to the treatment couch

When the treatment couch is set at a nonzero angle position, SGRT cameras can lose visibility of part of the ROI, particularly when the couch is at ±90° from the zero angle, even if the camera configuration in the room has been optimized (see Section 2.2.2). Although older studies have shown uncertainties of >0.5 mm at extreme couch angles,[86] enhancements in software and calibration procedures have been shown to improve the tracking accuracy at nonzero couch angles.[46,93]

Additionally, SGRT systems can highlight the limits of the linac mechanical systems. For example, current SGRT systems can detect couch walk-out of <1 mm. It is important that the QMP be able to distinguish patient motion from linac mechanical issues. When in doubt during a treatment, returning the gantry and couch positions back to 0° can be used to confirm the validity of the detected patient motion and rule out any camera occlusion issues (see Section 3.4.4). If available, stereoscopic kV imaging can alternatively be employed to verify the patient position. If the couch walk-out is well characterized for the linac, it can be taken into account when selecting and evaluating tolerances.

Motion or setup uncertainties during isocentric treatment of multiple lesions

SRS patients often present with multiple intracranial metastatic lesions, and, depending on the relative position, size, and fractionation scheme for each one, they might be treated independently (i.e., multiple isocenters and plans) or together (i.e., same isocenter and plan, often referred to as "single-iso multi-met" treatment). For the latter case, all lesions are treated simultaneously with the isocenter commonly placed at a mid-position relative to all lesions. SGRT systems currently only provide displacement information for a single ROI. Consequently, care must be taken when interpreting these displacements for multi-met treatments. When treating multiple metastases using a single isocenter with SGRT, tighter tolerances (i.e., ≤1 mm and ≤0.5°) may be required, particularly in pitch and roll, to reduce the dosimetric impact of positioning errors on metastases located farther from the isocenter.[94] With carefully selected case-specific tolerances, the use of real-time monitoring with SGRT allows for early identification and correction of these deviations.[47]

4.7 | Common pitfalls

Commonly encountered pitfalls may be mitigated by the growing experience of the clinical or treatment teams and by incorporating additional clinical and imaging information into the patient positioning process. Strategies for identifying common pitfalls and troubleshooting them are discussed below.

4.7.1 | Distinguishing changes in DIBH respiratory pattern from positioning errors

Changes in breath hold pattern may be difficult to distinguish from overall positioning errors with SGRT. Verification of the patient's position against a FB reference surface prior to breath hold can be used to eliminate or minimize the possibility of positioning errors. If the patient's breath hold position subsequently does not match the DIBH reference surface and repositioning does not resolve the discrepancy, X-ray imaging should be employed. Lateral kV X-ray can be used to verify the level of inspiration by comparing the separation between the sternum to the anterior vertebral bodies. Alternatively, the heart shape and/or location of the diaphragm may be helpful surrogates of the volume of inspiration in either MV portal or kV X-ray images. If the evidence points to a possible change in respiratory pattern that cannot be resolved by coaching, the planning (i.e., dosimetrists) and treatment teams should be prepared to adapt the treatment plan or adjust heart blocks accordingly and to generate a new reference surface for treatment.

4.7.2 | Identifying registration errors due to deformation or degradation of surface quality

Significant tissue deformation throughout the treatment course may decrease SGRT system accuracy, both for rigid and deformable registration algorithms.[27] This includes changes unaccounted for from the simulated position such as tumor shrinkage or swelling, weight loss, or physiologic motion such as blinking or swallowing. Because smaller ROIs may be more sensitive to deformation than larger ROIs, discrepancies between a large (e.g., the entire surface) and small (e.g., the breast surface) ROI can provide indirect evidence of tissue deformation.[58] Additionally, tools may be available in SGRT systems to quantify surface discrepancy resulting from tissue deformation and the users should be familiar with them. Use of an additional imaging modality (i.e., X-ray) could aid in extricating positioning errors from tissue deformation. Finally,

clinical examinations can also provide evidence of tissue deformation (i.e., breast swelling or seroma cavity changes).

Because SGRT systems detect the light projected onto the patient's surface, the skin tone must be reflective to an appropriate extent to generate a surface image. Camera systems allow camera exposure settings to be modified to accommodate a range of skin tones. Nevertheless, very dark skin tones can pose challenges resulting in surface degradations that appear as holes. Once the area of degradation is sufficiently large, the registration accuracy will suffer.[95] Care should be taken to characterize the range of skin tones suitable for the SGRT cameras during commissioning, as discussed in Section 2.2.2, and to remain vigilant to patients with dark skin tones that may undergo changes in skin tone during RT (i.e., dermatitis due to treatment with bolus). Once the tracked surface has degraded considerably and can no longer be tracked accurately, an alternate ROI that includes relevant areas that can still be tracked by the SGRT cameras, such as the contralateral breast, may be required for patient monitoring.

4.7.3 | Effects of nonspecific topography on SGRT accuracy

If the surface topography is not sufficiently unique, the registration algorithm may not produce an accurate result. For example, a flat surface will satisfy the algorithmic registration constraints regardless of how far laterally or longitudinally it is shifted. Highly symmetric structures (e.g., male torso) may also produce nonunique results.[96] Nearby surface geometry may need to be included to aid the algorithm in arriving at a unique and accurate registration. Robustness of the ROI may be assessed by comparing the registration output of two disparate ROIs (e.g., a large ROI with many salient features such as the entire patient's surface versus the postmastectomy chestwall) which should agree to within a couple of millimeters. Alternatively, verification of the registration results against X-ray imaging may also provide an indication of the ROI robustness.

4.7.4 | Discrepancy between X-ray-based and SGRT positioning

If a discrepancy between the calculated translations or rotations from X-ray and surface imaging is observed, this may be due to: (1) immobilization that does not accurately reproduce the simulated position, (2) a change in breath hold pattern, or (3) tissue deformation. The source of discrepancy should be identified by a process of elimination (see Section 4.7.). Close communication among all members of the entire team (e.g., physicians, therapists, QMPs) is necessary to address the discrepancies whether they affect a single patient or are more systematic and require changes in workflow and processes.

4.7.5 | Interpretation of SGRT results and training of the treatment team

A steep learning curve has been reported with SGRT[81] because therapists must reproduce a 3D surface instead of a few marks on the patient's skin, which can be manipulated manually to some extent. Analogously to the introduction of CBCT, the therapists will be presented with a large amount of new information with regard to positioning.[97] Also, the SGRT interface may be less intuitive than manipulating images that have been directly overlaid as in OBI. Repeated exposure to the process with close guidance or support at implementation is required to ease the transition and develop confidence in the system. In addition, the treatment team should be trained to inspect the surface images directly to check for concordance with the registration output. Troubleshooting occasional pitfalls may be most challenging, as they occur rarely and do not always present in the same manner. Clinics may consider compiling a case study library or setting thresholds for the treatment team to notify a QMP to aid in troubleshooting such pitfalls. Routine training of the treatment team and competency assessment are integral to a high-quality SGRT program. Training at more frequent intervals may be necessary following process changes (e.g., system upgrades, staff turnover) or when SGRT use is sporadic and/or infrequent.

5 | RISK ASSESSMENT (TG-100)

5.1 | Role of SGRT for risk assessment

A risk analysis on an SGRT system and workflow is necessary to identify potential failure pathways for the clinical use of these systems, as described by Manger et al. for the use of SGRT in frameless SRS.[98] In addition, SGRT can play an important role in an overall mitigation strategy to reduce treatment errors. As a noninvasive optical imaging modality, SGRT acquires 3D data of the patient's surface and determines the patient's relative position to their planned position and potentially other treatment devices.[3,4] Case studies have demonstrated that SGRT is capable of detecting "incorrect patient" errors,[99] isocenter localization errors, "incorrect immobilization" errors,[100] intrafractional motion, and changes in patient anatomy such as skin breakdown or breast swelling.[4,101] With the exception of magnetic resonance imaging (MRI), SGRT is the only system that provides

direct, real-time information regarding the patient's position (and potentially the target position) without the use of ionizing radiation. Moreover, it is the only imaging modality currently capable of providing additional safety measures such as collision detection (see Section 6.1.1).

5.2 | Example of risk analysis—Process for SGRT with DIBH treatment

Risk analysis using SGRT for DIBH patients or any other application can help to inform the recommendations for a QA program when using these systems. The Task Group members conducted a risk analysis following TG-100 methodology for a common application of SGRT, DIBH for breast cancer treatment, as an example of how to develop similar analyses for other SGRT applications. First, a process map was devised to define the steps involved in treating a patient using an SGRT system (see Appendix E). The process map was reviewed as a group and we noted failure modes for each of the 24 steps identified in the process. The Task Group members noted at least one failure mode for each step in the process (41 failure modes in total).

Next, the Task Group members conducted a Failure Modes and Effects Analysis. A potential cause and effect for each failure mode was noted to assist in further analyzing potential failure modes. The TG-100 scoring table was used.[2] This provided a common understanding of the scale and definition of each score. Seven participants contributed scores for Occurrence, Severity and Detectability (O, S, D) to determine a Risk Priority Number ($RPN = O \times S \times D$). The failure mode with the highest RPN value was identified as use of the wrong surface reference image and was further analyzed using Fault Tree Analysis (FTA). Basic causes for this failure mode were obtained, as shown in Figure 2. The results of this analysis can help the QMP to identify and design a QA program that mitigates the causes of failure modes with high RPNs.

6 | EMERGING CLINICAL APPLICATIONS AND ASSOCIATED QA CONSIDERATIONS

The potential uses of surface imaging in the clinical setting extend well beyond current applications. Although this technology has already shown its versatility as a valuable tool for a diverse array of treatment types, the full range of its utility is yet to be reached. Clinical users should conduct a risk assessment, (see Section 5) on any new uses of an existing technology, as in the case of emerging clinical applications of SGRT.

6.1 | Emerging applications

3D models of the patient generated with surface imaging can include detailed anatomical topography, as well as immobilization devices. Uses of such data are extensive and applicable across multiple subfields of medical physics. Examples include: collision prediction for external beam RT,[20–22] biometrics for facial[24] and body surface recognition,[99] physiologic monitoring of both heart and breathing rates,[102] motion compensation corrections for image reconstruction,[103,104] and evaluation of aesthetic outcomes after breast conserving RT.[105] It is evident from this list that as surface imaging uses expand, their applications have the potential to improve the quality of treatment delivery, image reconstruction, and overall patient safety.[101] Some of these emerging applications require surface imaging capabilities outside of what current clinical systems can provide. As emerging applications are expansive, this section will only focus on collision prediction for RT and biometrics. QA considerations associated with these two applications are difficult to establish at this time because clinical products for these uses have not been released. However, performance aspects of the cameras that can affect the reliability of these potential uses will be highlighted. Some of the QA tests currently performed on clinical SGRT systems may still be applicable for the emerging applications described here, and will be mentioned when pertinent.

6.1.1 | Description of algorithms and their purpose

Collision detection

Collisions between the patient and the treatment unit are an ongoing concern in RT.[101,106] This issue is exacerbated when using noncoplanar geometries and OBI,[107] particularly for treatment isocenters that are offset from the center of the patient. Thus, localization of the patient with respect to the treatment unit becomes a crucial factor in ensuring the safety and success of the treatment. Oftentimes, the information provided by the external contour of the planning CT does not fully encompass the anatomy of concern for collision prediction purposes. In the case of breast RT, the elbows, which tend to be the source of potential collisions, are often excluded from a typical CT scan. The use of surface imaging cameras to create a complete patient model in the treatment position, including immobilization devices, has been explored as a practical solution to this problem.[20–22]

Groups working to develop collision prediction algorithms have used Kinect cameras and other such nonmedical devices to acquire a surface model of the patient to calculate the deliverability of different treatment geometries. Although the sophistication of the collision prediction algorithms varies from coplanar

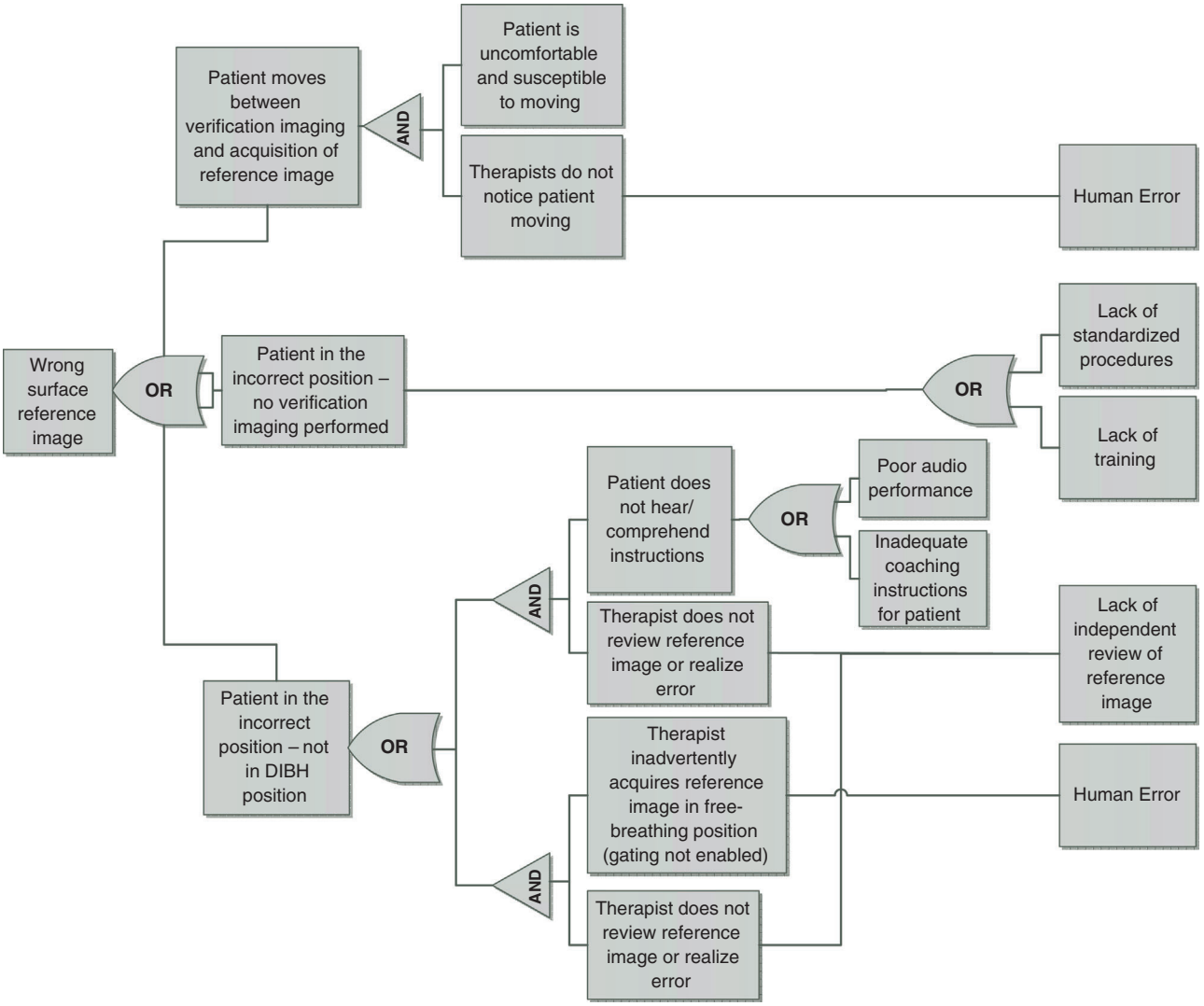

FIGURE 2 Example FTA for a patient being positioned for deep-inspiration breath hold (DIBH) with SGRT. Acquisition of a reference surface may be necessary when treating with bolus (see Section 4.6.1).

treatment geometries only[20] to noncoplanar,[21,22] all show the potential utility of modeling the entire patient's surface for this purpose. The use of a surface model to represent the totality of the patient's anatomy and immobilization devices for treatment provides a clear advantage over either the utilization of truncated anatomy encompassed by typical planning CT scans or scanning of a larger patient volume with ionizing radiation to achieve a more complete model.

Biometrics

Surface imaging enables measurement of physiological characteristics that can be used for patient identification or biometrics such as facial and body surface recognition. Although facial recognition is not a new tool, its application in radiation oncology is novel. Surface scanners, such as the Kinect camera, can be used to capture a model of the patient's facial features from which facial landmarks are extracted and compared to a reference surface of the patient for determining if an appropriate match has occurred.[24] While initial results are promising, the high specificity and sensitivity required for this task in RT is difficult to achieve as these algorithms are affected by variations in ambient light conditions or accessories worn by the patient.[24] Another approach for patient identification is to use the body surface detected during treatment by current clinical systems. This technique has been applied to breast patients by comparing daily surface images to the reference using a distance-to-agreement metric.[99] A large percentage of points (>80%) meeting a 3- or 5-mm distance-to-agreement could accurately identify the correct patient in this small cohort of 16 patients based on their surface anatomy alone. Although both approaches produced false positives in a small number of cases, they provide complementary information that could potentially be combined to improve the specificity for patient identification.

6.1.2 | Overview of additional QA tests to assess algorithm accuracy

For the emerging applications discussed above, it is imperative that the fidelity of the acquired surfaces is confirmed. QA tests to verify if the acquired surfaces truthfully represent the size, color, or texture, as applicable, of a given object will become critical for reliable implementation of these applications. High resolution will be required to reconstruct 3D surfaces with steep gradients, such as elbows or noses, and provide accurate and consistent distance measurements throughout the FOV. While inadequate surface reconstruction could also affect current clinical applications, they would have a larger impact on these emerging clinical applications. During collision calculations, for instance, the complete surface of the patient is utilized, so discrepancies in areas that are far from the treatment isocenter would negatively affect the reliability of the calculation results. Ambient lighting conditions could also affect the performance of surface imaging for emerging applications such as facial recognition.[24] In clinical SGRT systems that are sensitive to ambient lighting conditions, calibration of the cameras should be performed in the same lighting conditions as their intended use to minimize the impact of changes in ambient lighting on surface acquisition quality. Similarly, cameras for emerging applications should be tested in the appropriate lighting to identify performance limitations and establish utilization guidelines to achieve adequate surface models for the task at hand. Finally, a dependable method to identify surfaces that are too dark to be reliably reconstructed by SGRT systems should be implemented so that these algorithms can alert the user rather than utilizing missing data.

6.2 | Emerging clinical workflows

6.2.1 | SBRT

SGRT is increasingly utilized to help improve the overall treatment delivery accuracy of SBRT.[8] In general, the SBRT workflow mimics the cranial SRS workflow, in that SGRT is used to guide and monitor the patient positioning secondary to X-ray imaging techniques such as CBCT (see Section 4.6.2). SGRT is used for initial patient positioning and a new reference surface is acquired following verification with X-ray imaging (e.g., CBCT). This camera-acquired reference surface is then used for real-time monitoring to ensure that the patient does not deviate from the CBCT-verified position throughout this potentially lengthy treatment which commonly includes couch rotations. An early investigation of SGRT for lung SBRT found that the discrepancy between SGRT and CBCT was too large to be clinically acceptable for positioning males compared to females treated with SBRT.[96] This was attributed both to the incomplete coverage of the thorax surface due to the single-camera SGRT system used and the lack of sufficient salient topography in the male torso. In a retrospective analysis, Leong et al. demonstrated that while SGRT significantly reduced the discrepancy from the CBCT-verified position compared to alignment with lasers and skin marks, the maximum translational discrepancy between CBCT and SGRT could be as large as 14–24 mm in selected patients.[108] Alternatively, SGRT has the potential to verify the accuracy of the relative couch translations or rotations recommended by CBCT and may circumvent the need for a repeat CBCT after couch movement.

Selection of the ROI and thresholds for SBRT should be optimized as discussed in Section 4. The ROI should correlate with an area that represents the target motion while ensuring a low latency to enable a fast beam-off response time, if applicable. One advantage of monitoring a 3D surface over a single point or limited area near the diaphragm is that it is less susceptible to baseline shifts[80,109] and can distinguish between various respiratory patterns such as abdominal versus thoracic breathing.[109] Threshold selection would depend on the PTV margin used for planning (i.e., similarly to SRS) and on whether respiratory motion is expected to contribute to the setup uncertainty (i.e., similarly to FB breast treatment). For SBRT treatment that includes advanced motion management techniques, such as breath hold, SGRT may not track the internal target with sufficient accuracy, and internal imaging may be more appropriate. A synergistic approach is to use SGRT in combination with X-ray imaging to efficiently verify internal target position while ensuring proper patient positioning. The decision to use SGRT for SBRT should be assessed on a case-by-case basis by the QMP and treatment team.

6.2.2 | Proton RT

While the clinical workflows of surface guidance for proton therapy mirror those of photon therapy in many ways, there are a few variations related to differences in treatment unit installations and dosimetric considerations. First, many proton centers utilize either half-gantry or fixed-position beam lines without inline imaging. Because the treatment couch must be moved away from the beam line for setup imaging, these facilities utilize robotic couches that are not mechanically constrained to move isocentrically. Isocentric motion is accomplished via software programming of several robotic joints and incorrect couch motion must be considered as a potential failure mode.[110] Second, most proton centers utilize a queuing system for beam sharing between treatment rooms. It is not uncommon for patients to wait several minutes after being positioned before treatment,

creating a greater potential for patient motion. Third, changes in surface position relative to bony anatomy can have much more significant dosimetric consequences in proton therapy due to the fixed range of proton beams.[110] Finally, respiratory motion may be more problematic in proton treatment, particularly for beam scanning proton systems, where such motion could lead to undesirable motion interplay with significant consequences in dose variability.[110]

SGRT can be used to monitor motion throughout treatment to mitigate many of these factors. For example, patient setup imaging at the Mayo Clinic is performed at a couch angle of 270° due to the geometry of a Hitachi installation. Patients are then typically moved to one or two other couch angles for treatment. Initially, kV imaging was used after each couch rotation to verify positioning accuracy. This workflow was eventually replaced by capturing a reference surface immediately after setup positioning with X-ray, which was used to verify patient and couch positioning after each rotation, resulting in an estimated time savings of a few minutes per field. Because SGRT could provide the required setup accuracy of ±3 mm in depth required for robust proton treatment while also improving the positioning efficiency workflow, Batin et al. have replaced daily X-ray imaging with surface imaging for select anatomical sites such as postmastectomy chestwall.[111] Ideally, surface imaging would also be used to monitor motion throughout treatment but this was not possible at their particular institution since the snout needed to be in close proximity to the patient's surface.

Several factors should be considered for installation of an SGRT system in a proton environment. Because proton vaults often do not have suitable concrete mounting locations for surface imaging cameras, the most stable locations are often attachments to steel structures that are part of the proton vendor's system. Such installations should involve discussions between both the proton and surface imaging vendors. Some installations, particularly proton rooms with full gantry setups may not offer a suitable location to place a camera inside the ring of the gantry, limiting either the surface imaging FOV or system accuracy. Often the available camera mounting locations are at different distances from isocenter than what might be typical in an X-ray linac installation. This may require different camera lenses or software settings by the vendor, and a compatible installation is not as predictable as with a typical X-ray linac installation. Additionally, the motion of large gantries leads to vibrations that may impact the calibration of an SGRT system. Each vendor may have different techniques for handling these variations and the QMP should understand how these will affect overall system performance and capabilities. The QMP should also verify the interface between the SGRT system and the couch, the couch coordinate system, and/or the gating interface in a proton system. Many related features available in typical linac installations may or may not be available in the proton setting such as beam gating or automatic couch control. While neutron damage to cameras should be considered, it is not expected to be significant based on the experience of operating facilities.

6.2.3 | SGRT as a QA tool

As with any practice, QA tests should be constructed based on the clinical use of the system. When the system is being used to regularly verify robotic couch motion, for example, QA tests should include similar phantom-based isocentricity verifications. In many cases, SGRT can also serve as a QA tool. For instance, couch mechanical motion can often be easily and quickly verified using SGRT.[112]

6.3 | The importance of risk analysis when adopting SGRT for emerging applications and workflows

The user should conduct a risk assessment for any emerging application or new clinical workflow that includes surface imaging. In the absence of specific QA recommendations from this protocol or others, risk analysis helps to determine appropriate QA testing and frequency. The patient workflow that incorporates surface imaging in any capacity should be defined and analyzed prior to use. Potential risks or weak points in the process may be considered prior to clinical implementation. In theory, the application of surface imaging to collision detection, for example, should reduce the risk of patient collisions. However, the analysis may also consider the introduction of new risks as with any addition or change to a process.

7 | KEY RECOMMENDATIONS

7.1 | Recommendations for SGRT QA

- Follow TG-142 and TG-147 guidelines
- Select a phantom that is appropriate for current SGRT systems with features such as sufficient salient topography, nonreflective or opaque for optimal visualization, interior or exterior fiducials for end-to-end testing.
- During commissioning, perform the end-to-end test from CT through treatment to verify coincidence of SGRT with other imaging modalities and the treatment isocenter; repeat whenever major equipment changes occur.
- During end-to-end testing, find the optimal HU value for skin contouring in the TPS that minimizes localization errors with SGRT, and become familiar with the effects of discrepancies between DICOM and SGRT surfaces arising from CT-related factors (e.g., resolution, scan speed, artifacts) on the accuracy of DICOM-based initial setup.

- Assess the effect of surface color on localization accuracy by testing with both light- and dark-toned phantoms when possible, particularly if an institution treats a significant portion of patients with darker skin tones.
- Evaluate whether the overall system latency is adequate for the clinical application including ROI size considerations.
- If SGRT is used to aid in initial positioning of the patient, then it is recommended to incorporate SGRT QA into the daily IGRT QA program.
- For treatment units with SGRT-enabled automatic beam hold, verify beam-hold capability using SGRT on a monthly basis per TG-142.
- Per TG-147, QA should be performed by or under the supervision of a QMP (see Section 3.1).

7.2 | Recommendations for DIBH for breast cancer treatment

- TG-76 guidelines should be followed regarding patient selection and coaching to obtain a reproducible breath hold and to acquire two CT scans (FB and DIBH) during simulation.
- Use DICOM or camera-acquired surface at CT when possible to quantify both systematic and random errors.
- Verify heart position for left-sided cancers with another IGRT modality (MV, fluoroscopy, CBCT, MRI, etc.) at first treatment and thereafter at least once per week.
- FB surface to be used for initial setup and to detect anatomical changes, which could manifest as discrepancies in registration between the "Entire" ROI versus the "Breast" ROI
- Treatment with bolus and field matching is acceptable and should be verified with another IGRT modality at least weekly.
- Enable automatic beam hold when possible.
- Selected tolerances should be institution-specific and will depend on surface type, immobilization, and setup workflow but should be reviewed and tightened as the institution gains experience; for a DICOM reference surface most clinics should be able to satisfy 2–3° rotational and 3–5 mm translational thresholds in each dimension.

7.3 | Recommendations for intrafraction monitoring for frameless SRS

- Use DICOM surface from CT simulation for initial setup; use a camera-acquired surface taken at treatment machine after verification with internal imaging (i.e., CBCT) for intrafraction monitoring
- The ROI used for tracking should include forehead, nose, temporal bones but exclude movable anatomy such as the chin and eyes.
- If repositioning is needed during the course of treatment, re-verify with internal imaging (e.g., CBCT) and reacquire a new camera-acquired surface to represent the new treatment position.
- A minimum tolerance of 1 mm may be used, but can be larger depending on the PTV margins used for planning and inclusion of couch walkout effects.
- Care should be taken when using SGRT for mono-isocentric treatment of multiple lesions, and tolerances may need to be decreased to ensure comparable target coverage.
- Consider use of 6DOF repositioning capability to increase setup and overall treatment efficiency.

8 | CONCLUSIONS

TG-302 provides guidance on clinical implementation of SGRT for three workflows that have been widely adopted as determined by a survey of physicists in the United States: general patient positioning, DIBH breast cancer treatment, and frameless SRS. While recommendations for reference surface type, ROI delineation, and threshold selection are provided for these workflows, the report emphasizes that each case must be assessed on an individual basis by the QMP. The treatment team should be prepared to recognize and troubleshoot situations that cause the registration output to deviate from expected performance, which have been described in the report. While QA requirements were enumerated by TG-147, this report highlights how phantom selection, reference image quality, ROI delineation, and potential system camera occlusions could affect the QA results. The role of SGRT in emerging clinical applications (e.g., collision detection and avoidance, biometric monitoring) and workflows (e.g., SBRT, proton treatment) was described. Finally, risk analysis to inform QA practice and to ensure safe implementation of SGRT into the clinic is recommended and demonstrated in the report.

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CONFLICT OF INTEREST

1. The members of AAPM Task Group 302 on surface-guided radiotherapy listed below attest that they have no

potential Conflict of Interest related to the subject matter or materials presented in this document:

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2. The members of AAPM Task Group 302 on surface-guided radiotherapy listed below disclose the following potential Conflict(s) of Interest related to subject matter or materials presented in this document.

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Data Sharing: No data are available for sharing.

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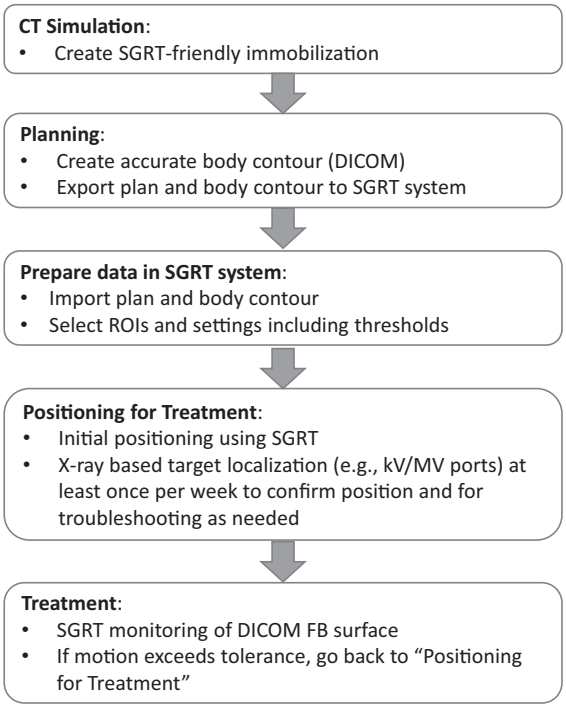
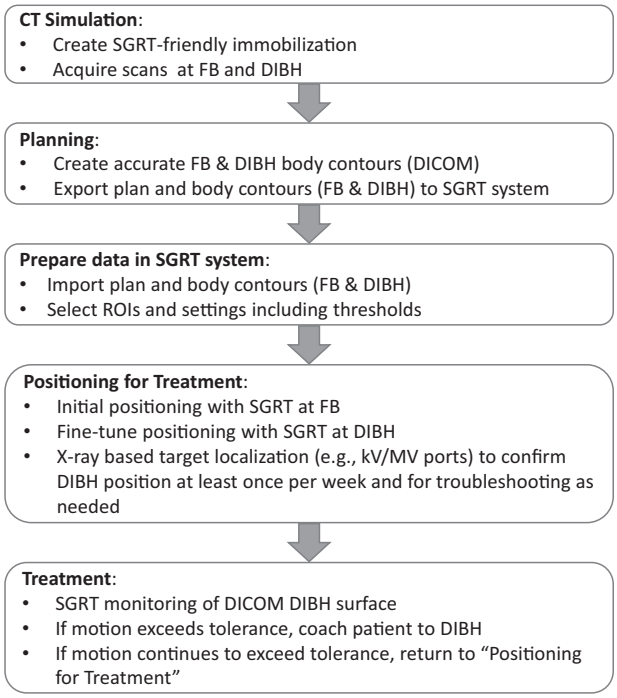
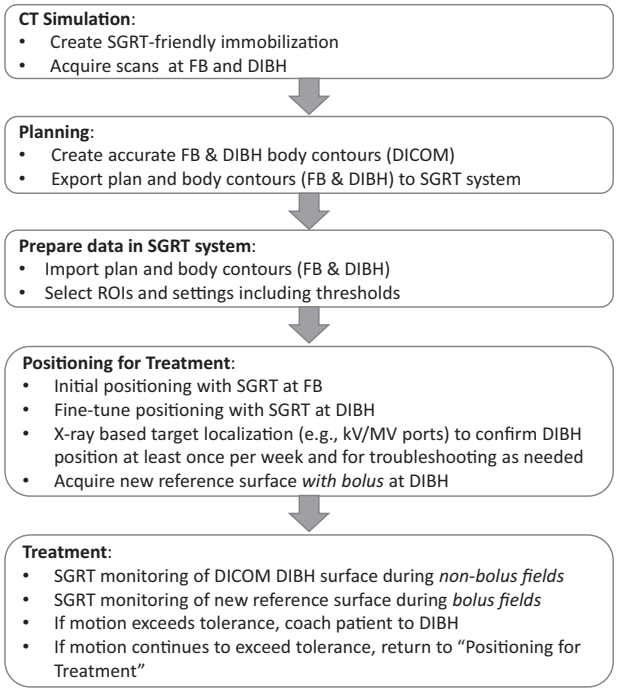
APPENDIX A
Workflow chart for free-breathing breast cancer treatment



APPENDIX B
Workflow chart for DIBH breast cancer treatment



APPENDIX C
Workflow chart for DIBH postmastectomy breast cancer treatment with bolus



APPENDIX D
Workflow chart for frameless SRS treatment

CT Simulation:
- Create SGRT-friendly immobilization

Planning:
- Create accurate head contour (DICOM)
- Export plan and head contour to SGRT system

Prepare data in SGRT system:
- Import plan and head contour
- Select ROI and settings including thresholds

Positioning for Treatment:
- Initial positioning with aid of SGRT head contour
- X-ray based target localization (e.g., CBCT)
- Acquire new SGRT surface at treatment position

Treatment:
- SGRT monitoring of new reference surface
- If motion exceeds tolerance, go back to "Positioning for Treatment"

APPENDIX E
Example of an SGRT process map