Quality assurance for image-guided radiation therapy utilizing CT-based technologies: A report of the AAPM TG-179

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Purpose: Commercial CT-based image-guided radiotherapy (IGRT) systems allow widespread management of geometric variations in patient setup and internal organ motion. This document provides consensus recommendations for quality assurance protocols that ensure patient safety and patient treatment fidelity for such systems.
Methods: The AAPM TG-179 reviews clinical implementation and quality assurance aspects for commercially available CT-based IGRT, each with their unique capabilities and underlying physics. The systems described are kilovolt and megavolt cone-beam CT, fan-beam MVCT, and CT-on-rails. A summary of the literature describing current clinical usage is also provided.
Results: This report proposes a generic quality assurance program for CT-based IGRT systems in an effort to provide a vendor-independent program for clinical users. Published data from long-term, repeated quality control tests form the basis of the proposed test frequencies and tolerances.
Conclusion: A program for quality control of CT-based image-guidance systems has been produced, with focus on geometry, image quality, image dose, system operation, and safety. Agreement and clarification with respect to reports from the AAPM TG-101, TG-104, TG-142, and TG-148 has been addressed.
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Key words: quality assurance, cone-beam CT, fan-beam MVCT, CT-on-rails

I. INTRODUCTION

The goal of radiation therapy (RT) is to deliver accurately a curative or palliative dose distribution to a well-defined target volume. Unlike dose calculation and measurement accuracy, the geometric accuracy of RT has been a challenge that could only recently have been quantitatively and pragmatically ascertained.[1] Lately, medical linear accelerator (linac) manufacturers and third-party vendors have developed integrated imaging systems to improve and facilitate internal patient anatomy visualization, enabling efficient positioning of these anatomical structures relative to the treatment room. These systems often use the accelerator isocenter as a reference point. The initial use of daily computed tomography (CT) has been for assessing internal organ position and defining the subsequent isocenter shifts to be performed at

TABLE I. Commercially available CT-based IGRT systems.

Make and model		Elekta XVI	Varian On-Board Imager	Siemens Artiste	TomoTherapy	Siemens Primatom
Imaging configuration		kV-CBCT	kV-CBCT	MV-CBCT	MVCT	kVCT-on rails
Field of view		$50 \times 50 \times 25.6$	$45 \times 45 \times 17$	$40 \times 40 \times 27.4$	40 cm	50 cm
Correction method	Translation	Automatic couch motion	Automatic couch motion	Automatic couch motion	Automatic in 2 directions	Manual couch motion
	Rotation	Optional	None	None	Optional	Optional
Geometric accuracy		Submillimeter	Submillimeter	Submillimeter	Submillimeter	Submillimeter
Dose (cGy)		0.1–3.5	0.2–2.0	3–10	0.7–3.0	0.05–1
Image acquisition and reconstruction time		2 min	1.5 min	1.5 min	5 s per slice	3 s per sec

the treatment unit.[2] Fan-beam MVCT has been introduced clinically by integrating it with helical tomotherapy based with IMRT-based dose delivery.[3] Megavoltage cone-beam CT (MV-CBCT) uses the accelerator's treatment beam and its portal imaging system to provide volumetric datasets with sufficient contrast for image-guidance[4,5] while kilovoltage CBCT (kV-CBCT) provides high contrast volumetric datasets using imaging components mounted orthogonally with respect to the treatment beam.[6] Clinical implementation of both kV-CBCT and MV-CBCT systems necessitates conducting calibration procedures that correct for accelerator and imaging component sags and flexes and to properly register to the treatment beam isocentre.[7] The clinical introduction of these guidance systems (Table I) has allowed the assessment and correction of patient positioning uncertainties, revealed internal organ motion and deformation, and is paving the way toward advanced and adaptive RT. By improving the geometric accuracy of RT, incremental improvements in tumor control probability, reduction in toxicity (thereby allowing dose escalation), conformal avoidance by intensity-modulated radiation therapy, and individualized PTV margins can be achieved. To fully exploit the information provided by these systems, clinics need to employ robust quality assurance (QA) programs that ensure that the system performance meets high expectations consistent with patient care requirements.[8] Due to the rapid deployment and adoption of image-guided radiation therapy (IGRT), clear and concise recommendations regarding clinical commissioning and QA of these technologies and their related clinical processes are desired by the community.

As of this writing, there exist no consensus guidelines for a comprehensive quality assurance of CT-based image-guidance systems. Early adopters of this technology have relied on the spirit of established standards, such as the AAPM TG-40 report,[9] vendor literature, experience acquired at the time of acceptance testing, and, less frequently, by assessing the long-term performance of this novel equipment by analyzing data from quality control (QC) tests. Early publications on quality assurance of CT-based IGRT systems have evaluated safety,[10] geometric accuracy,[7,11–17] image quality,[15,18–20] and imaging dose.[20–24]

Professional bodies interested in establishing QA and QC guidelines are beginning to expose device-specific QC to formal analysis of the frequency and severity of the risks or perceived failure modes involved with novel technologies. This is because many, if not most, undesirable events in RT have resulted from human error rather than equipment failure.[25] Users designing their own IGRT QA program should first identify clearly the clinical aims and align the QA needs to these aims, evaluating their resources to determine if additional resources are required. Physicists who are involved in starting CT-based IGRT technologies should study and understand not only the clinical potential of IGRT but also the intricacies of process design and development, workflow improvement, and change implementation within a busy clinic.

In this report, we present a succinct review of commercially available CT-based IGRT systems and present the general QA principles for these devices. This report concludes with a brief discussion of the safe and efficient implementation of these technologies.

II. EXISTING TECHNOLOGIES

II.A. CT-on-rails

Integrating a diagnostic CT scanner into a RT treatment room was perhaps the earliest implementation of volumetric image-guided radiotherapy. The first integrated clinical system combining a linac and an in-treatment-room CT unit was developed by Uematsu *et al.* in Japan.[26] The original system was primarily designed for noninvasive, frameless, fractionated stereotactic treatments of brain and lung cancers. The distinguishing feature of the integrated CT-linac system is the moving gantry CT scanner, which is mounted on rails (henceforth referred to as "CT-on-rails") so that it can move across the patient instead of the couch moving the patient through the scanner as in conventional CT scanner design. By rotating the treatment couch, usually by 180°, the couch is aligned with the CT gantry motion path, which acquires a patient's CT images while the patient remains in the immobilized position. Subsequently, the couch rotates back to the linac side to proceed with treatment. While diagnostic CT effective doses are in the range of 2 to 10 mSv,[27] imaging doses typically can be reduced further by a factor of 2–4 when used for daily targeting.[28] This is because the image quality from low-dose CT imaging is sufficient for image alignment.

II.B. Kilovoltage cone-beam CT

In the past several years, kV-CBCT has become an important tool for localization and patient monitoring in

traditionally fractionated and hypofractionated RT.[29–39] Traditional CT uses a fan shaped x-ray beam to acquire one or more thin slices (0.06–2.4 cm in length) per tube/detector rotation. In contrast, kV-CBCT uses a cone-shaped x-ray beam and acquires an entire volume (14–26 cm in length) in a single, relatively slow gantry rotation. To acquire the kV-CBCT projection data, flat-panel detectors are used in fluoroscopy mode, obtaining multiple projections per second, typically resulting in 2 projections per degree over 195–360° arcs. These projections are used to reconstruct the CBCT volumetric images.[4,40] Because of the high spatial resolution of the imaging panels, the kV-CBCTs can be reconstructed with submillimeter isotropic voxels. In radiotherapy applications, the kV-CBCT tube and detector are mounted on the same gantry as the linac treatment head, a configuration that is commercially available.[29,40] kV-CBCT produces a full CT data set that, though not of diagnostic quality, is generally adequate for imaging bone and, in some anatomic sites, soft tissue. kV-CBCT imaging dose varies widely with the acquisition technique. Doses ranging from 0.2 to 2 cGy per acquisition have been reported in the literature.[21,22,41] kV-CBCT image quality is limited compared to traditional CT for a number of reasons including motion blur due to the long acquisition time, scattered radiation due to the volumetric image acquisition, and image artifacts. Research is ongoing to alleviate these factors and likely to improve rapidly with advancements in acquisition techniques[42–44] and reconstruction algorithms.[45–51]

II.C. Fan-beam MVCT

The helical tomotherapy delivery system can be used to obtain fan-beam MVCT images of the patient in the treatment position.[52,53] The imaging beam is produced by the same accelerator that generates the treatment beam, but with the nominal electron beam energy reduced to 3.5 MeV for fan-beam MVCT.[54] In comparison with kV-CBCT (Sec. II A), those technologies using megavoltage beams for imaging suffer from fewer scatter and beam hardening artifacts.[55] Using megavoltage x-rays for imaging also eliminates artifacts normally caused when high-Z materials are imaged with kilovoltage x-ray beams. The megavoltage beam, however, inherently causes poor subject contrast.[56] During image acquisition, the beam is collimated to 4 mm at the isocenter and images are typically acquired with a *pitch value* of 1, 2, or 3, which translates into slice thicknesses of 2, 4, of 6 mm, respectively. The longitudinal extent of the scan is variable and is selected by the user. The field of view is 40 cm in diameter. The fan-beam MVCT imaging dose is typically in the range of 1–3 cGy per scan.[24]

Fan-beam MVCT image quality in terms of noise, uniformity, contrast, contrast linearity, and spatial resolution has been reported by Meeks *et al*.[19] Fan-beam MVCT scans are noisier than kVCT scans but the resulting low contrast resolution remains sufficient to identify some soft tissues.[19] Woodford *et al*. have tested the registration accuracy and precision of the fan-beam MVCT system using a set of anthropomorphic phantoms.[13,14] They have shown that the registration accuracy depends on the imaging slice thickness, pitch value, the superior-inferior scan length, and the scanned anatomical region. For head and thorax phantoms, registration accuracies in the ranges of 0.5–1.5 mm and 0.5–2 mm were reported, respectively. The registration error was dominated by the error in the superior–inferior direction.

II.D. Megavoltage cone-beam CT

As of this writing, the commercially available MV-CBCT system (Artiste™, Siemens, Concord, CA) consists of an a-Si flat panel adapted for MV imaging attached to a linear accelerator and an integrated workflow application to generate a three-dimensional representation of the patient in treatment position. Similar to fan-beam MVCT, the imaging beam is in the megavoltage range, thus rendering the images immune to typical high-Z artifacts. The system performs the acquisition of projection images, CBCT image reconstruction, automatic CT to CBCT volumetric image registration, and remote couch position adjustment.[57] This provides a 3D patient anatomy volume in the actual treatment position that can be aligned to the planning CT moments before the dose delivery, enabling the IGRT process. The MV-CBCT beam geometry is fixed by the manufacturer, with the flat panel positioned at 145 cm source-to-imager distance (SID). The field width is set by the manufacturer at 27.4 cm, which projects to the detector's 40 cm active region, and the field length is adjustable to a maximum of 27.4 cm. The MV-CBCT system can reconstruct a field of view of up to 27 cm, with a slice thickness ranging from 0.5 to 10 mm. The current generation of MV CBCT systems offers a half-beam acquisition mode, increasing the reconstruction size in the axial plane of up to 40 cm.

The MV-CBCT system demonstrates submillimeter localization precision[23,58–60] and sufficient soft-tissue contrast to visualize structures such as the prostate. The dose used for MV-CBCT depends on the clinical application but typically ranges from 3 to 10 cGy,[20,61] with the lower end used when daily acquisitions are performed on a patient, while 6 to 10 cGy are used for tumor monitoring studies or for treatment planning purposes. The imaging dose can be straightforwardly accounted for in treatment planning; so, published studies have used doses as high as 6–10 cGy per MV-CBCT scan.[20,61,62]

One benefit of the MV-CBCT system is its simplicity. There is only one x-ray source and one detector, the EPID. This geometry provides easier access to the patient by the therapists. The image is directly referenced to the beam, simplifying quality assurance of the system.[23,58]

III. TYPICAL CLINICAL APPLICATIONS

III.A. CT-on-rails

The CT-on-rails system produces diagnostic quality images. The use of the same imaging modality as that employed for treatment planning not only facilitates image registration to align the gross tumor volume (GTV) directly

but can also use the entire CT image set for adaptive replanning to account for interfractional anatomy changes. CT-on-rails systems have been used to study organ motion and soft-tissue localization for prostate cancer,[12,63–73] anatomy changes and their dosimetric impact in head and neck cancers,[74–76] and stereotactic hypofractionated lung and paraspinal cancer treatments.[77–84] The potential use of repeat in-room CT for online or offline adaptive radiotherapy has been studied by various researchers.[85–94]

III.B. kV-CBCT

In clinical applications, kV-CBCT offers a distinct advantage over projection imaging in that some soft tissue structures can be directly imaged and thus targeted. Two clinical sites that directly benefit by this are the prostate[95] and the lung;[31,96] the former cannot be directly targeted with projection imaging without implanted fiducial markers. kV-CBCT guidance is also utilized extensively in other treatment sites like head and neck,[97–99] breast,[36,100] esophagus,[101] liver,[102] and bladder.[103,104] Perhaps, the most important application of CBCT has been the simplification of hypofractionated, stereotactic body radiotherapy (SBRT). While robust patient immobilization for the long treatment times typical of this technique is still required, the high accuracy of kV-CBCT based target positioning has eliminated the need for body frames equipped with stereotactic coordinate systems.[32,105–108] Furthermore, the relatively low doses delivered by this modality permit more frequent patient position monitoring during those long sessions, reducing the effect of intrafraction position uncertainties.[109,110] kV-CBCT also makes adaptive planning possible, allowing for either margin reduction[104,111] or as a dataset for assessing dose-related anatomical changes.[112,113] Also, the intracranial stereotactic radiotherapy workflow has been adapted to benefit from the volumetric information obtained from CBCT.[114]

III.C. Fan-beam MVCT

Daily fan-beam MVCT-based alignments are performed typically for all patients who are treated with helical tomotherapy based IMRT. Alignments are based on soft tissue targets, bony anatomy, or implanted markers, depending on the visibility of the target in fan-based MVCT images. The use of fan-beam MVCT for alignments has been reported for prostate,[115,116] lung,[117] head and neck,[118,119] breast,[120] and gynecological tumors.[121] In addition to patient alignment, fan-beam MVCT imaging has been used to document anatomical variation for various anatomical sites. Lung cancer tumor regression measurements based on fan-beam MVCT imaging have been reported.[122–124] Deformation of the pelvic anatomy was reported for prostate patients.[125,126] Movement of the mesorectal space was evaluated on fan-beam MVCT images by Tournel *et al.*[127] The radiation response of an esophageal patient has been documented by Chen *et al.*[128] Li *et al.* report anatomical variations for kidneys, pancreas, uterus, and sarcomas.[129] Lastly, geometric changes in the parotid glands were reported for head and neck patients using fan-beam MVCT imaging.[130,131] Daily fan-beam MVCT scans can be used for dose calculations, and the variations of target and organ at risk doses have been reported.[126,130,132,133]

III.D. MV-CBCT

The MV-CBCT imaging procedure has been well integrated in the clinical workflow for the patient alignment and IGRT processes. Since the first MV-CBCT image of a patient was acquired in 2003,[4] many papers have reported on the clinical applications of MV-CBCT. These applications include prostate, head and neck, and lung alignments.[23,58,62] Other applications also include the monitoring of tumor growth and shrinkage[23,134] and more advanced IGRT strategies where a multiple adaptive plan IMRT procedure accounts for the independent movement of the prostate and pelvic lymph nodes.[135] MV-CBCT has been used clinically to improve the delineation of structures in CT images that suffer from metal artifacts, such as paraspinal tumors in proximity of orthopedic hardware,[136] pelvic structures in the presence of hip replacement prosthetics,[55] brachytherapy applicators and catheter visualization,[137] and, finally, the measurement of small lesions near metallic implants.[138] An emerging use of MV-CBCT images includes dose verification using dose recalculation[139–141] and dose-guided radiation therapy (DGRT), an adaptive strategy where treatment modifications are based on comparisons of the dose-of-the-day with the planned dose distribution.[142–145]

III.E. Stereotactic body radiotherapy requirements

SBRT is characterized by the accurate delivery of high doses of radiation in five or fewer fractions. When compared against conventional fractionation, the relatively high dose per fraction increases the potential for normal tissue damage or serious target underdosing, if even a single treatment is incorrectly delivered. Furthermore, it may be impossible to correct for radiation delivery errors by modifying subsequent fractions. Although the initial approach taken by SBRT developers was stereotactic in that the treatments were setup using body-frame coordinates, target position uncertainties due to organ motion and setup errors remained and were similar to those encountered with conventional radiotherapy. These spatial positioning issues have been addressed in large part by the widespread adoption of treatment machines with volumetric kilovolt or megavolt imaging capabilities. The geometric accuracy achieved by such machines has been deemed sufficient to permit bony or soft tissue localization or target-surrogates, and in many cases, normal tissues just prior to treatment, permitting immediate correction of initial and intrafraction geometric discrepancies. The AAPM Task Group 101 recommends the use of image guidance for all SBRT treatments to eliminate the risk of a geometric miss.[146]

Target or normal structure positioning relies on the ancillary imaging equipment in the treatment room, necessitating the development of a rigorous QA program. Patient safety, geometric accuracy (including linearity and alignment between the imaging system and the radiation isocenter), image quality, and spatial resolution need to be evaluated as part of a regularly scheduled QA program designed and managed by

medical physicists. Fortunately, geometric accuracy, localization, and geometric fidelity have been demonstrated, in a number of publications, to be well within 1 mm over extended periods of time.[7,11,12,15,17,18,147] The resolving power of CT-based IGRT systems can also be on the order of 1 mm under favorable scatter conditions, except for MV-CBCT where the localization accuracy is within 2 mm.[18,58] Such geometric accuracy is considered sufficient for both SBRT and conventional radiotherapy treatments.[1,148,149] Because of the critical importance of the imaging system in SBRT patient positioning, daily quality assurance checks of geometric accuracy are recommended. These checks can be easily made by imaging a phantom that has been positioned independently, with the room lasers, for example, and verifying that the setup correction is within tolerance. Because the geometric accuracy of CT-based imaging systems for image-guidance is inherently high, a well-designed QA program will satisfy simultaneously the requirements of conventional and SBRT radiotherapy.

Importantly, clinical and physiological process issues may ultimately affect the geometric accuracy of SBRT treatment delivery. While patients and tumors can be placed within the intended position immediately prior to treatment,[35,102,150,151] there is mounting evidence that internal and external patient motion displaces the target away from the intended position,[35,152–158] and patient position reassessment may be required throughout SBRT delivery depending on the chosen immobilization scheme, performance status, or length of time spent on the accelerator couch.[105,109]

IV. QUALITY ASSURANCE ISSUES

Recommendations from this report are summarized in Table II. These are generic test frequency and tolerance recommendations, representing the minimum imaging and registration performance needed for conducting IGRT with the technologies described in this report. Where noted, users can modify test frequency and tolerance according to clinical usage and machine capability, as specified elsewhere[159–161] and in Sec. II B of the AAPM TG-142 report.[160] Of note, image quality test frequency could be aligned with those of conventional CT scanners after sufficient experience with the image-guided systems. While this report is in full agreement with the AAPM TG-101 and TG-104, and TG-148 reports, a discrepancy, discussed in Sec. IV G, is noted for daily QC checks of CT-based IGRT technologies for SBRT as described in the TG-142 report. TG-179 is of the opinion that any major software or hardware upgrades that impact geometric accuracy, image quality, or imaging dose necessitate full recommissioning of the IGRT system. Likewise, service repairs and interventions should be followed by relevant and appropriate QC tests or baselines refreshing, as recommended by the manufacturer.

IV.A. Geometric accuracy

The value of CT-based image-guidance systems lies in their three-dimensional description of internal patient anatomy and its spatial relationship to the linac radiation isocenter. Therefore, for technologies where the imaging and linac radiation isocenters are mismatched (i.e., kV-CBCT, MV-CBCT, and CT-on-rails), the relationship between the two isocenters, henceforth termed geometric calibration, and the periodic testing of this calibration, must be considered carefully. It is recommended that the geometric calibration be tested daily (see Sec. IV G). The geometric calibration is typically expressed as a function of gantry angle since the

TABLE II. Summary of QC tests recommended for CT-based IGRT systems. Tolerances may change according to expectations, experience and performance.

Frequency	Quality metric	Quality check	Tolerance
Daily	Safety	Collision and other interlocks	Functional
		Warning lights	Functional
	System operation and accuracy	Laser/image/treatment isocentre coincidence OR	±2 mm
		Phantom localization and repositioning with couch shift	±2 mm
Monthly or upon upgrade	Geometric	Geometric calibration maps[a] OR	Replace/refresh
		kV/MV/laser alignment	±1 mm
		Couch shifts: accuracy of motions	±1 mm
	Image quality	Scale, distance, and orientation accuracy[a]	Baseline
		Uniformity, noise[a]	Baseline
		High contrast spatial resolution[a]	≤ 2 mm (or ≤ 5 lp/cm)
		Low contrast detectability[a]	Baseline
If used for dose calculation	Image quality	CT number accuracy and stability[a]	Baseline
Annual	Dose	Imaging dose	Baseline
	Imaging system performance	X-ray generator performance (kV systems only): tube potential, mA, ms accuracy, and linearity	Baseline
	Geometric	Anteroposterior, mediolateral, and craniocaudal orientations are maintained (upon upgrade from CT to IGRT system)	Accurate
	System operation	Long and short term planning of resources (disk space, manpower, etc.)	Support clinical use and current imaging policies and procedures

[a]These tests can be performed on a semiannual basis after stability has been demonstrated, 6–12 months after commissioning.

imaging and therapy system components flex during gantry rotation. A convenient method for performing kV-CBCT system geometric calibration, derived from the Winston–-Lutz procedure[162] and closely following the procedure described in Appendix G of the AAPM TG-66,[163] consists of placing a metal ball bearing (BB) near the radiation isocenter and using portal images acquired at the four cardinal angles to compare the ball bearing image centroid to the field edges. To eliminate imprecision in the jaw position, images are acquired with the collimator rotated by 180°. The ball bearing can then be moved iteratively toward the accelerator radiation isocenter until it indicates accurately the location of the isocentre.[7,164] Once positioned, the ball bearing images are obtained using the image-guidance system. Analyzing the apparent travel of the ball bearing on the projection images used for reconstruction of volumetric datasets provides a measurement of the components' flexing as a function of gantry angle. Once this relationship is known, the pixel coincident with the isocenter can be determined and the projection image pixel locations referenced to the isocenter pixel. A plot of the distance between the measured isocenter pixel and the pixel that would nominally intersect isocenter is termed a *flexmap*. The shifts identified in the measured flexmap are performed automatically by the image-guidance software. Not only does the flexmap correction remove the blur due to the imaging component flexes but also aligns the resulting image with the accelerator isocenter. The flexmap is typically measured at commissioning time, verified on a monthly basis, after system upgrades or after service that could potentially invalidate it.

While similarities exist between the kV-CBCT geometric calibration procedure and the Winston–Lutz test[162] used to verify the alignment of stereotactic radiosurgery frames and attachment equipment, the two should not be confused. The geometric calibration procedure described above expects flexes and other misalignments to occur and actively corrects them whereas the Winston–Lutz formalism assumes rigidity of all system components. The Winston–Lutz test is a comprehensive test to identify misalignment without explicitly identifying or correcting the cause of such misalignment.

Commercial vendors have proposed two automatic approaches to correct for system flex. The first approach is to digitally shift the projection images according to the measured flexmap prior to reconstruction of the volumetric datasets.[165] This first approach can take up to 2 h to perform, rendering it unsuitable for daily testing. The second approach consists of moving the image-guidance system x-ray detector according to the flexmap to ensure that the detector is always coincident with the radiation beam central axis.[16,166] The residual error is well below 1 mm after correction irrespective of the correction type for image-guided systems based on CBCT or for the CT-on-rails systems,[11,16] demonstrating that CT-based IGRT systems are capable of high geometric accuracy [typically, ±0.3 mm (Refs. 11 and 15)], irrespective of conventional or hypofractionated radiotherapy regimes. Users are cautioned, however, to perform the manufacturer recommended calibration procedures whenever service that could modify geometric calibration is performed on the IGRT components or after major software or hardware upgrades.

For fan-beam MVCT units, the imaging beam is generated by the same source that generates the treatment beam and the two beams share a common geometry. This leads to an inherent robustness of the MVCT imaging system geometry. However, the image acquisition, reconstruction, and registration process uses hardware and software components that have the potential to introduce geometric errors in the fan-beam MVCT IGRT process. The spatial and geometric accuracy of the fan-beam MVCT based IGRT system therefore needs to be tested routinely and consistently. Spatial accuracy and geometry tests for fan-beam MVCT are described in TG-148,[161] and the interested reader is referred to that task group for a detailed discussion. Briefly, on a daily basis, the image registration is tested for consistency, and the subsequent alignment process is tested for accuracy. A test of the image orientation and spatial integrity accuracy is recommended with a monthly frequency. An annual test of the imaging/treatment/laser coordinate coincidence is recommended. This is a phantom based end-to-end test intended to check the image registration and treatment delivery chain. A simultaneous test of the laser and imaging system coincidence with the imaging system enables the use of the laser system as a surrogate for the isocenter for daily and monthly consistency tests. Finally, the synchronization of the imaging and couch motions is explicitly tested. The test frequencies and tolerance values that are recommended in TG-148 are consistent with TG-142.

Similar to fan-beam MVCT, the CT-on-rails solutions offer high CT gantry motion rigidity and reproducibility. The alignment between the CT and the linear accelerator isocenter, however, does not have the same rigidity as does other CT-based image-guidance systems since the imaging and treatment equipment do not share a gantry. The treatment couch is rotated prior to align the patient with the CT scanner, and lateral and vertical shifts may be necessary to fit the couch through the CT bore. Under controlled conditions using rigid phantoms, CT isocenter to treatment isocenter alignment accuracy of better than ±1 mm has been demonstrated.[12] The clinical accuracy is expected to be worse because the process of rotating the patient couch into the CT imaging position introduces additional errors due to couch bearings eccentricity, patient motion, and the limited couch readout and control precision. Another approach to ensure high geometric accuracy is to image external fiducial markers, as is done during simulation, to transfer the radiation isocentre location into CT space. Fiducial markers, such as BBs, can be placed on the couch, immobilization device, or the patient's surface at the laser intersection. The couch coordinates of this location are recorded, enabling the BB images to act as registration markers, which couples patient location with couch coordinates. Shifts that will align the patient's anatomy with the planned isocenter can then be calculated and reported as updated couch coordinates. This method relies on the room lasers acting as accurate surrogates of the accelerator isocenter. The accuracy of this method is generally limited to the alignment of the room

lasers and to the couch readout accuracy and tends to be on the order of 1 mm. In either case, the 3D CT geometric accuracy should be checked annually and the alignment between the CT and the radiation isocenter or the lasers and the radiation isocenters should be checked daily. This can be done by imaging a device placed at radiation isocenter at a known offset, shifting based on an acquired CT, and verified with megavoltage portal images.

For MV-CBCT, a longitudinal (lateral) EPID positioning error will result in an error in the longitudinal (radial) position of the image isocenter with respect to the machine isocenter. Therefore, the positional accuracy of the EPID in the horizontal plane (i.e., the plane perpendicular to the beam central axis) is recommended to be checked daily by acquiring two portal images for a reticule with two orthogonal tungsten wires, one at a gantry angle of 0° and the other at 90°, and comparing the position of the projection of the crossing of the wires with the position of the central pixel corrected for the residual misalignments, with and without gantry sag effects.[23,58] EPID positioning errors with respect to the machine isocenter should not exceed 1 mm in the horizontal plane. The residual misalignments are recommended to be recalibrated and checked every 6 months. An error in the vertical position of the flat panel does not translate in an error in the reconstructed isocenter position, as the machine isocenter still projects to the center of the EPID. However, since the projection matrices derived during the geometry calibration procedure are only strictly valid at a SID of 145 cm, a vertical position error may result in some image distortion. Unlike the horizontal position, which is recommended to be checked daily, the vertical position of the EPID is recommended to be checked monthly, using a ruler, and with a recommended tolerance of ±5 mm. This tolerance was selected because an error of 1 cm in the SID results in a 0.7% magnification of the image.

A specialized phantom can be used to test MV-CBCT geometric accuracy and registration. The phantom is a cylinder with four tungsten beads placed 90° apart on the surface. The beads are positioned within a common transverse plane.[58] The position accuracy is checked by placing a reference point at the center of each bead in the CB image of the phantom and ensuring that the recorded position of that reference point is within 1 mm of the physical bead position in the phantom. To verify stability, this procedure can repeated five times, on five consecutive images of the phantom in the same position. A monthly check is recommended with all beads required to be within ±1 mm in the three principal directions.

IV.B. Image quality

The general principles of image quality QA for CT-based IGRT technologies follow those of fan-beam computed tomography systems (single and multislice third and fourth generation scanners operated in axial or helical modes) that have been described comprehensively in AAPM report 74[167] and reiterated in the AAPM TG-142 report.[160] Recommendations of this report are directly applicable to the CT on rails systems operating in a fan-beam mode. The design of other CT-based IGRT systems, summarized in Sec II A, differs from conventional CT scanner designs, utilizing a megavolt imaging beam and/or a cone beam geometry, differences that impact image quality.[168] Improvements in imaging physics and correction algorithms are required before image quality levels approach those achieved with fan-beam CT scanners. For commissioning purposes, the methodologies described in the AAPM report 74 have been adopted for CT-based technologies, with findings summarized below.[15,18–20] Evidence-based guidelines have not yet been established because few authors have repeated these tests over extended periods of time, so test tolerances and frequencies have not yet been determined.[18] At this stage, the AAPM TG-179 recommends that image quality tests be performed initially on a monthly basis, and ultimately on a semiannual basis, after parameter stability has been demonstrated by the users.

Technologies based on cone-beam geometry (i.e., MV-CBCT and kV-CBCT) require large area detectors, usually flat panel imagers (FPI) that are inferior, in terms of dynamic range and detector quantum efficiency, to the high quality detectors used in multislice CT scanners. Moreover, the large cone angle used by these technologies allow x-ray scatter to contribute undesirable signals to the reconstructed images.[40,169] As a result, x-ray scatter reduces soft tissue contrast, increases image noise, introduces cupping and capping artifacts in 3D reconstructions,[159,170,171] and reduces the reconstructed CT number accuracy.[18] Finally, blurring from internal structure motion affects the image quality since image acquisition takes up to 2 min.

The QA program of a CT-based IGRT system should be tailored to its utilization. IGRT systems are usually used to localize targets and organs at risk and drive correction strategies to minimize geometric uncertainties. Soft-tissue detectability is thus an important aspect of CT-based IMRT quality. CT number linearity and accuracy become important only if the CT scans are also used for dose calculation (e.g., patient too large for conventional CT bore or adaptive radiotherapy programs).

Most image quality control tests can be performed using commercially available phantoms that contain multiple inserts tailored to test various aspects of image quality. Examples include the CatPhan 500 phantom (The Phantom Laboratory, Salem, NY) or the AAPM CT performance phantom (CIRS, Norfolk, VA). Similar phantoms are being adapted for megavoltage imaging purposes (Siemens Medical Solutions, Concord, CA).[20,172] This section describes the general principles of these tests. It is recommended that the image quality tests be performed during system acceptance to obtain a system performance baseline that can thereafter be compared to quality assurance results acquired under identical conditions. For example, changes in the scatter environment (i.e., phantom size or field size) may yield spurious deviations from the baselines.[18] Measurements acquired over extended periods of time have shown that most image quality parameters do not vary much over time. Based on the available evidence and given the technological

improvements expected in a few years, the AAPM TG-179 recommends the test frequencies and tolerances presented in Table II. Users are justified to reduce the frequency of those image-quality tests marked by an asterisk to semiannual or upon extensive service after the stability of their own CT-based IGRT systems has been demonstrated.[18]

Several authors have reported on the scale and distance accuracy, low contrast resolution, spatial resolution, uniformity, and image artifacts.[15,17,18,20] These data are usually acquired by imaging one of the phantoms mentioned in the previous paragraph, therefore allowing several parameters to be analyzed, offline, using a single volumetric image acquisition.

IV.B.1. Scale and distance accuracy

Image scale and voxel size accuracy can be quantified by scanning objects of known sizes and comparing the object size in the image to the actual size. In general, CT-based IGRT systems have displayed distance accuracy well within 1 mm.[159] Deviations in scale and distance accuracy will affect image registration accuracy and may reduce patient positioning correction accuracy. Such deviations are likely to be caused by unintended changes in scanner geometry that could also degrade the spatial resolution. These changes should be fixed by the geometric accuracy calibration procedure described in Sec. IV A. A monthly test frequency is recommended initially, adopting a 6-month schedule when stability has been demonstrated.

IV.B.2. Low contrast resolution

Low contrast detectability requirements for a CT-based IGRT system are generally looser than for a diagnostic CT scanner. While the diagnostic CT scan is used to diagnose disease and identify the anatomy, the IGRT scan is mainly used for localization of the preidentified and segmented structures. Low contrast detectability is tested by scanning a phantom containing objects with a variety of linear attenuation coefficients. Contrast detectability depends on phantom size, object size, reconstructed voxel size, and imaging technique. It is, therefore, important to obtain the test images using clinically relevant parameters and keep these parameters constant for quality control checks. The visibility of 1% contrast objects that are 7 mm in diameter has been reported for kV-CBCT systems.[15,17] The fan-beam MVCT system can resolve 13 mm diameter objects with 2% density differences from background,[19] and MV-CBCT can resolve 2 cm objects with 1% contrast.[58] The required contrast resolution for clinical scenarios depends on the anatomical region. For example, the contrast difference between the prostate and the rectum is typically 2% while that between the normal breast tissue and a seroma cavity is 10–15%. The low contrast visibility should be tested against a baseline image on a monthly basis. Changes in low contrast detectability are likely related to changes in image noise and/or image uniformity. A monthly test frequency is recommended initially, adopting a 6-month schedule when stability has been demonstrated.

IV.B.3. Spatial resolution

Most CT-based IGRT systems clinically operate at a spatial resolution that is substantially lower than their best performance due to the large size of the volumetric datasets that would be obtained at full resolution. There is an intrinsic tradeoff between spatial resolution and low contrast detectability in computed tomography imaging. As the latter is more important for IGRT, spatial resolution can be compromised. Routine QA of the spatial resolution is, nevertheless, useful because a reduction in spatial resolution may indicate changes in scanner geometry and/or gantry angle readout calibration. Spatial resolution measurements are conducted by imaging a series of high contrast objects with suitable resolution objects, e.g., rods, plates, or bars, embedded in the image quality phantom. Authors report that spatial resolution is on the order of 6–9 line-pairs/cm for kV-CBCT,[15,17,18] and of up to 4 line-pairs/cm for MV-CBCT,[20] thus enabling visualization of high-contrast objects of 1–2.5 mm in size. In fan-beam MVCT images, the vendor's specification indicates that a 1.6 mm high contrast object should be resolved.[173] Spatial resolution has been shown to be independent of dose or location of the phantom with respect to the isocenter plane.[18] For routine QA, monthly spatial resolution evaluation against established baselines is sufficient.[159,160] A monthly test frequency is recommended initially, adopting a 6-month schedule when stability has been demonstrated.

IV.B.4. Uniformity and noise

Nonuniformities and artifacts can be easily detected during a visual inspection of a volumetric image of a uniform density phantom, such as a water bath or water-equivalent object.[174] The gray scale window width should be selected to reveal clinically relevant artifacts: examples of such artifacts are provided in the AAPM TG-104 (Sec. III B 6).[159] Ring artifacts are often caused by detector element malfunction and require recalibration of the defective pixels map.[175] Cupping artifacts (i.e., the center of the image of a uniform object appears darker than at the periphery) are mostly caused by scattered radiation. While commercial systems have cupping artifact correction calibrations, these calibrations occasionally cause their own artifacts.[170,171] These types of artifacts affect image uniformity, so scanning a uniform density phantom can provide quantitative image uniformity and noise values. Uniformity is characterized by the variability of the average signal over several small regions of interest (ROI) and should meet vendor specifications. Noise is characterized by the average signal variability over these ROIs and should also meet the vendor specifications. Note that rather than using multiple small ROIs, using a single larger ROI makes it difficult to decouple the effects of image noise and nonuniformity. Image uniformity may reduce with increasing object size because of the subsequent increase of scattered-to-primary x-ray fluence. Cone-beam CT systems are more susceptible to this effect, while fan-beam systems, such as CT-on-rails and tomotherapy, exhibit uniformity comparable to those of diagnostic CT scans,[19]

and such systems can hold the same generally accepted tolerances.[174] For cone-beam CT systems, repeating the uniformity measurements under conditions that were identical to acceptance testing will be important to be able to compare the results against the established baselines. For routine QA, comparing uniformity and noise with the established baselines is sufficient;[159,160] monitoring relative deviations is more useful than measuring absolute contrast values. A monthly test frequency is recommended initially, adopting a 6-month schedule when stability has been demonstrated.

Image nonuniformity also affects dose calculation accuracy. For fan-beam MVCT, for example, a maximum HU difference in peripheral and central ROIs of 25 HU is recommended in TG-148 if the images are to be used for dose calculations.[161]

IV.C. Image dose

CT-based IGRT has progressed rapidly as experience has shown it to be a good means for identifying and correcting geometric errors prior to initiating radiation therapy. Daily imaging doses are generally small compared to therapeutic doses but are distributed over the entire imaged volume. Dosimetric CT-based imaging studies have been published[10,22,24,172,176,177] and report dose ranging from 0.1 to 2 cGy/scan for kV-CBCT and 0.7 to 10.8 cGy/scan for MV-CBCT. For fan-beam MVCT images, the doses range from 0.7 to 4 cGy and depend on the selected CT pitch and the imaged anatomy thickness.[24] Dose can, therefore, cumulate from 3 to 370 cGy over a course of treatment, above the threshold doses reported in the literature for secondary malignancy occurrence.[178,179]

Image quality is intimately linked to imaging dose. It is, therefore, tempting to use relatively high mAs imaging techniques such as those used for diagnostic imaging, without reaching equivalent image quality for kV-CBCT, especially for large and low-contrast volumes. It is, therefore, justified to reduce the image dose while the task at hand (e.g., visualize bony anatomy to correct patient positioning) remains feasible and particularly indicated for smaller volumes containing high-contrast structures, such as head-and-neck. Strategies to achieve doses that are reasonably low may include reducing tube mAs, reducing the number of projections acquired for a whole scan or performing partial scans, reducing imaging frequency, or minimizing the field-of-view to reduce integral dose. Each of these strategies is the topic of current research.[119,180,181] Still, a compromise solution between the risk estimated from image doses must be balanced with the benefit offered (high precision treatment leading to reduced high dose volumes) and should be contrasted with the estimated risk from the extra doses that can result from IMRT and volumetric arc therapy.[182] At a minimum, each facility should evaluate the doses associated with each IGRT implementation and discuss the cost versus benefit with the radiation oncologists. This may be especially important in treating patients with long post-treatment life expectancies, such as pediatric patients. Simple measurement techniques and dose indices, usually variations on the CTDI dose indices used in conventional CT, have been suggested to describe imaging dose.[21,176,183] We refer the reader to the AAPM Task Group 75 report on advice on managing image dose for IGRT.[183]

IV.D. Accuracy of CT numbers

CT number accuracy becomes important when IGRT scans are used for dose calculations.[132,141,184,185] CT number accuracy is measured by scanning a phantom containing inserts with a wide range of electron densities and comparing the CT numbers in the image with the specifications for the inserts. CT numbers are defined as being proportional to linear attenuation coefficients, but individual scanners will exhibit inaccuracies in linear attenuation coefficient measurements. The relationship between electron density and linear attenuation coefficient for human tissues is bilinear.[186] CT number accuracy for CBCT suffers from the sensitivity of scatter-to-primary x-ray fluence to object and/or field size. The same holds true when a phantom size deviates from calibration conditions, so faithfully reproducing test conditions is crucial for obtaining meaningful quality control check results.[18,159,160] Research is ongoing to better correct for scatter contribution and thus improve HU integrity of CBCT scans. For these reasons, kV-CBCT does not provide quantitative CT because small deviations from acceptance phantom conditions significantly affect CT numbers. This is not the case for either fan-beam MVCT[132] or for CT-on-rails.[174] For fan-beam MVCT images, a monthly test of the HU calibration is recommended in TG-148. HU for materials with densities close to waterlike densities should be within 30 HU from the calibration data and within 50 HU for lung and bonelike materials. This test is recommended only if images are used for dose calculations.[161]

Because of the cupping artifact produced by scatter radiation and beam hardening, the calibration of MV-CBCT images is more elaborate than conventional fan-beam CT calibration. However, the smaller amount of scatter and the reduced energy dependence of the photon interactions in the MeV x-ray range produce a cupping artifact that is predictable. This allows for the use of simple nonpatient specific correction methods to improve the MV-CBCT image uniformity and provide accurate and stable CT numbers, making MV-CBCT suitable for dose recalculation. Using postprocessed images, dose calculations performed on MV-CBCT images agree with calculations conducted using conventional kVCT images within $\pm 1\%$ and 1–3% on phantom and patient images, respectively.[139–141,187]

Once the corrections mentioned above become available in released CT-based IGRT products, regular monitoring of the daily patient dose based on on-board images acquired of the patient on the treatment table can become a powerful tool for tracking the progress and accuracy of the treatment.[142,143,187]

IV.E. Image registration

Image registration is an important step in CT-based IGRT. Due to the nonrigid nature of patient's anatomy and

the limited correction methods, the "best" alignment may depend on the clinical case. A compromise between aligning soft tissue structures, bony, or implanted fiducial surrogates, and nearby critical structures, may be required. Selection between available intervention methods (simple couch translations, available couch rotations, online replanning methods, etc.) will also be required and will impact the registration method selection. At this writing, a uniform consensus for image registration quality assurance has not been developed, although the AAPM TG-132 is currently designing protocols for patient specific image registration and fusion software acceptance testing and quality assurance, so this area falls outside the scope of the current task group.

It should be pointed out that difficulties in differentiating soft tissues can arise with CT-based image-guidance systems. When soft tissue localization is ambiguous, it is prudent to adopt a two-staged image guidance approach. In this approach, automatic registration based on bony anatomy is used to identify and correct gross geometric discrepancies. Subsequently, manual or automated soft-tissue registrations are used to refine registration to improve the measurement accuracy. Users are cautioned to visually assess image registration accuracy not only over the target area but also in its surrounding volume. It is also highly recommended that the user establish site-specific clinical protocols to explicitly describe the volume of interest, alignment goals, and evaluation criteria.

Care should be taken to optimally derive a correction from a registration result. Ideally, the volumetric image registration algorithm should calculate both rotational and translational shifts; shifts that are too large for a specific treatment technology (e.g., any couch translation larger than 1 cm or rotation exceeding 3 degrees) might warrant repeating the patient setup procedure.[188] Careful assessment of the target position and rotation in combination with organs at risk or other anatomical landmarks should be performed; assistance with this task might be provided by projecting contours defined on the planning scan onto the daily volumetric image. As IGRT is employed to empower adaptive radiation therapy, commercial vendors will have to develop reliable algorithms to account for deforming or moving anatomy over a single treatment or an entire radiation therapy course and suggest test methods with the collaboration of early adopters.[189]

IV.F Accuracy of remote-controlled couch

A key component to any image-guidance system is the patient positioning device. This device typically involves a motorized, remote-controlled couch that translates the patient along three-axes.[190] A couch with 6 degrees of freedom (3 translations and 3 rotations) is also commercially available.[191,192] Patient positioning corrections need to be both accurate and precise to realize the full potential of IGRT. The accuracy and precision of correction movements should be assessed during commissioning. Submillimeter couch position accuracy has been demonstrated, for several commercial couches, using high-precision calipers,[190] portal imaging,[7,193] optical navigation systems,[194] film,[195] and the image-guidance system[196] itself. These data suggest that couch motion accuracy is well within the vendor-provided specifications or the tolerances suggested by the AAPM TG-142 report (i.e., $\pm 2\text{mm}/1^{\circ}$)[160] and should suffice for high-precision radiotherapy and SBRT. However, authors typically recommend repeating such procedures during regularly scheduled QA activities but fail to specify test frequency. Tracking the trends from repeating these tests over extended periods of time may guide appropriate test frequencies, as well as what long-term accuracy is achievable, but such time trends have not yet been reported.

The AAPM TG-179 recommends that the tolerances for accuracy of remote-controlled couches match those specified in TG-142. One benefit from the end-to-end QC test described in Sec. IV G is that the accuracy of couch motions is tested on a daily basis. Therefore, Table II does not specify additional recommended tests to those of TG-142.

IV.G. Daily operational issues

This task group recommends that daily CT-based IGRT QC tests be performed. The primary rationale for daily QC procedures is to identify any sudden performance changes or gross errors that could result from collisions, upgrades, or afterhours service. Another benefit of daily QC is to obtain a record of the geometric accuracy of the therapy equipment, using a more efficient procedure than the lengthy but more precise monthly procedure described in Sec. IV A. The rapid daily procedure described below inherently involves other routine QC items, such as warming up the x-ray tube, reporting certain warning messages and system interlocks, and verifying there is sufficient disk space for the work day.[159] In some implementations, the imaging equipment is positioned by powerful robotic arms that move near the patient, creating a potential for injury. Thus, the daily QC procedures also need to ensure the touch panels or motion interlocks are all functional.

Simple, integral tests have been described to check the overall CT-simulation processes accuracy,[163] and similar tests, with adapted phantoms, have been proposed for image-guidance systems.[8,15,159,197,198] A variety of methods have been proposed to achieve this goal. Cubic phantoms with a marker placed at the center can be aligned with the linac isocenter using room lasers or portal images; volumetric phantom images would therefore measure the isocenter localization accuracy.[8] A phantom with multiple markers at known positions would provide additional assessments, such as volumetric image orientation,[8] confirm source-to-imager distance,[197] assess image sharpness,[198] and even assess dose.[199,200] Typically, these phantoms are aligned to the accelerator isocenter using the room lasers, thereby speeding up the execution of the daily test at the cost of relating accuracy to the laser system rather than directly to the isocenter. A tolerance of ± 2 mm has been demonstrated for such daily geometric accuracy assessment; the accuracy should be confirmed with orthogonal portal images of the phantom.[11]

A variant of the daily QA procedure can be implemented to assess communication between the image registration software and the remote-controlled couch, to verify couch motion accuracy, and to provide a rapid end-to-end test of the IGRT process.[8,11,201] The image acquisition and registration software is typically independent of the treatment couch control system; hence, the software provides an objective measure of the couch positioning accuracy and precision. The "residual correction error" is a useful measure of the targeting and couch correction accuracy. This value can be estimated by first placing a phantom at isocenter and then displacing the phantom at predefined distances in three directions; this displacement is independently measured. The displacement should be less than 2 cm in any cardinal direction because remote-controlled movements for most IGRT couches are currently limited to 2 cm to reduce the likelihood of patient–machine collision. The daily QA procedure should also avoid repeated, trivial, or clinically irrelevant displacement magnitudes. For example, a displacement of (1,1,1) cm in the (L/R, S/I, and A/P) directions would not expose an error where the coordinate axes were mismatched between a scan from the CT-based image-guidance system and a reference CT scan.

After the displacement is applied, a localization image dataset is acquired to assess what couch motions are required to align the phantom to its nominal position. To mimic patient treatments, a reference CT scan of the phantom is used as a surrogate of the CT simulation scan. The shift is determined by comparing the localization and simulation images and a suggested couch shift is determined. The shift is applied and a verification image dataset is acquired and registered again to the reference CT dataset. The displacement indicated from registering the verification dataset to the reference CT defines the residual couch correction error. The residual error obtained with this simplified geometric accuracy check should be 0 ± 2 mm, based on a 95% confidence interval.[11] Repeated measurements of this residual error define the systematic error (mean) and the uncertainty (standard deviation) of the targeting and correction system; again, submillimeter accuracy has been reported on phantom studies.[202] However, the overall accuracy has been shown to depend on the IG modality (2D or 3D, kV or MV),[203] the x-ray technique (kV_p, mAs, or MUs), the target (fiducial or soft-tissue or bony matching), and the targeting method (manual or automatic). This daily QA procedure creates confidence in the IGRT system accuracy and precision. It is also useful for technical and clinical staff training as well as to provide a quick check after scheduled or unscheduled service events or other mishaps, such as a collision.

It should be noted that the tolerance supported by published data for daily geometric accuracy test is 0 ± 2 mm to a 95% confidence interval, in agreement with the AAPM TG-101 report.[11,146] The AAPM TG-142 report recommends that daily tests of IGRT systems demonstrate an accuracy of ± 1 mm for SBRT techiniques[160] while the AAPM TG-104 report does not distinguish between conventional and hypofractionated techniques.[159] The AAPM Task Group 179 is consistent with the TG-101 and TG-104 reports for a number of reasons. As described above, the daily test aims to detect gross, unintentional misalignments that may be caused by collisions, service, or research activities performed after hours. Second, the daily procedures described in this section provide rapid assessment of geometric accuracy, system integrity, and functionality; this rapidity is achieved at the cost of a reduced test precision relative to the geometric calibration procedures described at the beginning of this section. Daily geometric tests need to be performed in short amounts of time, and accuracy is compromised because the user manually aligns the phantom with room lasers and because the accelerator component flexes and torques are under sampled when only orthogonal portal images are used to assess coincidence of all isocenters. Finally, for some systems, manual image matching introduces further uncertainties in the test.[11] The AAPM TG-179 stresses that the complete geometric calibration procedure described in Sec. IV A has proven the submillimeter accuracy of CT-based IGRT devices over extended periods of time; repeating this procedure whenever extensive service or upgrades are performed should maintain a high, submillimetric geometric accuracy that suffices to both conventional and hypofractionated radiotherapy fractionation schedules. Verifying the geometric accuracy using the geometric calibration procedure described in Sec. IV A can take up to 2 h and so is inappropriate for daily QC.

V. COMMISSIONING THE IMAGE-GUIDED PROCESS

Clinical experience with CT-based image-guidance technologies is steadily growing. These technologies can achieve several aims. First, they can increase radiotherapy accuracy by verifying the patient position with respect to the treatment beam immediately prior to irradiation. Second, the enhanced geometric accuracy can be used to review and perhaps reduce setup margins for PTV design, leading to reduced doses to organs at risk and perhaps escalating dose. Finally, IGRT may also empower adaptive radiotherapy because clinicians can assess anatomical changes seen during a course of radiation and rationally respond to those changes. Secondary aims of IGRT might include replacing film or portal imaging to document positional accuracy, manage inter- and intrafractional organ motion during radiotherapy, or measure the actual efficacy of immobilization accessories. Thus, first-time users of this technology should ascertain which of these aims are desirable for their own clinical contexts and tailor their commissioning and QA programs accordingly.

One strategy for implementing wide-scale IGRT is to build on several short-term successes, starting with acceptance testing of the first CT-based IGRT device to develop image-guidance protocols. Several initiatives can be performed in parallel. Multidisciplinary teams can build their confidence in the IGRT process, using end-to-end tests where a phantom is treated exactly like a patient, from CT simulation to treatment delivery. Such end-to-end tests simulate the process in a multidisciplinary environment, help

identify and resolve issues, and develop expertise. Other issues include the following:

- developing an appropriate nomenclature for clearly and systematically communicating and documenting image-guided measurements;
- assessing performance under a clinical load;
- defining an appropriate frequency of site-specific image guidance protocols; and
- defining the roles, responsibilities, and involvement of team members in the image-guidance process

A powerful motivating factor for multidisciplinary teams is the clinical research required to establish safe and efficient clinical operation. Specific operating issues include obtaining soft-tissue contrast on volumetric datasets using doses lower than or comparable to portal imaging opens the possibility of frequent and accurate positioning of the patient at the onset of each treatment.[35,109,110] Teams can test and benchmark CT-based IGRT against portal imaging guidance, initially using rigid phantoms and end-to-end tests,[7] followed with patient studies.[36,95,96,99,105,204] Often, such studies involve verification imaging to assess the accuracy of the position correction; this build clinicians' confidence in the IGRT process accuracy. In parallel, a QA program must be established to ensure the safe, reliable, and consistent operation of the CT-based image-guidance technology,[175] accounting for the goals and aims to be achieved with such guidance systems, be it simply the correction of geometric uncertainties to empowering an adaptive radiotherapy protocol for routine use.

Clinical patient studies are introduced gradually, selecting a few anatomical sites prior to broadening the use of image-guidance across all anatomical sites.[205] Depending on the comfort and confidence levels of users, initial anatomical site groups can be selected based on (i) research or personal interests, (ii) sufficient patient volume to allow clinical team to learn without overloading it (about five patients initially on a treatment unit), (iii) difficulty of the imaging process, as influenced by visualization of soft tissues and mobility of internal organs, and (iv) when image contrast gains offered by kilovoltage over portal imaging are immediately obvious (lung, pediatrics, and brain). Coordination meetings help share the findings from various site groups and identify infrastructure issues, such as nomenclature, documentation of the image-guidance protocols, disk space, and defining data archiving requirements. A team with representation from all disciplines (i.e., therapists, physicists, and physicians) should be involved in the development of site-specific IGRT techniques. The team should develop an initial image-guidance procedure considering the following:

- definition of the initial positional accuracy requirements in the clinic;
- recommendation of appropriate imaging techniques for specific anatomical sites;
- keep radiation doses low;
- identify appropriate immobilization accessories;
- document results from end-to-end image guidance testing; and
- identify obstacles or potential pitfalls for safe and efficient use of the technology.

Subsequently, the analysis of positional data from end-to-end testing will help the team reassess setup margins, tolerances for residual positional errors, and opportunities for dose escalation. Vendors have an obligation to provide user training, and administrators need to allow extra time for staff to learn the new process, over the course of a few months, while making teams aware of the fiscal constraints that need to be met once the new IGRT processes are stabilized. Each team should fully document site-specific image-guided processes, with clear statements of accuracy requirements. These documents can then be used as learning tools for other staff.

Depending on the aims of individual clinics in implementing IGRT, the time and resource commitment to implement CT-based IGRT technologies differs between clinics around the world and between imaging systems. Table III summarizes the collected experiences of AAPM TG-179 members as an estimate of the resource needs to maintain image-guidance programs with CT-based technologies. Clinics are advised to plan for additional resources from radiation therapy, radiation oncology, and medical physics for successful wide-scale implementation of CT-based image guidance technologies and processes.

TABLE III. Estimated human resources required for image guidance using CT-based IGRT technologies. Estimates are obtained from the collected experiences of the task group members. More time is required when performing commissioning and quality control testing of 2D functions on some platforms.

Activity	Responsibility	Time	Notes
Acceptance testing and commissioning	Physicists	2.5 days	
Education	Physicists	2 days	First install only
	Therapists	2 days	First install only
	Dosimetrists	2 days	First install only
Operation	Therapists	5 mins/patient	Each treatment with IGRT; includes image acquisition and evaluation
	Dosimetrists	10 min/patient	Data transfers to imaging platform
Review of images	Physicians	5 min/scan	0 when performed by therapists
Daily quality control tests	Therapists	10 min	
Monthly quality control tests	Physicists	1–2 h	
Annual quality control tests	Physicists	2–4 h	
Continued clinical support	Physicists	0.05 full-time equivalent position	Ad hoc activity

VI. CONCLUSIONS

CT-based image-guidance systems have the potential to profoundly change how RT is delivered. The quality control protocols employed for these devices are highly dependent on their intended use. Since the primary aim of image-guidance is to detect and correct positional uncertainties, particular attention should be paid to their geometric accuracy assessment. As PTV margins become tighter, the geometric accuracy of radiation therapy delivery systems becomes as important as the dosimetric accuracy, warranting implementation of daily QC procedures.

Image quality requirements for QA differ, however. While most of the commercially -available systems are capable of visualizing bony anatomy, air, and some soft tissue, their performance is subject to variations caused by the x-ray scatter environment and beam hardening, both of which degrade image contrast, noise, and uniformity. For some configurations, it may be more difficult to use directly images from IGRT systems for soft tissue target alignment or for treatment planning because the CT number accuracy is object-dependent. The tests described in this report and corroborated in the reports from the AAPM TG-101, 104, 142, and 148 propose guidelines for test tolerance and frequency of testing should be based on the intended use of the images.

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