ACR–AAPM TECHNICAL STANDARD FOR MEDICAL PHYSICS PERFORMANCE MONITORING OF IMAGE-GUIDED RADIATION THERAPY (IGRT)

The American College of Radiology, with more than 40,000 members, is the principal organization of radiologists, radiation oncologists, and clinical medical physicists in the United States. The College is a nonprofit professional society whose primary purposes are to advance the science of radiology, improve radiologic services to the patient, study the socioeconomic aspects of the practice of radiology, and encourage continuing education for radiologists, radiation oncologists, medical physicists, and persons practicing in allied professional fields.

The American College of Radiology will periodically define new practice parameters and technical standards for radiologic practice to help advance the science of radiology and to improve the quality of service to patients throughout the United States. Existing practice parameters and technical standards will be reviewed for revision or renewal, as appropriate, on their fifth anniversary or sooner, if indicated.

Each practice parameter and technical standard, representing a policy statement by the College, has undergone a thorough consensus process in which it has been subjected to extensive review and approval. The practice parameters and technical standards recognize that the safe and effective use of diagnostic and therapeutic radiology requires specific training, skills, and techniques, as described in each document. Reproduction or modification of the published practice parameter and technical standard by those entities not providing these services is not authorized.

PREAMBLE

This document is an educational tool designed to assist practitioners in providing appropriate radiologic care for patients. Practice Parameters and Technical Standards are not inflexible rules or requirements of practice and are not intended, nor should they be used, to establish a legal standard of care[1]. For these reasons and those set forth below, the American College of Radiology and our collaborating medical specialty societies caution against the use of these documents in litigation in which the clinical decisions of a practitioner are called into question.

The ultimate judgment regarding the propriety of any specific procedure or course of action must be made by the practitioner considering all the circumstances presented. Thus, an approach that differs from the guidance in this document, standing alone, does not necessarily imply that the approach was below the standard of care. To the contrary, a conscientious practitioner may responsibly adopt a course of action different from that set forth in this document when, in the reasonable judgment of the practitioner, such course of action is indicated by variables such as the condition of the patient, limitations of available resources, or advances in knowledge or technology after publication of this document. However, a practitioner who employs an approach substantially different from the guidance in this document may consider documenting in the patient record information sufficient to explain the approach taken.

The practice of medicine involves the science, and the art of dealing with the prevention, diagnosis, alleviation, and treatment of disease. The variety and complexity of human conditions make it impossible to always reach the most appropriate diagnosis or to predict with certainty a particular response to treatment. Therefore, it should be recognized that adherence to the guidance in this document will not assure an accurate diagnosis or a successful outcome. All that should be expected is that the practitioner will follow a reasonable course of action based on current knowledge, available resources, and the needs of the patient to deliver effective and safe medical care. The purpose of this document is to assist practitioners in achieving this objective.

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1 *Iowa Medical Society and Iowa Society of Anesthesiologists v. Iowa Board of Nursing, 831 N.W.2d 826 (Iowa 2013) Iowa Supreme Court refuses to find that the "ACR Technical Standard for Management of the Use of Radiation in Fluoroscopic Procedures (Revised 2008)" sets a national standard for who may perform fluoroscopic procedures in light of the standard's stated purpose that ACR standards are educational tools and not intended to establish a legal standard of care. See also, Stanley v. McCarver, 63 P.3d 1076 (Ariz. App. 2003) where in a concurring opinion the Court stated that "published standards or guidelines of specialty medical organizations are useful in determining the duty owed or the standard of care applicable in a given situation" even though ACR standards themselves do not establish the standard of care.*

I. INTRODUCTION

This technical standard was revised collaboratively by the American College of Radiology (ACR) and the American Association of Physicists in Medicine (AAPM).

This technical standard is intended to provide guidance for quality assurance (QA) of systems used for external-beam image-guided radiation therapy (IGRT) (or image guidance), including: communication of modality, frequency, and alignment tolerances for imaging; and what QA processes should be implemented to ensure that the directives are followed. IGRT is a general term that addresses the application of imaging to the entire process of radiation therapy. However, in this document, IGRT discussion is limited to only the imaging used in the treatment room.

The goal of radiation therapy is to deliver radiation to the target volumes as precisely and accurately as possible while minimizing dose to critical normal tissues. IGRT is the process of using various imaging techniques to locate target and critical tissues and, if needed, reposition the patient for radiotherapy delivery. Image registration techniques are used to determine the amount of adjustment of the patient and therefore the target relative to the treatment beam. The basic imaging tools employed in IGRT have remained essentially the same since the publication of the ACR–AAPM Technical Standard on IGRT in 2014. However, advancements in IGRT techniques have seen the outgrowth of the subdiscipline of surface guided radiation therapy, and the ongoing paradigm shift toward adaptive radiation therapy, in which image guidance is coupled with image registration and replanning to generate an "updated" treatment plan that is "adapted" to the current patient anatomy if it is sufficiently different than that from the time of the initial planning.

II. QUALIFICATIONS AND RESPONSIBILITIES OF QUALIFIED MEDICAL PHYSICIST

A Qualified Medical Physicist is an individual who is competent to practice independently one or more of the subfields in medical physics. The American College of Radiology (ACR) considers certification, continuing education, and experience in the appropriate subfield(s) to demonstrate that an individual is competent to practice one or more of the subfields in medical physics and to be a Qualified Medical Physicist. The ACR strongly recommends that the individual be certified in the appropriate subfield(s) by the American Board of Radiology (ABR), the Canadian College of Physics in Medicine (CCPM), the American Board of Science in Nuclear Medicine (ABSNM), or the American Board of Medical Physics (ABMP)

A Qualified Medical Physicist should meet the ACR Practice Parameter for Continuing Medical Education (CME). [1]

The appropriate subfield of medical physics for this technical standard is Therapeutic Medical Physics (previous medical physics certification categories that include Radiological Physics and Therapeutic Radiological Physics are also acceptable). (ACR Resolution 17, adopted in 1996 – revised in 2008, 2012, 2022, Resolution 41f)

With the advancement of imaging technologies and new techniques being developed on IGRT, a Qualified Medical Physicist may not have the necessary experience on a particular IGRT technique and must be trained accordingly before implementing or performing the new IGRT technique in the clinic.

The Qualified Medical Physicist is responsible for the technical aspects of IGRT. Those responsibilities should be clearly defined and should include the following:

1. Planning and acquiring the appropriate IGRT systems for the program.
2. Acceptance testing and commissioning of the IGRT system(s), thereby ensuring its mechanical, software, and geometric precision and accuracy as well as its image quality verification and documentation. These generally include, but are not limited to:
    a. Communication with the treatment planning system
    b. Communication with the treatment delivery system
    c. Communication with the Oncology Information System
    d. Communication amongst multiple IGRT systems

e. Evaluation of adequate image quality and imaging dose
f. Testing of image registration software and application of results to patient shift coordinates
g. Communication of patient data between storage, retrieval, and display devices

3. Implementation and management of a QA program for the IGRT system(s) to monitor and ensure each of the following:
    a. Image quality to produce clinically useful images while keeping the imaging dose as low as possible.
    b. The geometric relationship between the image guidance system and the treatment delivery system.
    c. The proper functioning of the registration software that compares planning image data sets with IGRT data sets.
    d. Safety, gating, and treatment interlocks are functional.

4. Development, implementation, and documentation of standard operating procedures together with the radiation oncologists and pertinent team members for the use of IGRT (including how, when, and who is to perform the IGRT procedures for each patient treatment protocol, and the appropriate sequencing when multiple IGRT technologies are available and will be employed for treatment of a single patient).

5. Appropriate services, upgrades, and repairs are maintained.

III. IGRT METHODS

Imaging has been used to verify patient position since the earliest days of external-beam radiation therapy. The first method of imaging internal anatomy to verify the patient's position on the treatment couch used the treatment beam to expose radiographic film. These images are called port films and are acquired during the treatment course with a frequency that varies but is often at the start of treatment and weekly thereafter. This may be considered as the earliest form of IGRT. Portal imaging remains an important part of patient treatment management, even though radiographic films have been replaced by electronic imaging detectors. Several imaging techniques have been developed over the years to improve the accuracy of the patient positioning/target verification process.

Ultrasound and in-room computed-tomography (CT) were two early methods for routine volumetric imaging at the time of treatment delivery. Digital 2-D techniques were developed along a similar timeline and have evolved into 3-D and/or 4-D methodologies [2,3]. One of these 2-D methods uses the treatment beam to generate portal images on an electronic imager (or flat panel detector) that can be compared with treatment planning images. An important addition to all of these techniques is the implementation of computer software that manually or automatically registers the current image data set with the planning or reference image set to determine the treatment couch shifts (and/or rotations), which are then executed to correctly align the target to the treatment field. Another development of the in-room 2-D imaging approach is the use of dual electronic imager(s) and kilovoltage (kV) X-ray sources mounted in a fixed geometry in the treatment room to provide stereoscopic information to identify the the target's position. The use of kV energies produces better image quality compared with portal images acquired with the megavoltage (MV) treatment source. Some manufacturers mount the kV X-ray source and electronic imager on the treatment unit so that orthogonal images can be sequentially obtained with a simple rotation of the gantry.

Other innovations implemented by various linear accelerator manufacturers include integrated spiral data acquisition using a narrow MV beam at lower energy than the treatment beam to produce CT images of useful quality. Another technique that has become a standard feature of modern linear accelerators is cone beam CT (CBCT). CBCT is acquired using an integrated rotating large-field x-ray source and an opposing flat panel detector. After a full or partial rotation of the device around the patient, standard CT reconstruction algorithms are used to generate volumetric representations of the anatomy. This 3-D volumetric data set is aligned to the data set from the planning CT as part of the image guidance process.

Magnetic resonance imaging (MRI) has been introduced for IGRT in the last 10 years (ie, MR-guided radiation therapy (MRgRT)). The major advantage of MRI is its superior soft-tissue contrast, allowing more accurate delineation of target and organs-at-risk (OARs) and robust image registration with the planning CT. The initial

design of the commercially integrated MRgRT unit combined an MR scanner with a specially designed teletherapy machine. Newer MRgRT units are linear accelerator-based with a more powerful magnet for the MR scanner. Regardless of the design, the ultimate goal in MRgRT is to address intrafraction motion.

The various technologies currently available for in-room patient setup and target localization are summarized below. The differences inherent in the design of each IGRT system dictate the appropriate QA procedure that is needed for its safe clinical implementation. They are fundamentally described as either 2-D planar, 3D surface, or volumetric approaches.

1. 2-D planar

- kV X-ray head with opposed electronic imager panels mounted on treatment unit for obtaining two or more fixed views of the patient's anatomy.
- Dual kV X-ray heads with opposed imaging electronic imager panel mounted at fixed positions in the treatment room.
- Electronic imager panel mounted on the accelerator unit opposed to the treatment beam for obtaining two or more fixed views of the patient's anatomy.
- Acquisition of 2-D kV images during treatment triggered by elapsed time, monitor units delivered, gantry angle, and/or breathing motion.

2. 3-D surface

- Systems that use cameras and/or surface-mapping systems for external localization.

3. 3-D volumetric

- Ultrasound unit.
- In-room diagnostic CT.
- kV X-ray head with opposed electronic imaging panel mounted on treatment unit for CBCT.
- Incorporation of respiratory signal with 3-D CBCT to obtain 4-D CBCT.
- Electronic imaging panel mounted on the accelerator unit opposed to the treatment beam for obtaining MV CBCT images, with one view using a kV electronic imager and another view using MV electronic imager.
- A narrow MV beam with opposed detector for spiral CT data acquisition.
- MR guided systems

For 2-D IGRT, the process begins with the construction of a reference image set, such as 2-D digitally reconstructed radiographs or surface rendering from the treatment planning CT data set. A 3-D IGRT process uses the entire treatment-planning CT image set as the reference data set. These reference images are compared with the online IGRT images obtained before and/or during the treatment delivery process. The patient is repositioned based on the congruence of these image data sets such that the images are aligned to within some predetermined localization criteria. In this manner, the treatment will be delivered precisely and accurately according to the treatment plan approved by the radiation oncologist. Implicit in this IGRT approach is the assumption of rigid target geometry.

For the purpose of this technical standard, the software components that facilitate image registration and provide the shift coordinates for the patient support system are considered to be an essential part of the IGRT system. Additionally, improvements in motion management during IGRT, while applying separate technologies and methods, will also be considered as an essential component of IGRT in this technical standard.

Given this wide spectrum of IGRT methodologies, it is difficult to devise a single generic test procedure that is appropriate for guaranteeing the safe use of this integral technology. However, this technical standard will describe the features of tests that should be included so that the potential for error is minimized. This information will allow individual institutions to compare a particular QA procedure against this list of essential features.

The record of the IGRT procedure registered in the radiation oncology information system should be reviewed to confirm accurate reporting on the session in terms of applied displacements and timeline.

IV. IGRT QA

IGRT offers the possibility of improving the accuracy and precision of dose delivery in radiation therapy and is an important advancement in terms of margin reduction to better limit the dose to critical structures. However, similar to the changes in QA procedures that occur with the adoption of any new emerging technology, the introduction of in-room imaging to the radiation therapy process also leads to additional QA procedures for the dose delivery system. It is critical that a QA program addresses the equipment, procedures, and safety of image guidance.

One of the most important IGRT QA components is to guarantee accurate geometric alignment of the imaging system with the treatment delivery system [7,8]. This QA procedure must be designed to include tests to ensure that the image registration part of the IGRT process performs within the stated tolerances. QA methods must also be incorporated to evaluate the accuracy of motion management techniques in order to ensure optimal image registration. Moreover, QA tests to evaluate image quality must be performed periodically when IGRT is used. Given the recent availability of special patient support systems that allow translational and rotational position corrections, the tests must also include some verification of the performance of this part of the IGRT chain.

The frequency of testing of the coincidence between the radiation and mechanical isocenters for machines delivering various types of plans has been recommended by AAPM Task Group (TG)-142 and TG-226 (MPPG #2.b) [8,9][]. However, it should be performed at least each month when standard fractionation treatments are scheduled. It should be performed each morning when stereotactic radiosurgery, stereotactic radiation therapy, or stereotactic body radiation therapy treatment is scheduled.

IV. IGRT QA

A. Equipment Performance and Integration

An image guidance system consists of components to acquire images (radiation sources, detectors, and their mechanical assemblies), measure position (image alignment tools), and perform adjustments (interfaces and equipment for position adjustment). Each of these components requires validation before implementation as well as routine checks to ensure safe and effective utilization.

1. Image quality

Image quality is typically characterized by physical measurements, such as contrast, uniformity, resolution, and signal-to-noise ratio. It can also be evaluated by its impact on the performance of a person or alignment system that uses the images (eg, via a receiver operating characteristic curve). It is important that consistent measurement methods and phantoms are used for image-quality evaluation and that the methods are ultimately tied to the ability to use these images in practice. AAPM TG-142, TG-179, and TG-226 (MPPG #2.b) provide recommendations for comprehensive and essential QA practices, respectively [8-10][].

2. Mechanical integrity

Whether room-mounted and stationary, mounted on rails, or gantry-mounted and moving, imaging equipment must be able to maintain a known relationship to the treatment coordinate system (isocenter). The configuration and its stability should be established and monitored . AAPM TG-142 and AAPM TG-226 (MPPG #2.b) provide recommendations for the comprehensive and essential QA practices, respectively [8,9].

3. Registration software

IGRT equipment has both manual (eg, visual alignment) and automated image registration tools. These tools have advantages and limitations and should be understood by evaluation prior to patient imaging. Accuracy and reproducibility of alignment results should be tested using images similar to those acquired in a clinic and used in patient treatments. AAPM TG-142 and AAPM TG-226 (MPPG #2.b) provide recommendations for the comprehensive and essential QA practices, respectively [8,9,]).

4. Motion-management system

Use of motion management in IGRT may be done by multiple methods. Each of these methods requires its own evaluation for accuracy and effectiveness. Appropriate QA testing of each methodology should be done before its incorporation into the IGRT process. AAPM TG-76 and AAPM TG-142 contain recommended guidelines for QA and implementation of respiratory motion management, with AAPM's TG-290 focusing specifically on the application of respiratory motion management to particle therapy [8,14,15], TG-135 (and forthcoming TG-135U1) addressing Quality Assurance for robotic radiosurgery, and TG-264 highlighting implementation of multileaf collimator tracking in radiotherapy.

5. Imaging dose

Imaging parameters and associated doses for different IGRT applications should also be carefully assessed as defined by AAPM TG-75 and its complementary AAPM TG-180 [16,17]. It is important to clearly understand the imaging dose to the whole imaging volume for each IGRT procedure, especially when it applies to children or motion imaging. Note that the imaging volume is much larger than the treatment volume, so care should be taken to consider nontarget tissues receiving the imaging dose [16].

6. System integration

An appropriate phantom is essential for IGRT implementation. There are many commercially available QA phantoms for testing integration of IGRT systems. These phantoms and various test devices often come with a description of the recommended test procedure. It is essential that users verify the appropriateness of the test equipment and procedures to ensure the accuracy and precision of the different IGRT systems in their clinic, such as, for example, the congruence of the imaging and treatment isocenter in both 2-D and 3-D imaging systems and the proper functioning of the image registration software in terms of accuracy in positioning and repositioning (couch shifts) [11]. The results of any component testing, and the end-to-end testing, must be documented in detail because that forms the baseline values for all subsequent tests of the IGRT systems.

7. User- and technology-dependent issues

Ultrasound imaging localizes the interfaces of tissues that have different acoustic impedances. Whether ultrasound images are aligned to reference ultrasound or CT images, issues, such as interobserver variability, difficulty standardizing scanning techniques, and organ motion that is due to probe pressure, all affect accuracy in verification of patient positioning and should be appropriately considered in safe and effective use of ultrasound for positioning [18].

The use of cameras and/or surface imaging is not generally considered stand-alone image guidance for patient positioning because of the lack of internal anatomical information. Its utility for initial patient positioning and motion management must typically be supplemented with another form of internal imaging for verification. It is most useful for initial positioning and as a real-time surface monitoring aid to therapists as well as for cases requiring beam gating. AAPM TG 147 provides guidelines and recommendations on clinical implementation and QA procedures for nonradiographic localization systems [19].

Most Qualified Medical Physicists in radiation therapy are neither sufficiently trained in MRI nor qualified to perform QA of the MR scanner, and, more importantly, identify artifacts and differentiate them fromreal patient anatomy. It is prudent that a Qualified Medical Physicist with sufficient working knowledge of MRI be present at least in the first fraction of MRgRT and be available in subsequent fractions. This may necessitate seeking guidance from outside of the Radiation Oncology Department, from a Qualified Medical Physicist in diagnostic imaging or an MR Scientist.

8. Information technology

The introduction of IGRT creates a substantial amount of image data and associated information requiring storage and management. Information systems to manage the patient data, image data, treatment data, clinical trials data, etc, can be quite challenging (eg, data must be in Digital Imaging and Communications in Medicine (DICOM)

Radiation Therapy-RT format, HIPAA compliant, and accessible from multiple systems) and expensive, despite advancements in computer technology. The efficiency of storage, retrieval, and display may have significant impact on the clinical operation and information accuracy. The information flow from storage to retrieval should be tested for its accuracy, efficiency, and integrity [20]. Often, a number of information systems are involved in a single radiation oncology facility; effective and accurate communication between these systems should be ensured when implementing IGRT processes [21].

IV. IGRT QA

B. Correction Strategies

Use of image guidance involves determining a strategy for selecting when to image, which method to use (eg, ultrasound, X-ray, CT, or MRI), and how to use the acquired images. Appropriate staff qualifications and training must be considered. It is critical that implementation and maintenance of IGRT be supported by a rigorous program of documentation and training [3]. It is also important to maintain adequate staffing (a backup team for example) for each step in the IGRT process.

There exist three classes of correction strategies. The most common is online measurement and position adjustment. For online adjustment, decisions should be made about the tolerance for a correctable action, taking into account both the accuracy with which measurement and correction can be realistically applied and the sensitivity of plan objectives to these actions. Offline corrections based on retrospective analysis of images from prior fractions need appropriate testing mechanisms to correctly evaluate and implement the measured adjustments [22]. The last method, adaptive adjustment and plan modification, will require a plan-dependent decision process to be put in place [6,23].

The QA team, consisting of physicians, physicists, dosimetrists, and therapists, should work as a group to define image-guidance and correction strategies [24]. Tests of a given strategy should be performed to ensure that the processes and documentation are sufficient. Of significant importance is a practical understanding of the limits of information available for alignment. A physician's specific knowledge may be needed for image evaluation at the treatment unit. It is recommended to have a Qualified Medical Physicist available during the IGRT process to help solve issues that may arise on the imaging device, image registration, couch movements, etc. The practical tradeoff between treatment margins and the effort required to correct for errors needs to be evaluated. Another error component that IGRT does not address is target delineation uncertainty, which can be potentially significant [25]. The issue is even more critical in deformable image registration, but its broad scope precludes its inclusion in this technical standard.

IV. IGRT QA

C. Patient Dose

Imaging dose assessment is an important component for IGRT QA as recommended in AAPM TG-75 and AAPM TG-180 [16,17]. AAPM TG-75, TG-180, and TG-226 (MPPG #2.b) provide a useful overview of methods for measuring imaging dose from various IGRT modalities. These methods should aid the quality management program in the process of dose management [9,16,17]. IGRT methods using ionizing radiation will deliver an absorbed radiation dose to the patient and irradiate a significantly larger region than the treatment volume. Management of the IGRT doses requires radiation physics expertise because (1) the method of measuring dose depends on the imaging geometry (eg, 2-D or 3-D, fan beam or cone beam) and (2) comparing generalized diagnostic imaging metrics, such as air kerma or CT dose index, with individualized therapeutic absorbed doses is nontrivial. On the other hand, MR does not result in radiation dose to a patient. MRgRT is an established though continually evolving IGRT technique that has seen increasing clinical usage. It is expected to play an increasingly significant role in image-guided adaptive radiation therapy [26].

AAPM TG-75 [16] and AAPM TG-226 [11] provide a useful overview of methods for measuring imaging dose from various IGRT modalities. These tools should aid the quality management program in the process of dose management. Image quality is to be judged based on the critical endpoint of the IGRT process: targeting. This

endpoint provides a distinction in IGRT image quality that is different from that associated with diagnostic image quality. Thus, to control IGRT patient dose, it is recommended to implement dose management techniques that decrease the ionizing radiation imaging dose without affecting targeting whenever possible.

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*As of May 2015, all practice parameters and technical standards that are collaborative with only the American Association of Physics in Medicine are approved by the ACR Council Steering Committee and the ACR Board of Chancellors and will not go through the ACR Council (ACR Resolution 54, 2015). The effective date is the first day of the month following a 60-day period that begins on the date the document was approved.

Development Chronology for this Technical Standard

2009 (Resolution 5)

Revised 2014 (Resolution 36)

Revised 2019 (CSC/BOC)

Amended 2022 (Resolution 41f)
Revised 2024 (CSC/BOC)- Effective July 1st, 2024