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Revised 2014 (Resolution 36)*

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

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 care¹. 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 in light of 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 the condition of the patient, limitations of available resources, or advances in knowledge or technology subsequent to publication of this document. However, a practitioner who employs an approach substantially different from the guidance in this document is advised to document in the patient record information sufficient to explain the approach taken.

The practice of medicine involves not only the science, but also 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 sole purpose of this document is to assist practitioners in achieving this objective.

¹ Iowa Medical Society and Iowa Society of Anesthesiologists v. Iowa Board of Nursing, ___ N.W.2d ___ (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 of systems used for external beam image-guided radiation therapy (IGRT) (or image guidance) and adaptive radiation therapy. IGRT is a general term addressing the imaging application in the entire process of radiation therapy. However, in this document, IGRT discussion is limited to only imaging application in the treatment room. For the purposes of this document adaptive radiation therapy will not be discussed as it is not fully matured methodology.

The goal of radiation therapy treatment is that radiation be delivered to the planned target volumes as precisely and accurately as possible while minimizing dose to critical normal tissues. IGRT is a process of using various imaging techniques to locate target and critical tissues and, if needed, reposition the patient just before or during the delivery of radiotherapy. Image fusion techniques are used to determine the amount of adjustment of the patient position and therefore the target relative to the treatment beam.

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, or by the American Board of Medical Physics (ABMP)

A Qualified Medical Physicist should meet the [ACR Practice Parameter for Continuing Medical Education \(CME\)](#). (ACR Resolution 17, 1996 – revised in 2012, Resolution 42)

The appropriate subfield of medical physics for this technical standard is Therapeutic Medical Physics. (Previous medical physics certification categories including Radiological Physics and Therapeutic Radiological Physics are also acceptable)

If the above training did not include IGRT, then specific training in IGRT should be obtained prior to performing any IGRT procedures.

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

1. Acceptance testing and commissioning of the IGRT system, thereby assuring its mechanical, software, and geometric precision and accuracy, as well as image quality verification and documentation. This includes:
 - a. Communication with the treatment planning system
 - b. Communication with the treatment delivery system
 - c. Evaluation of adequate image quality and imaging dose
 - d. Testing of image registration software and translation to patient shift coordinates
 - e. Communication of patient data between storage, retrieval, and display devices

2. Implementation and management of a QA program for the IGRT system to monitor and assure each of the following:
 - a. The geometric relationship between the image guidance system and the treatment delivery system.
 - b. The proper functioning of the registration software that compares planning image datasets to IGRT datasets.
3. Together with the radiation oncologist, development, implementation and documentation of standard operating procedures (SOPs) for the use of IGRT (including how, when, and who the IGRT procedures should be done for each patient treatment protocol).

III. IGRT METHODS

Imaging has been used to verify the patient position since the earliest days of external beam radiation therapy (EBRT). The first methods 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. Port films remain an important part of patient management. In recent years, a large number of other imaging techniques have been developed to improve the accuracy in 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 more recently evolved into 3-D and/or 4-D methodologies [1,2]. One of these 2-D methods uses an electronic imager (or flat panel detector) that, similar to the port films, uses the treatment beam to generate images that can be compared to treatment planning image information. An important addition to all of these techniques is the implementation of computer software that manually or automatically registers the 2 image datasets (planning or reference and periodic or online in-room imaging) so that the treatment table shift (and/or rotation) information is generated and automatically executed in the treatment room. A new development of the in-room 2-D imaging approach is the use of additional electronic imager(s) and kV x-ray sources to provide approximately orthogonal stereoscopic information that can be rapidly gathered to identify the position of a target in space. These implementations often use x-ray generators that are in the diagnostic energy range to obtain better image quality as compared to traditional treatment portal images. In addition, some imaging systems mount the x-ray sources and electronic imager using a fixed geometry in the treatment room. Other manufacturers mount the x-ray source and electronic imager to the treatment unit so that stereotactic images can be sequentially obtained with a simple rotation of the gantry around the patient.

Other innovations have also been implemented by various linear accelerator manufacturers. These include integrated spiral data acquisition using the treatment beam to produce CT images that are otherwise analogous to the imaging available from diagnostic helical CT scanners. Another technique that has been gaining popularity uses an in-room 2-D imaging system to collect the projection data in 2 dimensions so that a full-volume representation of the anatomy can be reconstructed with a single full or partial rotation of the device around the patient. Standard CT reconstruction algorithms are used to build a volume image of the patient; the technique is called cone-beam CT (CBCT) imaging. Similar to the 2-D approaches described above, either the treatment beam can be used for this type of imaging or a diagnostic x-ray head can be mounted on the gantry of a standard accelerator system to improve image quality.

Systems that use the treatment beam are typically referred to as mega-voltage (MV) imaging systems, whereas those using a diagnostic x-ray source are kilo-voltage (kV) imaging systems. For some MV imaging systems, beam tuning and/or target are changed to improve image quality. A recent innovation incorporates the use of magnetic resonance (MR) imaging for IGRT applications.

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

- Ultrasound unit
- In-room diagnostic quality CT scanner
- kV x-ray head with opposed electronic imager panel mounted on treatment unit for cone-beam CT (CBCT)
- kV x-ray head with opposed electronic imager panel mounted on treatment unit for obtaining 2 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 2 or more fixed views of the patient's anatomy
- Electronic imager panel mounted on the accelerator unit opposed to the treatment beam for obtaining megavoltage cone beam computed tomography images One view using kV electronic imager and another view using MV electronic imager
- A 1-D MV beam with opposed 1-D detector for spiral CT data acquisition
- Systems that use cameras and/or surface mapping systems for external localization.
- MR systems [3-6]

For 2-D IGRT, the process begins with the construction of a reference image set, such as 2-D digitally reconstructed radiographs (DRRs) from the treatment planning CT dataset. 3-D IGRT utilizes the entire treatment planning CT image set as the reference images. These reference images will be compared to the online IGRT images obtained before and/or during the treatment delivery process. The patient will be repositioned based on the congruence of these image datasets such that the images align 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 important new technology. However, this technical standard will describe the features such a test should include 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.

IV. IGRT QUALITY ASSURANCE

IGRT offers the possibility of significantly enhancing the accuracy and precision of radiation therapy methods and is an important advance in terms of margin reduction to better limit the dose to critical structures. However, similar to the changes in the QA procedures that occur with the adoption of any new emerging technology, the introduction of this in-room imaging step in the radiation therapy process also leads to additional QA procedures for the dose delivery system. It is critical that a QA program address 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 assure that the image registration part of the IGRT process performs within stated tolerances. QA methods must also be incorporated to evaluate the accuracy of motion-management techniques in order to assure optimal image registration. Moreover, QA tests aimed at monitoring the image quality must be performed periodically when IGRT is used. Given the recent availability of special patient support systems that allow pitch and roll positioning corrections, the tests must also include some verification of the performance of this part of the IGRT chain.

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 prior to 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, resolution, and noise. 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 operation 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 practices. AAPM TG-142 and TG-179 provide recommendations for best and minimum QA practices, respectively [8,9].

2. Mechanical integrity

Whether room-mounted and rigid or gantry-mounted and moving, imaging equipment must be able to maintain a known relationship to the treatment coordinate system. The configuration and its stability should be established and monitored (eg, checking of flex maps for centering projections as a function of angle in a gantry mounted system). AAPM TG-142 and TG-226 provide recommendations for best and minimum QA practices, respectively [8,10].

3. Registration software

IGRT equipment has both manual and automated alignment tools. These tools have advantages and limitations, should be understood by evaluation prior to patient imaging. Accuracy and reproducibility of alignment results should be tested using images similar to those expected to be acquired in a clinic. AAPM TG-142 and TG-226 provide recommendations for best and minimum QA practices, respectively [8,10].

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 prior to its incorporation into the IGRT process. AAPM TG-76 and AAPM TG-142 contain useful recommended guidelines for QA and implementation of respiratory motion management [8,11].

5. Imaging dose

Imaging parameters and associated doses for different IGRT applications should also be carefully assessed as defined by AAPM TG-75 [12]. It is important to clearly understand the imaging dose to the whole imaging volume for each IGRT procedure, especially when it applies to motion imaging. Note that the imaging volume is much larger than the treatment volume [12].

6. System integration

There are many commercially available QA phantoms for testing IGRT systems, and an appropriate phantom should be considered essential for IGRT implementation. 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 to ensure the accuracy and precision of the different IGRT systems in their clinic.

The following list describes elements of a typical end-to-end test that can be used to evaluate an IGRT system:

- a. A solid phantom that includes a number of high-contrast markers and line patterns can be used to verify the performance of the IGRT system. A motion simulator may be used in conjunction with the phantom to evaluate motion-management strategies.

- b. The procedure should start with a CT simulation process that scans the phantom to locate the position of the markers (or targets and critical organs).
- c. The treatment planning system is used to target each marker with at least 2 small treatment fields that are orthogonal or near orthogonal.
- d. The phantom is positioned within the coordinate frame of the delivery system in accordance with the previously generated treatment plan. Setup deviations from planned treatment are introduced by displacing the phantom with translations of known magnitude. Rotational errors can also be introduced to test the correction process when a patient support system with 6 degrees of freedom is available.
- e. After phantom imaging and image registration, the calculated translational and/or rotational displacements are applied in accordance with the clinical procedure for error corrections. Positioning errors are commonly corrected by treatment couch displacements controlled remotely from the delivery system console. Verification images should be taken after positioning to validate the intended shifts.
- f. An independent imaging system (eg, electronic imager or film) is then used to demonstrate that the markers appear with the small treatment fields at the predicted position.
- g. The record of the IGRT procedure registered in the radiation oncology information system should be inspected to confirm accurate reporting on the session in terms of applied displacements and timeline.

The test frequency has been recommended according to TG-142 [8]. However, it should at least be performed each month when standard fractionation treatments are scheduled. It should be performed each morning when stereotactic radiosurgery (SRS), stereotactic radiation therapy (SRT), or stereotactic body radiation therapy (SBRT) treatment is scheduled.

Intrafraction monitoring systems have emerged in recent years [13-18] but have not seen widespread usage since early reports on clinical intrafraction motion management in 2002–2003 [11,19-21]. Use of these systems requires testing with phantoms that provide both expected movements and related signals to the imaging and/or sensing systems.

7. User- and technology-dependent issues

Image guidance is unique in that routine operation involves alignment, a potentially subjective process. An observer's ability to discern soft-tissue changes using the different IGRT technologies can vary widely. In some cases, it is extremely difficult to directly view the target tissues as well as critical structures that are to receive a reduced dose relative to the prescription. In these situations, some surrogate must be used instead. Although surrounding bony structures are often used to verify positioning, there must be a careful determination that variation of the location of the target and surrounding critical structures relative to the bony landmarks is adequately compensated for with the use of appropriate margins. It is sometimes possible to use implanted metal markers as a surrogate for the positioning of the target or targets. This approach also requires QA steps aimed at guaranteeing that the markers accurately indicate the extent of the target tissues, and that in a brachytherapy treatment, the seeds do not migrate from the time of treatment planning through the entire treatment delivery course.

Ultrasound imaging localizes 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 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 [22].

8. Information technology

Introduction of IGRT allows accurate targeting of the treatment beam to tumors. On the other hand, it also creates substantial amount of image data and associated correction information for management. It therefore requires the effective management of vast amounts of imaging data and patient information. Information systems to manage the patient data, image data, treatment data, clinical trials data, etc, can be quite challenging. 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 [23]. Often, a number of information systems are involved in a single radiation oncology facility; effective and accurate communication between these systems should be considered when implementing IGRT processes [24].

B. Correction Strategies

Use of image guidance involves determining a strategy for selecting when to measure, which method to use (eg, laser, x-ray, CT), and how to act on a measurement. Included in these decisions are selection of appropriate staff qualifications and training. It is critical that implementation and maintenance of IGRT be supported by a rigorous program of documentation and training [2].

Three classes of correction strategies exist. The most common is online measurement and adjustment of position. 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 appropriately tested mechanisms for correctly evaluating and implementing measured adjustments [25]. The last method, adaptive adjustment and plan modification, will require a plan-dependent decision process to be in place. At present, adaptive therapy and a related technology deformable image registration are still too early in the developmental stage for appropriate guidelines to be given.

The QA team, consisting of representatives from physicians, physicists, dosimetrists, and therapists, should work as a group to define image-guidance and correction strategies [26]. Dry runs 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. The practical tradeoff between treatment margins and the effort required to correct for errors needs to be evaluated. Another contribution to error that IGRT does not address is target delineation uncertainty, which can be potentially significant [27], but its broad scope precludes its inclusion in this technical standard.

C. Patient Dose

Imaging dose assessment is an important component for IGRT QA as recommended in AAPM TG-75 [12]. IGRT methods using ionizing radiation will deliver an absorbed radiation dose to the patient that can in some situations be a significant portion of the prescribed dose for treatment. Furthermore, x-ray imaging irradiates a significantly larger region than the treatment volume, and therefore doses to critical structures may be larger than intended. 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, to individualized therapeutic absorbed doses is nontrivial.

AAPM TG-75 [12] and TG-226 [10] 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 that dose management techniques that decrease the ionizing radiation imaging dose without affecting targeting be implemented whenever possible.

ACKNOWLEDGEMENTS

This technical standard was revised according to the process described under the heading *The Process for Developing ACR Practice Parameters and Technical Standards* on the ACR website (<http://www.acr.org/guidelines>) by the Committee on Practice Parameters and Technical Standards -Medical Physics of the ACR Commission on Medical Physics in collaboration with the AAPM.

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GLOSSARY

AAPM	American Association of Physicists in Medicine
ACR	American College of Radiology
ART	Adaptive radiation therapy
CBCT	Cone-beam CT
CCRT	Computer-controlled radiation therapy
CT	Computed tomography
DDR	Digitally reconstructed radiographs
EBRT	External beam radiation therapy
IGRT	Image-guided radiotherapy
IMRT	Intensity modulated radiation therapy
kV	kilovoltage
MV	Megavoltage
QA	Quality Assurance
SRS	Stereotactic radiosurgery
SRT	Stereotactic radiation therapy
SBRT	Stereotactic body radiation therapy

*Practice parameters and technical standards are published annually with an effective date of October 1 in the year in which amended, revised, or approved by the ACR Council. For practice parameters and technical standards published before 1999, the effective date was January 1 following the year in which the practice parameter or technical standard was amended, revised, or approved by the ACR Council.

Development Chronology for this Technical Standard

2009 (Resolution 5)

Revised 2014 (Resolution 36)