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AAPM task group 224: Comprehensive proton therapy machine quality assurance

Bijan Arjomandy[a)]
Karmanos Cancer Institute at McLaren-Flint, McLaren Proton Therapy Center, Flint, MI, USA

Paige Taylor
Imaging and Radiation Oncology Core (IROC) Houston, University of Texas MD Anderson Cancer Center, Houston, TX, USA

Christopher Ainsley
University of Pennsylvania, Philadelphia, PA, USA

Sairos Safai
Center for Proton Therapy, Paul Scherrer Institute, Villigen, Switzerland

Narayan Sahoo
University of Texas, MD Anderson Cancer Center, Houston, TX, USA

Mark Pankuch
Northwestern Medicine Chicago Proton Center, Warrenville, IL, USA

Jonathan B. Farr
Applications of Detectors and Accelerators to Medicine, 1217 Meyrin, Switzerland

Sung Yong Park
National Cancer Centre Singapore, Singapore, Singapore

Eric Klein
Rhode Island Hospital, The Warren Alpert Medical School of Brown University, Providence, RI, USA

Jacob Flanz
Massachusetts General Hospital, Burr Proton Therapy Center, Boston, MA
Harvard Medical School, Cambridge, MA, USA

Ellen D. Yorke
Memorial Sloan-Kettering Cancer Center, New York, NY, USA

David Followill
Imaging and Radiation Oncology Core (IROC) Houston, University of Texas MD Anderson Cancer Center, Houston, TX, USA

Yuki Kase
Proton Therapy Division, Shizuoka Cancer Center, Shizuoka, Japan

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Purpose: Task Group (TG) 224 was established by the American Association of Physicists in Medicine's Science Council under the Radiation Therapy Committee and Work Group on Particle Beams. The group was charged with developing comprehensive quality assurance (QA) guidelines and recommendations for the three commonly employed proton therapy techniques for beam delivery: scattering, uniform scanning, and pencil beam scanning. This report supplements established QA guidelines for therapy machine performance for other widely used modalities, such as photons and electrons (TG 142, TG 40, TG 24, TG 22, TG 179, and Medical Physics Practice Guideline 2a) and shares their aims of ensuring the safe, accurate, and consistent delivery of radiation therapy dose distributions to patients.

Methods: To provide a basis from which machine-specific QA procedures can be developed, the report first describes the different delivery techniques and highlights the salient components of the related machine hardware. Depending on the particular machine hardware, certain procedures may be more or less important, and each institution should investigate its own situation.

Results: In lieu of such investigations, this report identifies common beam parameters that are typically checked, along with the typical frequencies of those checks (daily, weekly, monthly, or annually). The rationale for choosing these checks and their frequencies is briefly described. Short descriptions of suggested tools and procedures for completing some of the periodic QA checks are also presented.

Conclusion: Recommended tolerance limits for each of the recommended QA checks are tabulated, and are based on the literature and on consensus data from the clinical proton experience of the task

group members. We hope that this and other reports will serve as a reference for clinical physicists wishing either to establish a proton therapy QA program or to evaluate an existing one. [https://doi.org/10.1002/mp.13622]
Key words: particle beams, proton therapy, QA, quality assurance, radiotherapy

TABLE OF CONTENTS

1. INTRODUCTION

1.A. Background and purpose

Over the past decade, the number of proton therapy centers has grown rapidly, and the rate of growth is expected to be maintained as applicable treatment indicators are expanded beyond those already established (e.g., pediatrics and ocular melanoma).[1–4] As proton therapy becomes more popular and accessible for treating cancer,[5–7] comprehensive quality assurance (QA) guidelines—and methodologies to determine these guidelines for proton therapy delivery—will be essential to ensure that patients are treated safely and effectively. Task Group 224 was therefore charged with describing the considerations needed to define QA procedures (beam delivery mechanisms, beam parameters, and instrumentation) and identifying examples of comprehensive QA procedures for proton therapy machines. In response, the Task Group has considered the various technologies and design characteristics implemented by different manufacturers, and has determined recommended tolerances for parameters that directly influence the accuracy and precision of proton treatment beam delivery.

One of the underlying principle for QA of medical accelerators is based on the International Commission on Radiation Units and Measurements (ICRU) recommendations that the dose delivered to a target volume in the patient be within −5% to +7% of the prescribed dose.[8–10] Several Task Groups of the American Association of Physicists in Medicine, TG 40[11], TG 142[12], TG 179[13], and MPPG 2a[14] have developed

recommendations for photon/electron based machines and their image guidance components. Correspondingly, a new Task Group report following the same principles as TG 40 and TG 142 was needed to provide the users of proton radiotherapy machines with recommendations and guidelines for safe and accurate proton beam delivery.

The procedures for proton therapy QA require an in-depth understanding of beam-delivery methodology. Only a few publications address QA procedures for proton radiotherapy, and some of the details they contain are unique to specific beam delivery systems.[15–21] A comprehensive set of QA procedures for passively scattered proton therapy delivered with a synchrotron accelerator was published by Arjomandy et al.[22] in 2009. However, different beam delivery techniques (e.g., pencil-beam scanning), image based imaging guidance systems (e.g., cone beam CT (CBCT), portable CTs, CT-on-rails), and auxiliary devices (e.g., multi-leaf collimators (MLCs)) are used with a newer generation of proton therapy machines, thus requiring updated tests. MLCs may be replaced by sliding collimation systems[23] or some other variant, but will likely to continue to be used even in scanning beam delivery. Furthermore, different manufacturers produce and deliver proton beams using different accelerator technologies and beam delivery systems. Hence, it is essential to develop a process that will enable users to identify QA procedures appropriate for their equipment and to provide recommendations that can help ensure that these proton therapy systems deliver protons safely, precisely, and accurately.

It is important to distinguish which categories of QA measurements do not require a detailed knowledge of the technology (e.g., the delivered beam performance) from those specifically tailored to a particular proton therapy machine. Although this report also addresses the various technologies and design characteristics of different manufacturers, its main objective is to identify a comprehensive set of QA procedures that may be applicable to any generic proton radiotherapy machine. Importantly, an institution may elect, based on a clear set of processes, to refine the suite of checks described.

The report also recommends tolerance limits and ranges for the parameters that directly affect the precision of beam delivery during treatment based on reviewing the clinical values used at proton therapy centers around the world and recommendations from the literature, recognizing that they may not be appropriate for any specific practice. The frequency of various measurements and tests to be performed (such as online* during or before treatment, daily, weekly, monthly or annually) are normally determined by risk assessment analysis methodologies,[24] but this report provides examples based on typical use in clinical proton facilities to help guide physicists and other qualified personnel in ensuring accurate beam delivery. QA procedures at any facility should be established with consideration of the procedures in which the equipment is used, and therefore, the QA procedures recommended by this Task Group should be used only as guidelines and implemented as supported by a facility's risk analysis, based on equipment-specific characteristics and limitations. Furthermore, the medical physicist may adjust the frequency of procedures based on the consistency and reproducibility of the specific proton machine's QA results and in light of the risks attached to failures of the corresponding QA tests to patients or staff.

A robust QA program considers the failure modes of the system and implements the necessary steps to measure system performance to detect these possible failures. To help readers understand the rationale for QA, the report briefly discusses the methodologies and requirements of the parameters that contribute to assuring consistent performance of proton beam delivery systems. Ocular or "eye" lines are not considered in this document, although many QA procedures from this report may be applied to such beam delivery systems.

1.B. Methodology of quality assurance

Quality assurance protocols include the procedures necessary to provide confidence that a radiotherapy machine is functioning as commissioned for patient treatment and that the planned dose will be delivered safely and accurately within the established tolerance limits. Quality assurance has three key branches: (a) general equipment functionality, including dosimetry, imaging, and mechanical QA; (b) patient-specific QA; and (c) Treatment Planning System (TPS) QA. This report focuses on QA of general equipment functionality or machine QA. Patient-specific and TPS QA are not discussed in detail.[25]

The dose distribution predicted by the TPS must actually be produced and delivered by the machine. The clinical commissioning of a beam delivery system involves measuring the beam parameters for a particular machine and incorporating them into the TPS to create an appropriate proton beam model from which proton doses can be calculated. Given that proton dose distributions are calculated from these parameters, the parameters must be checked routinely. Equipment parameters and clinical data used for dose distributions and monitor unit calculations should be checked periodically to ensure consistent dose delivery.

Machine QA procedures can be divided into several categories. One category is dosimetry parameter checks, which monitor absolute absorbed dose to the target and relative dose distributions. Two other categories are mechanical checks and imaging system checks, both of which ensure the correct absolute position of the target before it receives dose.[26] Lastly, safety checks monitor the functions of key equipment that ensure patient, staff and visitor safety.

For each of these categories, QA tasks can be further divided into daily, weekly, monthly, and annual procedures.

*Online measurements refer to beam parameter quality checks performed during therapeutic irradiation by devices such as segmented ionization chambers.

Although this Task Group provides a comprehensive set of recommendations based on existing proton system QA protocols, which are closely related to earlier machine QA TG recommendations,[12] *any of the recommendations may be modified for a different frequency to accommodate unique machine characteristics and the requirements of each individual institution and organization*. All QA results should be recorded (preferably electronically) for statistical process control, which can help set action levels and differentiate between systematic and random errors.

1.C. Delivery techniques

Three delivery techniques are widely used in proton therapy, namely passive scattering (including single scattering and double scattering (DS)), uniform scanning (US), and pencil beam scanning (PBS) (which can deliver uniform or modulated dose per field).[27] Single scattering, commonly used in ocular or "eye" lines, is not discussed in this report.

For all these delivery techniques, an accelerator (cyclotron, synchrotron, or synchrocyclotron)[28–30] produces a narrow beam 2–4 mm in cross-section when exiting the accelerator with a specific energy, typically in the range of 70–250 MeV for treatment purposes. In the case of a cyclotron or synchrocyclotron, the beam energy or range is adjusted using a range shifter (also called a "degrader"), which increases the angular dispersion and emittance of the beam. A series of magnetic components (dipoles, quadrupoles, etc.) in a spectrometer configuration, combined with spatially and spectrally collimating slits, may be used to reject portions of the phase space inadequate for clinical application. A synchrotron produces beams of protons of a desired energy without using a degrader by spilling the nearly mono-energetic protons in durations ranging from milliseconds to several seconds.

When the narrow beam of nearly mono-energetic protons with a Gaussian cross-section is transported to the nozzle (sometimes referred to as the "radiation head"), various beam-shaping and/or beam-modifying components are placed in its path. The protons are spread to produce a beam that conforms to the treatment target. How this conformity is achieved depends on the type of beam-spreading system used. The various alternatives are discussed below.

1.C.1. Double scattering (DS)

Several configurations of proton beam delivery systems scatter the beam laterally. In a DS delivery system, as the name implies, two series of scatterers spread the beam. The first scatterer widens the Gaussian-shaped beam laterally. The second scatterer further broadens the beam and flattens its radial intensity profile for therapeutic use.

Several methods can modulate the penetration of the beam to create a Spread-Out Bragg Peak (SOBP), such as a ridge filter [31] or a range modulation wheel (RMW).[32] Some manufacturers use a single scatterer upstream of the monitor chamber with the RMW positioned between the scatterer and monitor chamber, whereas another place both the RMW and scatterer at the same location upstream from the monitor chamber (Fig. 1). For some delivery systems, a single RMW may be used to produce range modulations of different widths. This process requires precise synchronization of the beam current and wheel angle as the modulation wheel is rotating (i.e., ~ 400 RPM).

Dose conformity to the target volume laterally and distally (with specified margins) is achieved with apertures (sometimes called "blocks") and range compensators (sometimes called "bolus"), respectively. Combined, these devices produce a three-dimensional dose distribution for conformal proton therapy (Fig. 2). Dual ionization chambers monitor the beam flatness and symmetry, as well as the dose delivered during irradiation.

Because of the number of devices involved and potential errors resulting from these components in a scattered proton therapy system**,** several QA procedures must be performed to ensure that the system is delivering the required clinical beam within the parameters determined during commissioning for accurate treatment delivery. For example, any displacement of the beam center from the center of the first scatterer may degrade beam flatness and symmetry.[33] Another example is the incorrect synchronization between the beam timing and the rotating range modulator wheel, which may affect the characteristics of the SOBP. This type of error does not exist for a system using a ridge filter to obtain range modulation. Thus, the probability of such an error is lower than that in a system using a range modulator wheel. Such an analysis is helpful in identifying which QA procedures are necessary and how often they should be performed.

The dosimetry parameters and their dependencies for scattering beam delivery are listed below. Formal definitions of these parameters are given in Section I.D.

1. The **range of the beam in water**, which is governed predominantly by the range of the most distal contributing Bragg peak, but reduced from this value owing to the small contribution from the second most distal peak.
   a. This range is mainly determined by the beam energy that is governed by a degrader (cyclotron) or ring frequency (synchrotron) prior to entering the nozzle.
   b. In addition, the beam energy is modified by the materials through which the beam traverses:
      i. scattering devices
      ii. range-modulating devices
      iii. vacuum-to-air transitions (exit window)
      iv. material that makes up in-beam (e.g., nozzle) instrumentation
      v. other nozzle components.

Any of these parameters can be in error (e.g., the wrong beam energy or material degradation in the exit windows), although the relative probabilities depend on the details of the system.

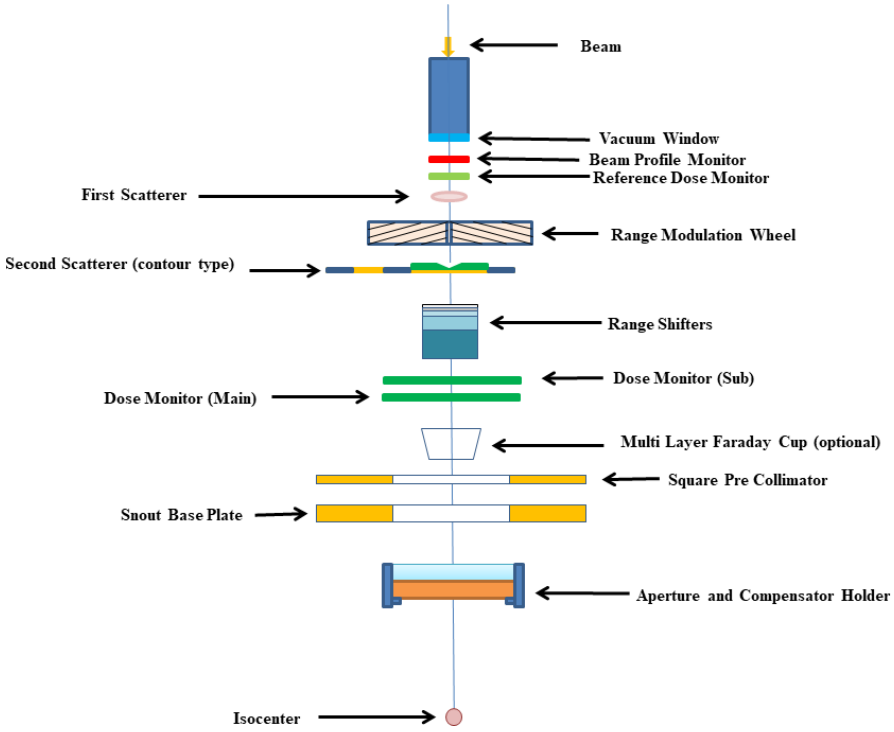

FIG. 1. Arrangement of the components for a modulator system with double scatterers.

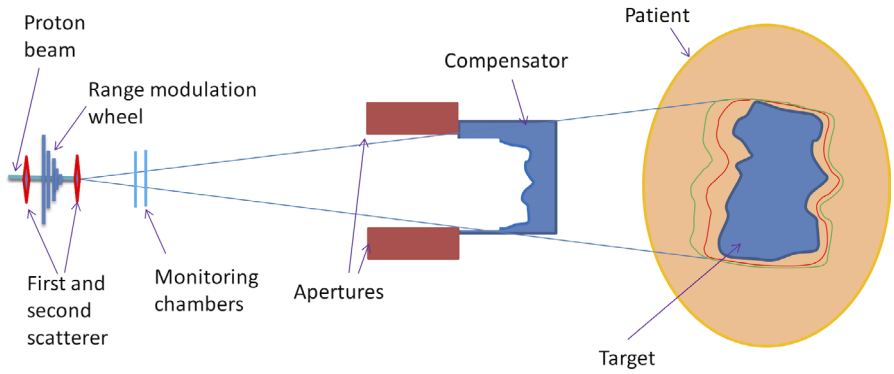

FIG. 2. Beam-modifying equipment (apertures and compensator) and a modulation wheel generating a Spread-Out Bragg Peak dose.

2. The **distal dose falloff**, which depends on

   a. the initial energy spread in the beam
   b. the range straggling created when the beam traverses material in the nozzle and in the patient.

3. The **width of the SOBP**, as measured between specific distal and proximal dose points on the depth-dose curve. The flat portion of the SOBP is generated by appropriately weighting the intensities of proton beams of different, predetermined energies at the nozzle exit. Devices used to modulate the Bragg peak include:
   a. range-modulation wheels
   b. binary filters[34,35]
   c. ridge filters.

4. The **lateral dose uniformity**, which results from a variety of sources:
   a. scattering material
   b. the aperture/collimator
   c. the air gap between the collimator and the target
   d. the distance between the effective source and the target

5. The **lateral penumbra**, which also results from a variety of sources:
   a. the aperture/collimator
   b. the air gap between the collimator and the target
   c. the effective source size and location
   d. multiple scattering in the patient (i.e., the depth of the beam)
   e. the thickness of the compensator (bolus)

6. **Depth-dose uniformity**, which depends on the following:
   a. the range-modulator wheel design
   b. the binary filter design
   c. the ridge filter design
   d. the synchrony of the beam gate with RMW rotation (if applicable).
   e. These six beam parameters are the most important beam parameters created by the beam delivery system and used by the TPS to calculate dose distributions.

1.C.2. Pencil beam scanning (PBS)

Methods of beam delivery that involve scanning a proton beam are divided into two main categories, one generally called "spot scanning" and one generally called "continuous scanning". Spot scanning involves irradiating one specific location in a volume—depositing the required dose in that location, turning off the beam (in the "discrete" form of spot scanning) moving to the next location, turning on the beam, and then irradiating that location. As it is currently termed, "raster scanning" is a form of spot scanning in which the beam is not turned off between spot delivery. In both cases, the process is repeated until the entire target is irradiated. In continuous scanning, the beam stays on while the spot moves, and the dose at any given location is determined by the beam current and/or the speed of the motion of the beam.

For each of these scanning methods, the actual dose delivered is monitored by the control system, which checks the dose delivered with redundant sensors, delivered charge and the time the beam spends in each area of the field to measure and control the spot position, charge, and/or scanning speed. However, the errors that can lead to incorrect dose distributions are somewhat different. In a continuous scanning system, the speed of the scanning magnets is an important source of error, as is the beam current control (although a drastic change in the beam current control can contribute to an error in spot scanning). The relative severity of a given error will be different in different systems, a fact that should be factored into the design of the QA protocols.

One advantage of the PBS design, among many, is that scattered radiation from the primary beam and neutron production in the nozzle are minimized because very little material lies in the beam path (Fig. 3).

Range shifters can be used with scanning beams to reduce the range of protons to treat very superficial layers (e.g., for systems whose minimum transportable energy is 100 MeV, a range shifter is needed to access treatment depths shallower than ~7.5 cm).

In the case of a PBS beam, the concept of an SOBP is less relevant because the PBS delivery method offers both distal and proximal dose conformity. Clinical PBS fields will possess a varying SOBP width across the perpendicular widths

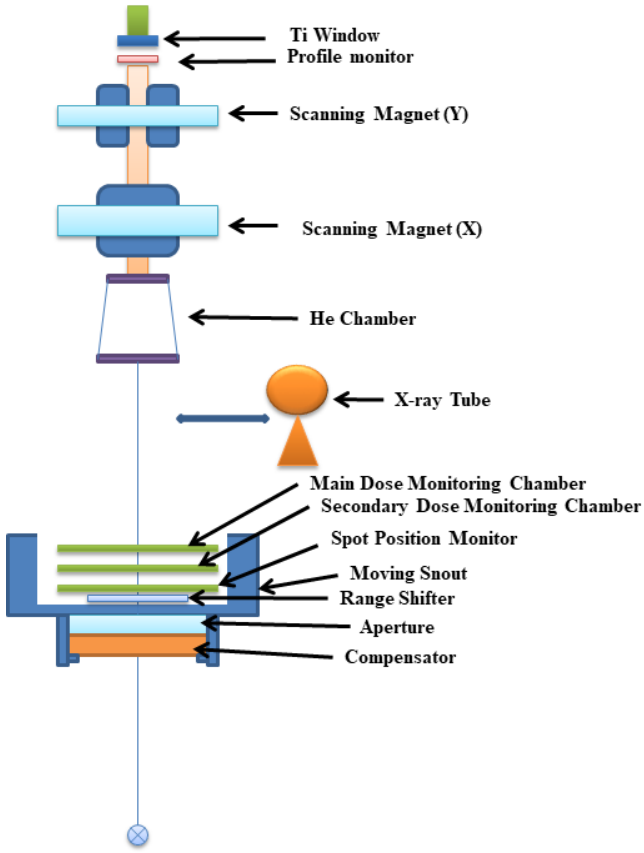

FIG. 3. Arrangement of the components for a pencil beam scanning system. Compensators and apertures are seldom used.

of the target. PBS delivery methods also introduce the capability to vary the proton dose across any given field. For the case of treatment fields generated using multi-field optimization methods, the field intensity may be extremely nonuniform throughout the target volume, and the concept of an SOBP becomes irrelevant. The concept of measuring a consistent SOBP in PBS delivery QA is therefore only a potential tool to evaluate whether the desired range spacing is being obtained. It is not a practical measurement of a clinical PBS field. Whether or not this spacing is measured explicitly is up to the institution when evaluating its particular system.

The pertinent beam parameters, formally defined in section I.D., are (Fig. 4):

1. The range in water of the pristine Bragg peak
2. The distal dose falloff of the pristine Bragg peak (used to evaluate energy spread)
3. The position of the centroid of the beam profile
4. The full width at half-maximum (FWHM) of the pencil-beam spot profile or one sigma of its approximate Gaussian representation, where relationally FWHM = 2.35 σ, measured at a specific position (either in air or in water)
5. The shape of the beam spot which comes primarily from the accelerator output and any material the beam

has passed through as well as its dependence on gantry angle, if any. It is generally assumed to be of Gaussian form, but may vary from that. If it is not Gaussian, it may have an impact on the dose distribution depending upon the beam delivery parameters and will be visible with a gamma index analysis compared to the desired distribution.

The dose distribution delivered by a scanned beam is constructed by superposing pencil beams of a particular width, position, and integrated number of protons. Beam scanning can be done in various ways, but in all cases, the delivery can be characterized by pencil beams of a particular width separated by a particular spacing. (In a continuously scanned beam, the motion in one direction may be continuous and therefore the effective spacing in that direction is zero.) Owing to the importance of this concept for PBS delivery and the fact that it is so different than scattering beam delivery modalities, more detail is devoted to the concepts related to the spot parameters.

A small displacement (e.g., ~1.5 mm) of the position of one line of spots (for a beam with a width of σ = 3 mm) can introduce dose errors on the order of 20% when an unmodulated narrow beam is used to produce a broad flat field (Fig. 5). Similarly, errors in the spacing of energy layers can manifest equivalently on depth-dose nonuniformity.

Whether or not the dose uniformity will be so affected depends on the degree to which these parameters are incorrect. This allows tolerances to be set.

A 3D dose distribution can be delivered in several ways. For example, a specific spot spacing (in the case of spot scanning) can be defined and that spacing maintained for all range layers, or the spot spacing can be adjusted as a function of the layer because the beam spot size is a function of energy. Despite the fact that this QA test is facility-dependent, the one factor that will not vary among institutions is that a deviation of the dose distribution from the desired pattern will be caused by an incorrect beam spot position relative to the beam size. The discussion below is related to the effects of a constant beam size in one dimension.

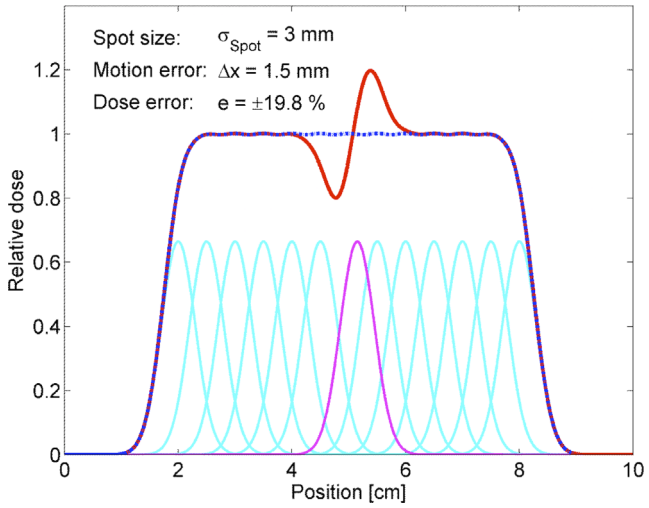

FIG. 5. The dose profile error resulting from a small displacement of a single line of spots in a rectangular field comprising uniformly weighted spots (courtesy of Dr. David Meer, Paul Scherrer Institute. Private communication).

Consider the case of three different spot positional separations of 0.75, 1.5, and 2.0 σ relative to the beam sigma (σ), respectively, (Fig. 6) and restricting these only to geometric aspect of beam size and position. The curve at the top in Fig. 6 is the sum of the Gaussian curves. As the spacing is increased, at some point, the uniformity of the sum deteriorates. Unless continuous (line) scanning is used, the number of spots can, depending on the system, dictate the time required for an irradiation, and therefore this number should be minimized, resulting in a spot spacing of about 1.5 σ. If, in this case, the beam size is incorrect (i.e., too small), the spot spacing will appear to be too large (for that incorrect beam size), and the dose distribution will be incorrect. Therefore, the spot spacing for the nominal beam size is chosen, to allow for some variation in the beam width as well as other aspects of the dose distribution. A different spacing will result in a different tolerance. These factors must be known to determine the appropriate tolerance levels for regular machine QA.

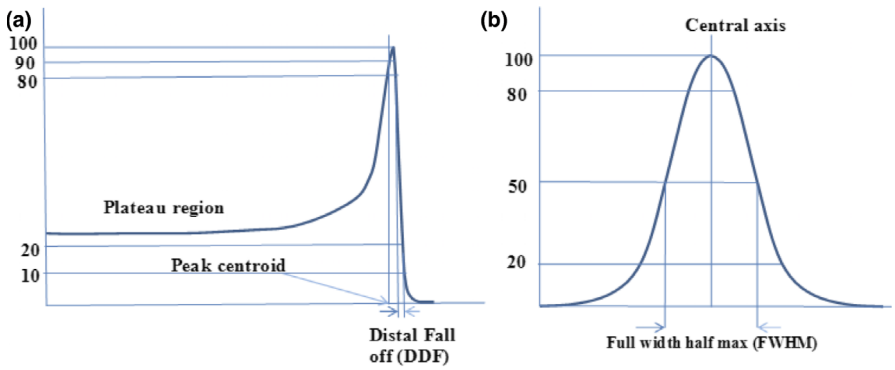

FIG. 4. a) Integral depth-dose and b) lateral profile parameters characterizing a narrow monoenergetic pencil-beam spot (pristine Bragg peak).

Isolated positional errors can also occur (Fig. 5). In this case, one spot is shifted by 50% of the beam σ and results in a local nonuniformity of about 20% (for a spot spacing of 1.67 σ). The position tolerance scales with beam σ for a given relative spot spacing. Therefore, to obtain a uniformity of ±3% the local shift must be below 13% of beam σ. For a 3 mm-σ beam, for example, there would be a positional tolerance of about ±0.4 mm; for a 10-mm σ beam, there would be a positional tolerance of about ±1.3 mm. Therefore, a different beam size will result in a different absolute tolerance number, which must be determined for each facility.

Therefore, it is imperative to make sure that: (a) spot position and profiles are consistently within acceptable clinical limits, and (b) the monitoring chambers that measure these parameters are functioning properly. Additionally, the gantry-angle dependence of the beam parameters needs to be checked for constancy.

The recommended QA tasks in this report are not exhaustive and may in some circumstances be more than necessary. They are intended to ensure that some of the important dosimetry and safety parameters that may affect the quality of the delivered dose distribution of broad patient treatment fields are periodically checked. The QA procedures for PBS are evolving and are expected to mature in the near future.

1.C.3. Uniform scanning (US)

Uniform scanning systems share concepts from scattering and PBS delivery (Fig. 7). Rather than using a physical scatterer to spread the beam laterally as scattering systems do, US systems use scanning magnets to distribute a relatively large spot (1σ = 6–20 mm at the isocenter in air) across the treatment field at high speed (3–50 Hz). Some US systems use the first scatterer to control the beam spot size, whereas others achieve the desired condition from magnetic optics alone.

Uniform scanning patterns include Lissajous, circular, raster, triangle, and spiral configurations.[36] Spot size, scanning frequency, and pattern spacing can vary with beam energy and need to be optimized to meet lateral flatness specifications during the commissioning phase[35] and in turn should be verified for consistency as part of the ongoing QA program. Uniform scanning systems use the method of energy stacking, in which protons of fixed energies deposit dose to individual layers at specific depths, one at a time, in a predefined intensity ratio. To achieve a reasonable overall treatment time, switching from layer to layer quickly is necessary (e.g., less than 1 s).[37] For that reason, currently, the layer switching is done in the nozzle with a set of range shifters and/ or a range modulator wheel (moving a step at a time). More recently, it has been shown to be possible to switch beam energies in less than a tenth of a second, and it may be possible to apply this method for US in the future. Currently, US requires some scattering and energy degradation, and therefore some material in the nozzle is required.

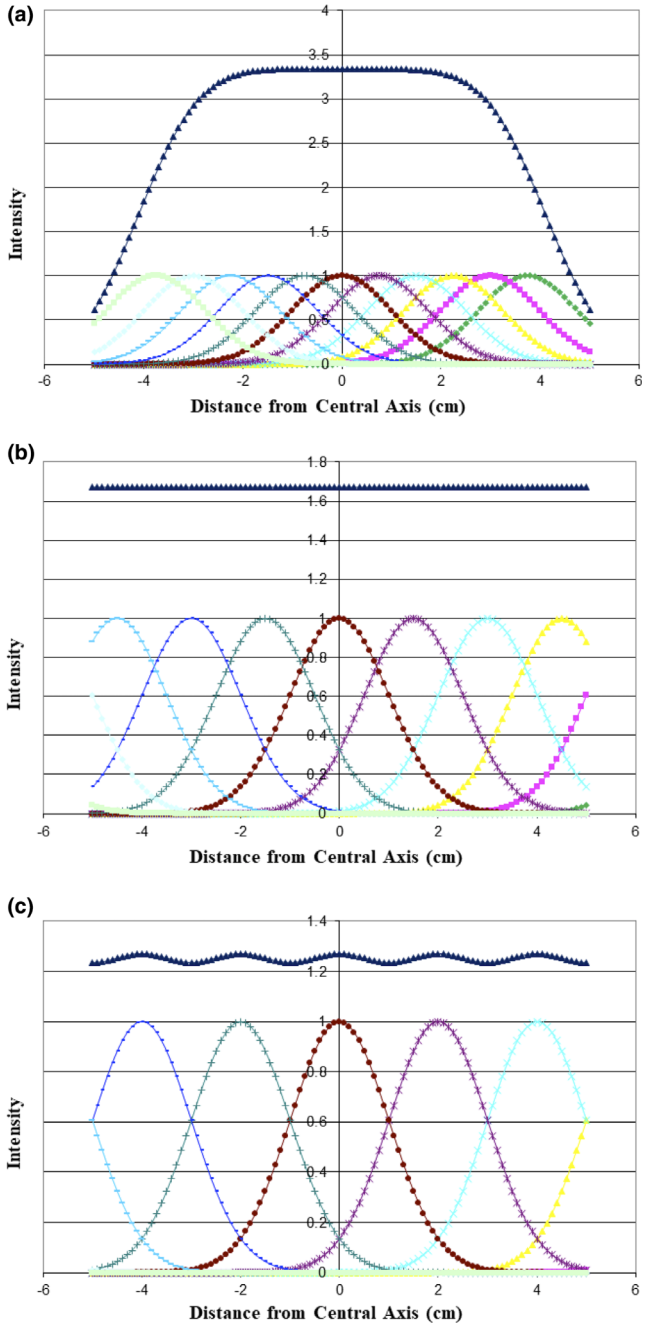

FIG. 6. (a) A broad beam profile from the sum of the proton beam spots with a Gaussian shape and with 0.75σ spot positional separation. (b) A broad beam profile from the sum of the proton beam spots with a Gaussian shape and with 1.5σ spot positional separation. (c). A broad beam profile from the sum of the proton beam spots with a Gaussian shape and with 2.0σ spot positional separation.

As in scattering systems, patient-specific apertures are usually required to define the field edges. A US system has also been proposed with a small spot scanning system, eliminating the need for apertures.[38] In both types of US systems, energy layers are delivered as uniform planes. Compensators provide two-dimensional range shifting to minimize the dose to tissues distal to the target.

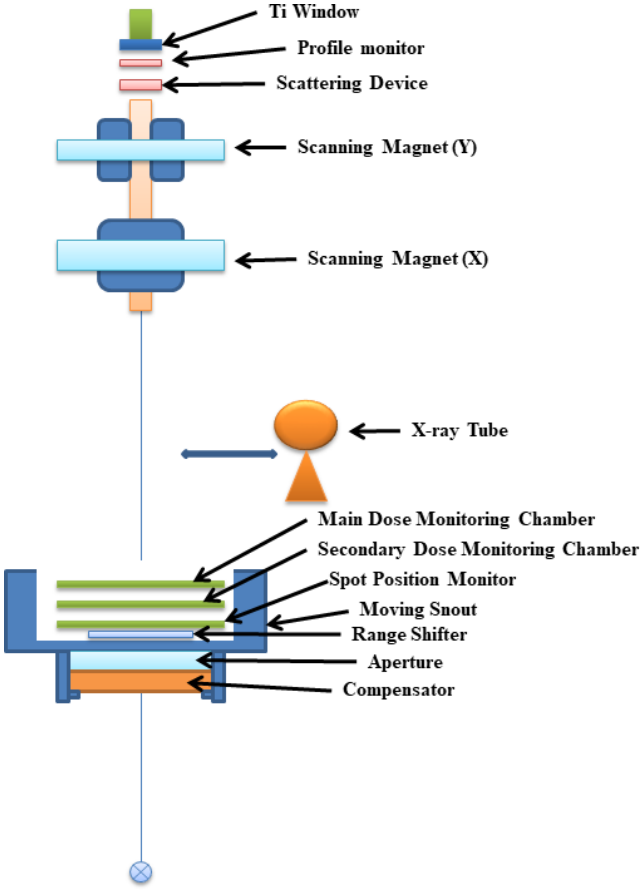

FIG. 7. A possible arrangement of the components for a uniform scanning system. Compensators and apertures are always used for patient treatment with US, as in the case of DS.

The reduction in scattering material in this system reduces neutron production and uses particles more efficiently than they are used in scattered delivery, but US is not superior to PBS in these respects. In a scattered system, field specific neutron leakage is proportional to the scattered beam that will be used for treatment. In the US system the proportionality of neutron leakage is reduced by optimizing the useful beam with the most efficient, field specific scan pattern, and by limiting the amount of overscan of the US fields.[39–41] Compared to systems that use scatterers to spread the beam laterally, US systems can penetrate to a deeper maximum depth for the same accelerator output energy because there is less material in the beam path in the nozzle. Uniform scanning can provide a larger field size (up to 30 × 40 cm^2 at isocenter). However, the actual dose distribution delivered with US may be more sensitive to organ motion than when a scattered beam delivery technique is used because of the temporal dependencies of the layer stacking methods used in US.[42]

1.D. Clinical machine characteristics and equipment

To develop QA procedures, it is useful to distinguish between two types of measurement: a direct measurement of a beam parameter and a measurement of parameters associated with a physical device that controls or modifies a beam parameter. Thus, this QA process identifies the important clinical beam dosimetric properties, relates them to the equipment parameters that can affect them, and then determines whether a QA measurement involves measuring a dosimetric quantity of the beam or whether the behavior of a specific component would affect that dosimetric quantity. QA practice may depend on the difficulty or time involved in either of those measurements and/or on the probability of a particular error that may or may not be revealed by either of the two types of measurements.

The dosimetric regions of interest for the two key beam delivery methods, scattering and scanning are shown in Fig. 8. Beams can be spread by different methods, highlighting the need to identify for each delivery method the crucial parameters that characterize the dose distribution to develop the most appropriate QA procedures.

Each delivery system should be analyzed in detail. For scattered beams, the original beam extracted from the accelerator can be described in terms of its energy, energy spread, lateral size, and current. These basic inputs combine to create various clinical parameters relevant to patient treatment. These parameters need to be checked to ensure the consistency and accuracy of beam delivery. Understanding the connection between the descriptors of the original beam and the clinical parameters helps trace problems to their source, should deviations arise.

It is important to make sure that: (a) the beam flatness and symmetry, or in the more general case, the dose agreement to the prescription, is always within acceptable clinical limits

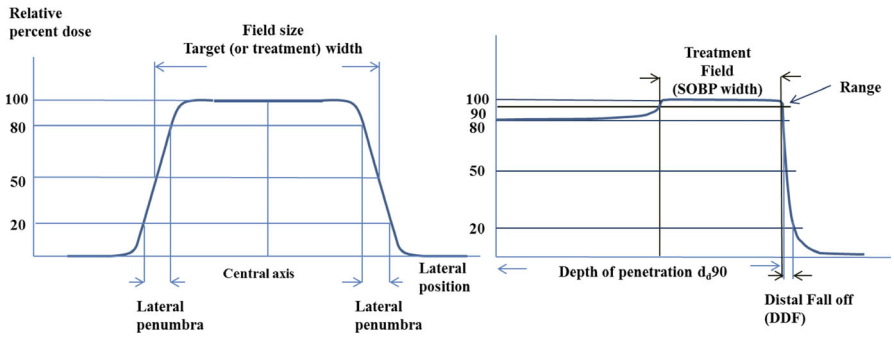

FIG. 8. Proton beam characteristics and dosimetric parameters.

and (b) the monitoring chambers that measure the clinical beam parameters are functioning accordingly and are capable of stopping the beam as needed. Some of these parameters may be checked online using devices along the beam path within the delivery system (i.e., the original beam profile), if the control system is capable of monitoring the desired beam parameters. These devices should therefore be checked periodically, if feasible. If the tests are performed as part of periodic maintenance by a vendor, the medical physics staff should be aware of the performance results.

Following ICRU 78,[17] the following parameters for broad proton beams relevant to DS, US, and PBS delivery systems have been identified (Fig. 8).

1. The beam range in water (usually defined at the distal 90% dose level, or simply d_d90 (i.e., depth at distal 90% dose), although d_d95 and d_d80 are both used at some proton centers).
2. The distal dose falloff (DDF) width (the distance along the beam axis where the dose in water reduces from 80% to 20% or simply d_d20-d_d80).
3. The SOBP width or layer stacking consistency (e.g., the distance in water between the proximal and distal 90% dose or simply d_d90-d_p90. Some institutions use d_d90-d_p98 or d_d90-d_p95 to define the width of the SOBP. However, the chosen definition may be imposed on the user by the proton system and/or treatment planning system).
4. The lateral uniformity (defined as the flatness and symmetry of a broad beam about the center of the beam profile over 80% of the FWHM)

   a. *Lateral flatness* is defined as

   $$F_{lp} = \left(\frac{d_{lp\max} - d_{lp\min}}{d_{lp\max} + d_{lp\min}}\right).$$

   where $d_{lp\max} and d_{lp\min}$ are the maximum and minimum absorbed dose values in the lateral beam profile measured at the center of modulation.

   b. *Lateral symmetry (in percent) is defined as*

   $$S_{lp} = \left(\frac{D_1 - D_2}{D_1 + D_2}\right)100.$$

   where D_1 and D_2 are the integral absorbed doses in each half of the lateral profile about the central axis.
5. The lateral penumbra width (the distance perpendicular to the beam axis where the dose in water at a specified depth reduces from 80% to 20% or simply d_l80- d_l20).

In a PBS beam, because the beam is delivered one energy at a time with layer-stacking methods, the dosimetric parameters to be measured are essentially the raw beam parameters, as discussed above (1.C.2). A key addition is the effect of the scanning system on the beam parameters, which can change beam size and position. Thus, the clinical beam parameters can be related to the beam-specific characteristic parameters through the equipment that spreads the beam.

1.E. Multileaf collimators in proton therapy

In proton therapy, MLCs have been used in conjunction with scattering and uniform scanning delivery systems as a direct alternative to brass apertures or Cerrobend® blocks.[43] In this way, the aperture defined by the leaves remains static throughout the delivery of each field in its entirety, as in three-dimensional conformal radiation therapy (3DCRT).[44–48] Multileaf collimators are not currently providing planar fluence modulation[49] equivalent to that which allows the delivery of intensity-modulated radiation therapy (IMRT)[50–57] with photon beams. Given the availability and ever-increasing maturity of rival PBS systems capable of providing this fluence modulation at a more fundamental level and with a substantially lower secondary neutron dose, it remains uncertain at this time if demand for dynamically-adapting MLCs for proton therapy operating in this fashion will arise in the future. In this report, we therefore restrict our attention of QA processes to the use of MLCs in static field-shaping, consistent with current practices. Nevertheless, some newer systems are now offering MLCs providing layer-by-layer collimation in PBS. Additional considerations applicable to the QA of MLCs used for dynamic beam-shaping of proton beams will need to be developed when such systems become standard in proton clinics. A discussion of these considerations is beyond the scope of this report.

AAPM guidelines on the QA of photon MLCs employed for 3DCRT were formulated by AAPM TG 50.[58] These QA checks are similar to those required for collimator jaws and apertures.[11] The principal concerns are mechanical alignment of the MLC reference frame with the accelerator reference frame and the accuracy and reproducibility of leaf positions.[59–61] These recommendations have since been refined and extended to encompass the use of MLCs in IMRT applications in the TG-142 report.[12] Given current proton therapy clinical practices, MLC QA processes for proton delivery follow closely the TG-50[58] report. However, given that proton therapy MLCs are not fixed in position relative to isocenter but are instead mounted on snouts that translate back-and-forth along the beam direction, tests for leakage must be performed at several snout positions. Furthermore, because interactions of protons with components of the MLC system can generate radionuclides, activation tests are also required.

1.F. Imaging in proton therapy

In proton therapy, the most commonly used image guidance system, available in all proton centers for patient setup, employs kilovoltage x-rays acquired with digital imaging panels.[62,63] Planar x-ray images are obtained and registered to digitally reconstructed radiographs (DRRs)

generated from the TPS or by the imaging control system. The x-ray tubes may be mounted in the nozzle, in orthogonal planes, or in the floor or ceiling, as long as stereoscopic alignment can be obtained. Evaluating the geometric accuracy of this imaging system relative to the proton beam is essential.

Volumetric imaging is readily available in photon clinics for accurately positioning the beam onto the target and evaluating internal anatomical reproducibility. Although currently not common practice at most proton centers, considerable efforts are being made to integrate cone beam CT, portable CT, or CT-on-rails into routine clinical workflow. Some of the new proton therapy centers are presently using volumetric imaging for patients' alignment.[64–66]

Successful proton therapy treatment requires accurate and reproducible patient positioning. The importance of geometrical precision and anatomical reproducibility may be even greater than for photon treatments.[67] Appropriate image guidance for routine patient set-up is an essential clinical tool and, as such, the imaging devices must function as expected.[68] Often, fiducial markers are implanted into the target[69–78] or into structures related to the target position, such as the skull for brain treatment, to assist in alignment.

The recommendations from TG 142,[12] TG 179,[13] and MPPG 2a[14] on image guidance systems are substantial and can be directly applied to image guidance systems in a proton therapy clinic. Task Group-224 recommends that the QA tests suggested by TG 142,[12] TG 179,[13] and MPPG 2a[14] be performed for the image guidance systems in the proton therapy environment as well. However, some differences need to be noted.

Mechanical and beam optics constraints do not always allow the imaging x-ray source to be located at the same distance from the isocenter as the proton source. This difference will lead to inconsistencies between the divergence of the proton field and the x-ray image-guidance system. If the x-ray source is to image the beam's eye view, incompatible projections of the aperture outline will appear on the x-ray image when an aperture is employed. The TPS, the image guidance system, or both, must acknowledge this difference, which must be properly validated for accuracy in the commissioning process.

Many proton delivery systems use an applicator to collimate the treatment field and to hold an aperture and a range compensator in place. The applicator holding the patient-specific device is often placed as close to the patient as possible to minimize the geometric penumbra of the proton beam, which can reduce the clearance of the imaging system. Position tolerances of the applicator and mechanisms become a part of the QA.

Many image guidance consoles are located outside the physical treatment space. The space needed for robotic arms as the main support of the patient positioning system (PPS), or the future use of imaging devices, such as CT on rails, may preclude locating the imaging console in the treatment room. Appropriate acceptance testing with continual QA tests must be performed to ensure the accuracy and safety of such systems, especially the mapping between the positioning space and the treatment space.

At the time of this writing, no delivery systems use the proton beam as an imaging tool for patient localization. Several vendors and research groups are developing transmission proton radiograph and CT capabilities.[79–89] Careful evaluations of these systems, including positional accuracy, image quality, and patient dose, will be necessary.

1.G. Frequency and types of procedures for quality assurance

This report has emphasized that proton therapy can be delivered with different machines with different beam delivery modalities. Failure modes and effects analysis (FMEA) techniques can determine and prioritize the risk associated with errors. Proton therapy centers are encouraged to consider and implement the risk assessment techniques to evaluate the probability, severity, and detectability of an occurrence using techniques similar to those outlined in TG 100.[24] These factors may be important in determining the frequency and methods of a QA measurement. As experience is gained along with supporting data defining of the probability, severity, and detectability of an event, the frequency and/or the method of testing may change. A QA program is a living program with data feeding back to the protocols defined. Analyzing all possible proton therapy systems is outside the scope of this Task Group. Therefore, an example of a comprehensive program, based on protocols currently used in proton therapy facilities (or rather a combination of protocols and not one specific set of protocols for one facility) is provided below.

2. DAILY QUALITY ASSURANCE PROCEDURES

The identification of a particular set of QA procedures is dependent upon an analysis of the particular system being used. What is included herein (and for the other time-dependent sections) is not a blanket recipe to be followed for all systems, but a summary of procedures that may be applicable to one system or another, and therefore should not be used as a blind standard for all systems. It is envisioned that the local medical physicists can and should consider all these procedures for their system and write a document identifying which procedures are to be followed for their system and which are not.[90] For example, might one measure either the penumbra or spot size for PBS beams. Those procedures not followed ought to be accompanied by an explanation either via a clear description of the logic, experience, data obtained and possibly of risk assessment, as noted in the previous section.

Daily QA procedures may be performed by a trained radiation therapist or physics assistant, but all results should be reviewed daily by a qualified medical physicist (QMP), and any daily check that is out of tolerance should be immediately reported to the supervising QMP.

TABLE I. Daily QA procedures for proton therapy.

	Tolerances			
	Method of delivery			
	DS/PS	US	PBS	Comments
Dosimetry				
Output constancy	±3%	±3%	±3%	Measured for different ranges on different days with-
Depth verification:				One consistent field
Distal	±2 mm	±1 mm	±1 mm	Difference from baseline at distal 90%[a] depth dose
Proximal	±2 mm	±2 mm	-	Difference from baseline at proximal 90%[a] depth dose
SOBP width	±2%/±2 mm	±2%/±2 mm	-	Width between proximal and distal 90%[a] depth dose
Spot position	-	-	±2/±1 mm	Absolute/relative-If dose pattern is used, the dose uniformity and homogeneity should reflect the same accuracy from baseline.
Mechanical (all delivery systems)				
Couch translation motion		±1 mm		Performed if patient is not reimaged after couch shifts
Lasers position accuracy		±2 mm		At isocenter
Imaging				
X-ray isocenter vs Laser isocenter		±2 mm		
X-ray and proton beam isocenter coincidence		±1 mm		
Image acquisition and communication		Functional		This includes file swap between R&V and delivery system as well as verification of images
CBCT				Daily procedures outlined in TG-179, TG-142, MPPG-2a
Safety				
Door interlock		Functional		
Audio monitor		Functional		
Visual monitor		Functional		
Beam on indicator		Functional		
X-ray on indicator		Functional		
Search/clear button		Functional		
Pause beam button		Functional		
Emergency motion stop button		Functional		
Monitor unit interlocks		Functional		
Collision interlocks		Functional		When applicable
Radiation monitor (Neutron and X-ray)		Functional		
Optional				
Range modulation wheel timing	±2%	–	–	With respect to frequency of rotation
Field light		Functional		
Field width	±2 mm	–	–	
Proximal depth verification	–	–	±2 mm	Difference from baseline at proximal 90%[a] depth dose
SOBP width	–	–	±2%	Width between proximal and distal 90%[a] depth dose
Field symmetry	±1%	–	–	From baseline
Field flatness	±2%	–	–	From baseline
Dose rate	±2%	–	–	
Gantry angle read out accuracy		±1°		
Interlock test therapy delivery system		Functional		
Interlock test therapy verification system		Functional		

DS/PS, Double Scattering/Passive Scattering; US, Uniform Scanning; PBS, Pencil Beam Scanning; TG, Task Group; MPPG, Medical Physics Practice Guidelines.
[a]Some centers may define distal and proximal depth dose at 95% or 98%.

2.A. Beam dosimetry parameters

A variety of detectors and phantoms may be considered for daily QA measurements (Section VI). Which detector or phantom to use depends on the type of measurement to be made.[91,92] For daily QA checks, phantoms that are easy to set up and reproducible are desirable; for example, a near-water-equivalent plastic. Regardless of the phantom material chosen, the relative linear stopping power (RLSP), the energy dependence of the RLSP, and effects

of nuclear interactions should be known.[93–95] Table I lists the recommended parameters that are essential to check on a daily basis for each delivery technique. There are also optional parameters that are listed for different proton therapy machines.

2.A.1. Dose per monitor unit (D/MU)

Measuring the beam dose per monitor unit (D/MU) daily is required. This measurement can verify the integrity and reliability of the system's monitor chambers, as well as check beam characteristics and fluence consistency. A baseline reference range (or ranges) for the D/MU should be established at the time of commissioning using an easily reproduced setup.

Regardless of the field used for daily QA measurements, the measurement point should be in a low-dose gradient region, which may be at (or near to) the center of modulation (the center of the SOBP) for a broad beam (scattered or scanned) planned to deliver uniform volumetric dose throughout a well-defined region. The relative D/MU of beams with differing beam parameters (i.e., different energy or different modulation) may be checked on alternate days as a part of daily QA, but at least one consistent field should be measured daily.

A stable dosimeter, such as parallel plate ionization chamber (e.g., PTW Markus or Bragg peak ionization chamber) can be used to measure the D/MU constancy at a specific depth every day the system is used for patient treatment. Some proton centers use standard daily QA devices[96] commonly used in photon clinics, with some minor modifications. For PBS, the measurement can be performed for a proton pencil beam spot of single energy for a fixed number of monitor units at a selected depth, such as the nearly flat proximal region where the dose gradient is least steep. Because the objective is to check the constancy of the dose monitor's functionality, it may not be necessary to check dose for spots for multiple energies every day.

2.A.2. Range

There are dosimetric parameters which identify and characterize the stability of the machine for delivery of predetermined beam energies (ranges). A daily range measurement is recommended to ensure the integrity of the accelerator delivery system.

For synchrotron machines, beam range for a selection of different energies (so as to encompass all second scatterers) may be measured on different days, if desired, to measure them all in a reasonable period.[97] Although a cyclotron produces a single energy, the degrader system (the energy selection system) should still be checked for correct energy by in-room QA measurements. For PBS, the ranges of single-layer beams should be verified.[98]

When a large field is applied, a plane-parallel ionization chamber (with a high spatial resolution for distal fall off) may be used for range measurements. The chamber should be positioned in a sufficiently thick solid phantom material, such that the front plate is positioned in the distal fall-off gradient. The measurement is sensitive, and the appropriate phantom thickness and position must be carefully established. If a point dose measurement is used to obtain the ratio of dose at the distal depth to the reference dose (e.g., at a depth corresponding to 3 g/cm^2), the change in depth, corresponding to the deviation of the measured dose from that of the expected dose, must be characterized to evaluate whether the measurement meets the specified tolerance (in mm). This change in depth can be characterized with a best-fit or linear interpolation of the depth-dose curve to correlate dose percentages with depth.

The integrity of the range shifters in the nozzle should also be checked as part of the daily QA program to ensure that the shift in range occurs by the appropriate amount when a range shifter is inserted in the beam path.

Range consistency should be verified. A standard photon daily QA device, in conjunction with a QA field customized compensator, can be used to place various detectors of the QA device at different effective depths. This method can measure the depth-dose consistency of a specific field in a single measurement using commercial devices available for photon units.

Other techniques can measure the ranges of multiple proton beams simultaneously using a two-dimensional array or other commercial tools. The resources most practical for a particular clinical environment are left to the discretion of the QMP.

2.A.3. Measurement of SOBP width and the relative beam range

Measuring the modulation width for at least one modulated field every day is recommended for beam delivery systems that employ beam gating or current modulation in combination with a rotating RMW or ridge filter. For PBS, the beam range adjustment capability should be verified to ensure that the online energy switching systems are operating correctly. One verification technique is to measure an SOBP. Although this concept may not be used in many PBS fields, it does confirm that the Bragg peaks combine as expected and are positioned at the correct place for the specific SOBP tested. Different combinations of range and SOBP widths can be measured on different days, such that the QA covers combinations pertinent to clinical practice.

The modulation width is commonly defined as the distance between the proximal and distal 90% dose levels (Fig. 8), although this definition may vary by center. Each institution should collaborate with their proton therapy system manufacturer to ensure consistency between the delivery system, treatment planning, and physics in defining SOBP width for proton beam measurements.

The clinical modulation width, an important parameter, is designed based on the target width plus an additional margin.[99] Any increase or decrease in SOBP width can produce either an overdose to critical structures or an underdose to the

target. In some proton accelerators, beam extraction and intensity are synchronized with the rotation of the modulator wheel to produce uniform dose distributions (in a homogenous medium).[32,100] In a scanning delivery system, a combination of precise energy stacking and fluence modulation by the control system will produce the desired uniform dose distributions.[101]

Spot checks of the dose at predetermined depths in a phantom can easily verify the doses at the proximal and distal bounds of the SOBP. One method involves using a single planar device (such as an ion chamber array) in combination with a custom phantom of varying thicknesses.[96,102] Therefore, precise, daily measurements of the range and D/MU could be an alternative to SOBP checks, if a relevant number of clinical ranges can be verified daily.

2.A.4. Spot delivery constancy (PBS only)

To date, every scanning beam nozzle has a spot monitoring system. This on-board monitor measures dose or MU per spot parameters continually during the irradiation. The accuracy of patients' clinical plans depends on a predictable delivery of spot parameters that are consistent with those obtained at the time of commissioning and used for modeling within the TPS. The spot monitoring system is used by the delivery system to verify the constancy of the spot shape and spot position. In addition, the spot profile monitors can be used as a feedback mechanism to the delivery system to apply minor corrections, such as corrective offsets to spot positions.

To ensure proper dose delivery to patients, the consistent performance of the spot monitoring system needs to be checked on a daily basis. The ability to deliver the desired dose distribution is directly related to the ability to position the beam, control the size of the beam, and control the number of protons at any given position.

In current clinical practice, there are two main methods used to verify spot delivery constancy. One method evaluates the size and position of individual spots directly; the other evaluates the consistency of a known composite distribution of spots through evaluations of the spot distribution's uniformity and penumbra.[103] The goal of either method is to confirm with an external device that the beam monitoring system is performing within the specified tolerances. External devices that may be used to accomplish this task include film, an ion chamber array, strip chambers, or CCD detecting systems (e.g., Lynx® [104]as is described in section 4).

In the individual spot evaluation method, spots are placed far enough from each other to allow each to be assessed individually. A minimum set of positions may include the central spot (un-deflected beam) and spots in the far corners of the maximum deliverable field size, or near the corners of the maximum size of the external measurement device. Patterns may include spots of various energies. Absolute positions of the spots' centroids are evaluated at the various locations and should be correlated with the imaging system. The centroids of individual spots can also be evaluated relative to each other. Each pencil beam spot is also characterized by a Gaussian distribution with a particular σ (Fig. 4), which can be compared to its baseline value. By assuming a baseline σ of 5 mm in air for 70 MeV and less for higher energies, a 10% tolerance on this baseline value would keep the variation in the clinical beam's 80–20% lateral penumbra below 1 mm at the Bragg peak for all energies.

In the method employing a composite distribution, measurements can be made of a uniformly-spaced spot pattern that is dense enough to create a uniform 2D dose distribution. If errors are present in the positions of spots relative to each other, evaluations of the dose uniformity across the distribution can be used to assess clinical impact. If spot size inconsistencies are present, evaluation of the pattern's penumbra region can be evaluated and compared to baseline values. Correlation of the position of the integrated pattern relative to the imaging isocenter should be evaluated to ensure the absolute spatial accuracy of the delivered pattern.

2.B. Patient setup verification

2.B.1. Couch translation

The positional accuracy of proton patients is particularly important due to the sensitive nature of the proton range in varying patient anatomy and many proton systems make use of robotic patient positioners that can correct the patient's position with translations and rotations. When using these robotic systems a simple linear motion may require a complex articulation of several robotic joints. While couch translational accuracy is not typically checked daily for linear accelerators, it is recommended that this test be performed for proton treatment couches if the patient is not typically re-imaged after couch shifts are applied. If the patient is reimaged after each couch shift, it is still recommended to test couch translational accuracy on a weekly basis.

2.B.2. Lasers

If used in a system, lasers are designed to project marks at the location of the radiation and gantry mechanical isocenters. If the initial patient setups are performed with lasers, their accuracy must be verified daily. As described in the next section, a specially designed QA phantom (e.g., QUASAR™, Modus Medical Devices Inc., London, Canada; Iso Cube Daily QA Phantom, CIRS, Norfolk, VA, and others) that contains internal markers may be positioned and aligned using the treatment room lasers. Imaging the phantom and identifying the fiducial marker locations verifies the accuracy of the positioning via lasers. Laser alignment can also be verified against mechanical devices, which may be provided by the manufacturer during the commissioning procedures. Simply marking the lasers' lines on opposing walls in the treatment room or gantry enclosure may quickly verify laser alignment. In the case of a rotating gantry, deformation of the wall shape should be considered during verification.

2.B.3. Imaging systems

Proton therapy is image-guided radiotherapy (IGRT). As indicated in section I.F., before treatment, the patient setup is verified using either orthogonal planar imaging or volumetric imaging. Daily verification of the x-ray and proton beam isocenter coincidence is recommended, in addition to verifying the functionality of the image acquisition system.

An easy verification procedure consists of imaging a QA phantom, positioned such that it designates the gantry isocenter. The acquired images can verify the setup accuracy of the imaging alignment against room lasers or the cross-wires, which are located on the detector panels or embedded in the imaging software to identify the isocenter location. More elaborate verification can be done by fusing the daily acquired images with a baseline image acquired and verified during commissioning.

A variety of software tools can verify image alignment, such as spy glass, color fusion, and checker board tools. The difference of the image on a given day, compared to the nominal image, yields the offset. An IGRT QA phantom can be used to check the performance of the IGRT and radiation system by irradiating radiographic films placed on the phantom with the proton beam after imaging shifts have been applied.[104] As an alternative, one may use the IGRT system to localize a beam-measuring device directly to examine the coincidence of the IGRT and beam delivery systems.

The required procedures outlined in TG 179,[13] TG 142,[12] and MPPG 2a[14] should be used for daily QA of CBCT if the treatment room is equipped with this system.

2.C. Data communication

A simple image acquisition and file swap between the record-and-verify (R&V) system and the image registration software before patient treatment will identify any problem with the communication of electronic data. A simple way to test and facilitate this is to load a QA patient from the R&V system to aid in setting up the measurement, verification, and recording processes.

2.D. Safety

Several daily safety checks are required. Some checks are mandated by state regulations. Beam pause, door interlock, audio and visual monitoring systems, and radiation indicators (beam on) should be verified daily to ensure functionality. In general, mechanical safety checks can be performed by producing the warning message or an interlock (e.g., by pressing an emergency stop-button), verifying that the proper reaction is triggered (e.g., the movement stops), and verifying that the system recovers from the reaction in a reasonable time.

Different facilities have different levels of emergency stops. An emergency stop button that kills power to the mechanical components in the treatment room may be quicker to recover from than an emergency stop that shuts down the proton accelerator. These buttons should be tested as frequently as reasonably achievable.

Dedicated plates equipped with sensors that can detect a collision are often used to stop mechanical movements by activating an interlock ("collision interlocks"). These "collision plates" are especially important when mechanical components are operated remotely, for example, from the control room, or in general when movements are performed automatically, even when a "dead man" switch is not being held down by the operator. Such collision plates are often found around imaging devices or around the nozzle. The functionality of these sensors should be verified daily.

3. WEEKLY QUALITY ASSURANCE PROCEDURES

Weekly QA checks should be limited to procedures that have less impact on clinical safety if errors are left undetected and that occur less often than they do in tests performed daily or more often than they do in tests performed monthly. Some institutions may decide rather than performing these tests weekly, lower-risk tests may be incorporated into monthly tests, whereas the higher-risk tests may be performed daily. A risk assessment process is encouraged to assist in these decisions. The review of daily QA results should be part of weekly QA and should include evaluating any systematic drift or inconsistency in the daily tests. As above, a physics assistant can perform the QA procedures, and a QMP should review all results. Table II summarizes the recommended weekly QA checks and tolerances.

3.A. Gantry angle vs gantry angle indicators

The accuracy of the gantry angle as indicated on the gantry angle indicators or digital readout (usually better than 0.25°) is crucial in delivering the planned dose. A small deviation in actual gantry angles from that indicated may cause the beam to pass through more- or less-dense media than was intended on the treatment plan.[105] The gantry angle should be verified at least for the cardinal angles. A simple mechanical or digital leveling device or lasers may be used for this purpose.

TABLE II. Weekly QA procedures for proton therapy.

Review of daily QA checks	Tolerances	Comments Reviewed for systematic problem
Mechanical (all delivery systems)		
Gantry angle	$\pm 1^{o}$	
Snout extension	± 10 mm	
Optional		
Couch positional accuracy	± 1mm/1^{o}	Translational/rotational

3.B. Snout or applicator extension

In the case of scattering, US, and, less commonly, PBS,[106] apertures are introduced into the beam path to limit the dose to critical structures by defining the treatment field and sharpening the penumbra. Range-shifters are sometimes introduced in the beam path to treat shallow tumors and to minimize the penumbra for PBS beams. To minimize scatter in air and to sharpen the penumbra, the snout is extended to a point where the air gap between the block surface and patient surface may be as little as 2 cm. Thus, the snout extension should accurately reflect the requirements of the treatment plan. Snout extension can be verified by measuring the extended distances from the isocenter with a measuring tape or a ruler.

3.C. Imaging systems

Some imaging systems acquire positional verification images of the patient from outside the physical space where the patient will be treated (as is done in systems using in-room CT-on-rails). When imaging for patient positioning is performed outside of the treatment space, weekly checks are necessary to verify the accuracy of the patient positioner (PP) in the treatment space. Such tests could include verifying the PP coordinates for couch-embedded BBs by placing each BB at isocenter under different couch rotations.

4. MONTHLY QUALITY ASSURANCE PROCEDURES

Monthly QA procedures monitor parameters that have a lower likelihood of drifting or of causing errors over a shorter time and/or that have less-severe consequences if the test fails. Table III summarizes the recommended monthly QA procedures for proton therapy. A QMP should be responsible for all monthly QA checks regardless of who is performing them.

4.A. Dosimetry

A scattered beam's field-shaping system contains many components that can affect the beam quality, such as flatness, symmetry, intensity, and range. These components have less of an impact on PBS systems, where the scanning magnets in the nozzle and spot size affect beam quality instead. Other factors, such as energy resolution and beam spread, can contribute to scanning beam quality as well. The nozzle components and arrangement of beam-spreading devices may vary among manufacturers and, as such, each system may require unique QA tests.

Beam centering on the first and second scatterers is critically important.[33] For PBS, the reproducibility of the spot size and shape is just as critical as the beam centering for scattered and uniformly scanned beams.[107,108]

One of the functions of the monitor chambers in the nozzle is to check the flatness, symmetry, and MU of the proton beam. In the case of PBS, the spot position, shape, and intensity are verified by these chambers in the nozzle. Therefore, routinely verifying the proper functionality of these monitor chambers, as well as their control systems, is important. A suitable QA device can help reduce the workload for these checks. For example, verifying the flatness and symmetry of broad passive scattering fields can be combined with measuring D/MU as a function of the gantry angle using a two-dimensional ion chamber array.[19] The data for uniformity of broad fields of PBS spots may be evaluated with gamma index analysis tools.[109]

The need and the extent of such monthly tests also depend on the amount of dosimetric data that can be verified daily. Especially for PBS, the choice of the daily QA devices is therefore critical. For example, strip chambers can efficiently measure the beam position and beam width in air at the isocenter plane and at other planes for a large number of spots daily. Alternatively, different gantry angles and energies can be verified on different weekdays, eliminating the need for a monthly check.

4.A.1. Dose per monitor unit (D/MU)

In addition to daily checks of the monitor chamber D/MU constancy, the dose monitor should be calibrated monthly with a different dosimetry system (i.e., an ionization chamber and electrometer), in a manner similar to the monthly D/MU check for linacs. The internal monitor chamber response or beam optics may change with the gantry angle.[110,111] Because the consistency in the fluence of the proton beams is critical to ensure correct dose delivery, verifying the D/MU at several gantry angles is recommended.

A variety of techniques can verify D/MU. The D/MU can be checked in a phantom by measuring the dose at a fixed depth along the central axis of a broad field, or a simple jig that holds a chamber at its center[22] may be used to measure the fluence at different gantry angles, such as every 60° or 90°, depending on the gantry's full range of rotation (e.g., 180° or 360°).

Dose per monitor unit constancy should also be verified for all RMWs (for scattering) or options for reference SOBP widths using a calibrated chamber, either in a solid phantom or water. The baseline values for these constancy checks are established during clinical commissioning and annual QA checks.

4.A.2. Range

Range measurements should be verified for proton delivery systems (DS, US, and PBS) each month. These measurements should cover several different energies that span the full range of energies used for patients. For PBS, the monthly verification can be performed with a single central beamlet or PBS distribution for each measured energy. As mentioned above, this monthly test could be skipped if

TABLE III. Monthly QA procedures for proton therapy.

	Tolerances			
	Method of delivery			
	DS/PS	US	PBS	Comments
Dosimetry				
Output constancy	±2%	±2%	±2%	Measured at different gantry angles (relative to baseline)
Field symmetry	±1%	±2%[a]	±1%	Measured at different gantry angles (relative to baseline)
Field flatness	±2%	±2%	±2%	Measured at different gantry angles (relative to baseline)
Range	±1 mm	±1 mm	±1 mm	For several clinically relevant energies
Spot size			±10%	At different gantry angles
Mechanical (all delivery systems)				
Gantry isocentricity		≤2 mm		Diameter of a circle
Couch isocentricity		≤2 mm		Diameter of a circle
Couch translational accuracy		≤1 mm		All axes
Couch rotational accuracy		1°		
Couch trueness		≤1 mm		Vertical axis
Snout trueness		≤1 mm		
MLC:				
Light/radiation field coincidence (symmetric)		2 mm or 1%		On a side (if light field is used for clinical setup)-Similar to TG-142
Light/radiation field coincidence (asymmetric)		1 mm or 1%		On a side (if light field is used for clinical setup)-Similar to TG-142
Collimator angle indicator		±1°		Four cardinal angles-Similar to TG-142
Leaf position accuracy (2 designated patterns)		±2 mm		1 mm if MLC is used for field matching/patching-Similar to TG-142
Compensator placement accuracy		±2 mm		
Imaging and treatment coordinate coincidence		±2 mm		Four cardinal angles
Congruence of proton and x-ray field		±2 mm		
Safety (all delivery systems)				
Emergency motion buttons		Functional		Inside and outside of the treatment room
Exposure from long-term activation		<0.02 mSv/h @ surface		Should be checked more frequently if the radiation is higher.
Imaging (if applicable)				
Image quality				TG-179 and TG-142
Respiratory gating		Functional		Refer to TG-76, TG-142 and MPPG-2a

DS/PS, Double Scattering/Passive Scattering; US, Uniform Scanning; PBS, Pencil Beam Scanning; TG, Task group; MPPG, Medical Physics Practice Guidelines.
[a]Depending on the US delivery vendor, 1% symmetry consistency may not be achievable due to random beam start times of a layer's wobble pattern

enough dosimetric data are accumulated as part of the daily QA procedures.

4.A.3. Flatness and symmetry of broad fields

Lateral flatness and symmetry for the largest available fields must be measured monthly and be within ±2% and ±1% to 2%, respectively, with respect to the commissioning data in the TPS. Lateral flatness and symmetry should also be checked at different gantry angles to verify the stability and reproducibility of the beam optics.

The scanned spot size, scan pattern, scanning starting position, scanning stopping position, and the number of re-paints of an individual US field will affect the flatness and symmetry across the field. In some US systems, a symmetry consistency of 1% from a baseline value may not be achievable because of a layer delivery logic that uses a random starting position for an individual stacked layer. This results in slight field-to-field symmetry variances that may be greater than 1%, but less than 2% when comparing a single measurement but that will average to less than 1% over an entire treatment course.

4.B. Mechanical

4.B.1. Gantry and couch isocentricity

Gantry and couch isocentricity should be verified to ensure correct dose delivery to the intended target, with a frequency consistent with the experience of the installed equipment, which could be monthly. A slight shift in the location of isocenter could affect the proton beam radiological path, which influences the range and the lateral

position of the field. Importantly, given the immense weight of a proton gantry, the isocenter position may depend on the gantry angle. Thus, verifying the diameter of the gantry isocenter is important to ensure its consistency with commissioning data. Gantry and couch isocentricity may be verified using a star-shot technique with the proton beam or with any apparatus designed for CBCT isocentricity checks.[112]

4.B.2. Couch rotational, translational, and vertical axis accuracy

The accuracy of couch rotation angles should be verified. The couch angle digital readout must be accurate to within 1°. The couch angle should be tested over a range of clinically relevant couch angles.

Couch translational movements should be checked over the range of distances used for patient setup (i.e., ±10 cm) and monthly over the maximum possible range of movements. This test verifies the linearity of the motion, which may not be detected during daily QA for small movements. The test should be done for all axes of motion. Couch translational motion accuracy should be confirmed for the most extreme movements and should have a tolerance of ±1 mm.[113–115]

The "trueness" of the couch positioning is defined as the motion of an object in a straight line without any deviation from that line. The couch vertical axis trueness should be verified because the couch can be subject to accidental collisions or to malfunction resulting from wear and tear.

4.B.3. Snout or applicator longitudinal accuracy

The snout (or applicator) is a part of the nozzle that is used heavily during patient treatment and QA procedures. Wear and tear and possible collisions may affect its motion. Like the couch, the snout's longitudinal motion should be verified for its accuracy and trueness each month.

4.B.4. Coincidence of x-rays, light field, and proton radiation field

This section is only applicable to proton centers that have an x-ray source and a light field in their nozzle assembly.

The Task Group does not recommend conducting light-field to radiation-field tests because the two fields will not always be congruent for most treatment conditions, given that the radiation source (the effective source position) is not fixed and varies with field size, range, modulation, and nozzle (applicator) position. However, a clinic may decide to adjust the light field to match the radiation field for a particular combination of delivery parameters.

For example, if light-field matching is used to match fields for cranial-spinal fields, the light field can be adjusted to match the radiation field derived for that particular source position.

On the other hand, the congruence of x-ray and proton fields needs to be verified monthly because for most treatment conditions, the x-ray images verify patient alignment, and the fields' edges are verified with respect to the proton treatment fields. However, the user needs to be cautioned that the x-ray source and the proton source are often at different positions. The tolerance limit for coincident x-ray and proton fields should be consistent with an overall beam to target accuracy of less than 1mm.

4.B.5. MLC alignment

This is a similar requirement as in photon MLC QA and readers are referred to TG 50 and TG 142. This is only applicable to proton machines with MLC.

4.B.6. MLC leaf positioning

This is a similar requirement as in photon MLC QA and readers are referred to TG 50 and TG 142. This is only applicable to proton machines with MLC.

4.C. Safety

4.C.1. Emergency stop

Usually, pressing dedicated emergency stop buttons inside or outside the treatment room stops the movement of one or more mechanical components. Often, emergency-stop buttons have a dual function that stops not only the mechanical movements but also the particle and/or x-ray radiation. In this case, testing the functionality of these buttons is both a mechanical and a radiation safety check. The functionality of these buttons should be checked monthly.

In conjunction with monthly checks of the beam stop buttons, the delivery system and the record and verify system should be checked to ensure that they read/record the actual number of monitor units delivered when treatment is interrupted by an interlock. For patient treatments, this ensures that the proper number of remaining monitor units will be delivered when treatment is resumed.

4.C.2. Interlock functionality

All pertinent interlocks should be tested monthly, as per the manufacturer's recommendations and specifications, and after careful evaluation by the QMP. Specific interlocks, such as absolute dose, flatness and symmetry, spot positions and spot sigma (for PBS) should be tested. For systems utilizing MLCs, beam delivery should be impossible when a plan calls for leaf positions that are beyond the maximum permissible extended or retracted positions. As another example, for a multi-purpose nozzle capable of delivering double scattering, uniform scanning, and PBS, where only the first two techniques use an MLC, the control system must park and retract all leaves when PBS beam delivery is requested. Specific QA

tests should be determined by the QMP and may vary by institution and manufacturer. Interlocking devices, such as apertures, rings, or range shifters (to name a few), should be tested as well.

4.C.3. MLC activation

Nuclear interactions between protons and the material of an MLC system can generate radionuclides.[116] To ensure that radioactivity does not increase over time from the accumulation of long-lived isotopes, radiation levels must initially be monitored monthly at times when the proton delivery system is "cold" (e.g., when there has been no beam delivered to the room for several hours, such as before the start of a treatment day). In all instances, national and local regulatory limits must be adhered to, such as a maximum dose of 50 mSv/year to radiation workers.[117]

4.D. Respiratory gating equipment

Respiratory motion can markedly influence dose distribution by changing radiological path length for treatment sites, such as the lung, liver, and mediastinum. Respiratory gating can reduce the interplay of the motion in such cases.[118] The criteria of QA checks for the respiratory gating systems used in proton therapy are the same as the recommendations outlined in the AAPM TG 76 report.[119]

4.E. Imaging

The image quality of the imaging system needs to be checked monthly because the clarity and contrast of an imaging system can influence the accuracy of patient positioning. Image quality checks, including low- and high-contrast resolution, uniformity and noise, scaling for planar imagers, and geometric distortion and HU for CBCT, should be reviewed against baseline values. The recommendations and procedures outlined in TG 142[12] are suitable for such tests and checks. The required procedures outlined in TG 179[13] and TG 142[12] should be used for monthly QA of CBCT if the treatment room is equipped with this system.

5. ANNUAL QUALITY ASSURANCE PROCEDURES

Annual QA testing requires considerably more time than monthly testing. It includes checking all mechanical functionality, evaluating the quality and accuracy of the operation of the imaging devices, safety procedures and interlocks, and verifying a subset of the dosimetric data collected during commissioning and the calibration of the proton beam dose output. Depending on the manufacturer and the functionality of the equipment, other parameters and/or devices may require checks and verifications for safe and proper operation. Table IV lists the recommended checks for annual QA. These may be modified based on the proton center's particular systems and available QA devices.

A QMP should be responsible for all annual QA.

5.A. Dosimetry

5.A.1. D/MU constancy

The Task Group recommends that the proton beam be calibrated annually using the standard calibration protocol, the IAEA TRS Report 398[18] and a dosimetry system calibrated by an Accredited Dosimetry Calibration Laboratory (ADCL). All of the ionization chambers and QA devices used for daily and monthly QA tests should be cross-calibrated in the reference proton beams against the institution's ADCL-calibrated reference dosimetry system. In spot scanning, special attention must be paid to recombination effects and dose rate effects. Any chamber used in a proton beam should be properly commissioned by including ion recombination measurements and chamber response tests at different dose rates.

Clinical dosimetry data used to calculate monitor units and dose distributions should be verified against the commissioning data. Deviations should be confirmed by repeating the measurement and, if confirmed, resolved. For PBS, output behavior as a function of beam flux, beam position, and energy should also be calibrated. Beam data, including depth-dose data, pencil beam lateral width, SOBP factors, range shift factors, and relative output factors should be checked and compared with commissioning data.

Flatness, symmetry, and D/MU of beams at different gantry angles other than those tested with monthly QA tests should also be checked (such as every 45°). State requirements may govern the quantity and type of QA tests and the number of gantry angles required to be checked. As stated, this report recommends checking at least four angles for fully rotating gantries and three angles for 180° (1/2) gantries.

5.A.2. Range

Range constancy of the proton field should be checked annually for detection of cracks or wear of scatterers used in scattered systems.[17,101] The range measurements should be within ±1 mm of commissioning values.

For PBS, the range of individual spots or a broad field must be verified, and some off-axis and gantry-angle-dependent, beamlet range verifications are recommended in the annual QA tests. This range is normally verified by measuring depth-dose for a selection of beams at depths corresponding to 90% of the depth-dose. It can also be measured with range uniformity profiles perpendicular to the beam at a depth within the distal fall-off.

The integrity and measured range loss of range shifters should also be verified, as well as their encoding if provided. This integrity check could be a visual inspection or a CT scan of the range shifter that looks for cracks or warping of the material.

5.A.3. SOBP width

The SOBP width should be verified annually for clinical treatment delivery combinations, including for various snout

TABLE IV. Annual QA procedures for proton therapy.

	Tolerances			
	Method of delivery			
	DS/PS	US	PBS	Comments
Dosimetry				
Standard output calibration	±2%	±2%	±2%	TRS 398 calibration
Range verification	±1 mm	±1 mm	±1 mm	Measured at 90% depth dose
SOBP width	±2%/±2 mm	±2%/±2 mm	-	Width between proximal and distal 90%[a] depth dose
Depth doses verification	±2%	±2%	±2%	Maximum difference at any depth
Lateral profile penumbra	±2 mm	±2 mm	±2 mm	80–20% for selected beams at different depths$dummy$and gantry angles
Range uniformity	±0.5 mm	±0.5 mm	±0.5 mm	Corresponding to depth of 90% dose at points off axis
Field symmetry	±1%	±2%	±1%	Measured at different gantry angles (relative to baseline)
Field flatness	±2%	±2%[b]	±2%	Measured at different gantry angles (relative to baseline)
Spot position		1mm/0.5 mm	1mm/0.5 mm	Absolute/relative
Spot size			±10%	At different gantry angles
Uniformity of spot shapes[c]			2% & 2 mm	Multiple gantry angles. Gamma: ≥ 90% of pixels passing
Inverse square correction	±1%	±1%	±1%	From effective source position
Monitor chambers:				
Linearity	±1%	±1%	±1%	
Reproducibility	±2%	±2%	±2%	
Minimum/Maximum dose/spot	Functional	Functional	Functional	Minimum and Maximum are determined by manufacturer
End effect	1 MU	1 MU	1 min MU	For PBS: minimum deliverable MU
SOBP factors	±2%	±2%	±2%	
Range shifter factors	±2%	±2%	±2%	
Relative output factors	±2%	±2%	±2%	
Verification of daily QA equipment	±1% and/or ± 1mm	±1% and/or ± 1mm	±1% and/or ± 1mm	Compared with ADCL calibrated equipment
Cross calibration of field chambers	±2%	±2%	±2%	Ionization chambers used for daily and monthly against standard ADCL chamber
MLC leakage				
Interleaf				Consistent with baseline
Leaf-end				Consistent with baseline
Shielding support				Consistent with baseline
Mechanical (all delivery systems)				
Coincidence of proton and x-ray field		±1 mm		
Coincidence of proton and light field		±1 mm		If light field is used for setup
Gantry angle accuracy		1°		
Gantry isocentricity		≤2 mm		Diameter of a circle
Gantry x-ray isocentricty		≤2 mm		Diameter of a circle
Couch sag		≤1 mm		Weight limit and position as specified by manufacturer
Snout extension accuracy		±10 mm		
Snout rotational accuracy		1°		
CBCT isocentricity		2 mm		Diameter of a circle
Imaging System functionality				
Image system perormance and dose				TG-179 and TG-142
CBCT				TG-179, TG-142, and MPPG-2a
Standard annual x-ray system checks				State regulations

Table IV. Continued.

	Tolerances			
	Method of delivery			
	DS/PS	US	PBS	Comments
Safety checks				
MLC activation test		<0.02 mSv/h		Exposure from short-term activation
Collision protection interlock tests		Functional		
Dead man switch		Functional		On the pendant
Radiation warning sign		Functional		Inside and outside treatment room
Door interlock		Functional		
Beam pause		Functional		
Room beam stop		Functional		Inside and outside treatment room
Facility beam stop		Functional		Inside and outside treatment room
Beam delivery indicator		Functional		Inside and outside treatment room
Radiation monitors		Functional		
Audio and visual monitoring		Functional		
Gantry rotation sensor		Functional		
Room clearance push button		Functional		
Room sensor		Functional		For detection of motion
Visual inspections				
Modulation wheels		Functional		Visually check removable modulation wheels
Block and compensator doors		Functional		Check for wear/tear and cracks

DS/PS, Double Scattering/Passive Scattering; US, Uniform Scanning; PBS, Pencil Beam Scanning; CBCT, Cone beam computed tomography; TG, Task group; MPPG, Medical Physics Practice Guideline.
[a]Some centers may define distal and proximal depth dose at 95% or 98%.
[b]Depending on the US delivery vendor, 1% symmetry consistency may not be achievable due to random beam start times of layer's wobble pattern.
[c]See text for discussion of effects of spot shapes. Note also that penumbra and spot size may be viewed as interchangeable for some distributions.

applicator sizes and combinations of range and SOBP width. For scattered beams, this test can be done using a scanning water tank with a plane parallel chamber.

Because both scanning methods (PBS, US) deliver the proton beam layer by layer, measuring depth-doses with a single ionization chamber is time-consuming. Because of the delivery method, depth-doses and profile measurements made with a typical scanning water tank would require the entire scanning field to be delivered over the full volume multiple times (i.e., for each data point), to be sure that the dose accumulates to each individual scan point. This process could require more than an hour to measure a single field's depth-dose distribution, depending on the depth of penetration, the extent of range modulation, the spacing of depth-dose measurements, type of detector, and field size. New multi-chamber devices have been introduced that improve the efficiency of measuring scanning beams. An MLIC for depth-dose measurements and a multiple pad ionization chamber for profile measurements have greatly improved the efficiency of data collection.[19,120]

5.A.4. Range uniformity

Range uniformity refers to the uniformity of the planar dose at the most distal edge of a field. The range uniformity of proton beams is crucial for sparing critical organs located distally and adjacent to the treatment target. This uniformity is especially critical for patch field combinations, in which a change in range could deliver a large over- or under-dose (a 20% to 50% difference in prescribed dose) to healthy tissues.[121]

Annual measurements of range uniformity are important for validating the proton beam ranges that correspond to the depth of the distal 90% dose in water. Distal edge range uniformity must be maintained across an entire broad beam that is produced either from DS beams or by a single layer of spots of a given energy that produces a large-area Bragg peak. The tolerance for range uniformity should be within ± 0.5 mm from baseline.

Different techniques may be employed to test range uniformity.[21] A practical method is to use a QA device with multiple ionization chambers that can measure D/MU and range uniformity, as well as provide flatness and symmetry information of broad-beam proton beams at the same time.[96]

5.A.5. Integral depth-dose distribution (PBS only)

Although depth-dose measurements of PBS systems can be made for large fields of uniform dose, measuring spot integral depth-dose (IDD) distributions is a more common

component in the configuration of the TPS for dose calculations.[122] The IDD is the area integral dose of the spot at different depths and is usually measured using a large-area ion chamber (such as a Bragg peak chamber) in a water tank equipped with scanning capabilities. A wide selection of IDD scan data that sample IDDs acquired during commissioning must be collected annually in water. The IDD should be checked after any repair in the beam delivery system that may affect the spot dose distribution or when the measured and planned dose distributions differ greatly during the patient-treatment-field QA measurements.

In addition, the constancy of the three-dimensional volumetric dose delivery process in PBS should be checked annually by measuring the dose distribution of a broad field used during commissioning. Commercial three-dimensional dosimeters are not currently available, but testing can be done by measuring both the two-dimensional dose distribution at different depths and a depth-dose curve and then comparing with the established baseline data obtained during commissioning.

5.A.6. Spot angular-spatial distribution and lateral dose profiles (PBS only)

Like the IDD, spot dose profiles are important dosimetric quantities that need to be checked periodically to assure that the spot lateral shape remains the same as that used in the TPS for all possible beam configurations. Profiles should be checked after any repair of the nozzle components that may affect the spot shape, after any changes to the beam tunes (in particular, those affecting the beam optics), and in general, if any unusual difference occurs between the planned and measured dose during patient-treatment-field dosimetry QA. The spot lateral dose profiles in air at different distances from isocenter for a range of energies and different gantry angles (i.e., cardinal angles) should be checked annually. Usually film dosimetry or scintillating foils[123,124] are used to measure lateral profiles. In addition, combined scintillating screen and camera-based systems are sometimes employed,[111] as are high-resolution dosimeters, such as conductive wire profile monitors or gas emission multiplication detectors.[125]

5.A.7. Spot position (PBS only)

To verify the machine's ability to deliver a known pattern of spots and to predict the spot position in the treatment volume according to its position in the spot position monitor (SPM) system, a comprehensive set of clinical data of spot alignment measurements at the isocenter plane and at other clinically relevant transverse planes should be acquired annually. This test is an expansion of the tests described in the daily QA section II.A.d and aims to validate both absolute and relative spot alignment. A more elaborate periodic test is needed to ensure that the SPM interlock prevents the dose delivery if the spot position is out of tolerance. Such a test should be performed after any repair of the SPM or during the annual QA process. The test must follow the manufacturer's recommendations. The resulting spot positioning error in the treatment delivery system should then abort the delivery of the remaining spots and confirm that the interlock system of the SPM is functional.

5.A.8. Inverse-square correction test

An inverse-square correction can correct the dose for broad fields when the distance of the point of measurement from the "effective source" position varies. The validity of this approximation should be checked annually in a phantom by measuring the dose with an ionization chamber at different distances from isocenter and comparing them to the predicted doses using the inverse-square-correction factor. This correction is not relevant for PBS because the effective source is fixed but the absolute correction could be verified annually.

5.A.9. Monitor chamber linearity, reproducibility, and min/max checks

The monitor chamber's dose linearity and reproducibility should be verified annually. The linearity test can be performed, for instance, in the entrance plateau of a single energy layer beam of uniform intensity spots, with the measurement repeated for different spot doses spanning the clinical range of spot MUs. Monitor chambers also have predetermined minimum and maximum dose criteria per spot that also need to be checked annually. Checking consists of verifying that the delivery system vetoes any beam containing one or more spots below the minimum deliverable MU or above the maximum deliverable MU.

5.A.10. Monitor chamber end effect

The monitor chamber dose "end effect" is the difference, in monitor units, when the same amount of charge is collected in a series of short radiation exposures as during a single, long radiation exposure. This difference should be examined to ensure the constancy of response of electronic equipment used for measurements.

The MU in a PBS system does not have the same intuitive relationship with the dose for a broad field as with scattering and US systems because the MU for PBS is the sum of MUs for all the spots in the field. Therefore, using a broad field to check the monitor end effect may require creating special spot patterns in which the MUs of every spot in the field are equal and can be linearly increased or decreased without exceeding the maximum or minimum MU/spot limits of the system. This pattern can determine the end effect by linearly extrapolating the dose at a point measured using an ion chamber to zero MU for all spots. It may be easier to use a single spot to determine the end effect instead of a broad field, or a special pattern which can be repeated with different MUs. There are a number of options, and the one chosen should be appropriately justified. The constancy of the end effect can be checked annually by extrapolating the dose-versus-MU

curve measured with an ionization chamber for a single spot to obtain the dose for zero MU.

5.A.11. Dosimetry factors

Dosimetry factors used for monitor unit calculations or for verifying dose[126] need to be spot-checked. These factors include, but are not limited to, range shifter factors (RSF), SOBP factors, and relative output (D/MU) factors (ROF) for a representative subset of the available energies and modulations.[21,127] The RSF is the relative measured dose at the center of an SOBP for each proton beam energy, extending from values with different range shifters placed in the path of the beam to no range shifter in the beam path, but where the sum of water equivalent depths in the patient and range shifter are the same in all cases. The SOBP factors for each proton beam are the measured doses at the center of modulation for different SOBPs relative to that of the reference SOBP defined at each proton center. The SOBP factor varies slowly with beam energy. The ROF is the ratio of the dose at the center of a reference SOBP for different energies to that of the standard proton beam calibrated according to a calibration protocol.[128]

5.A.12. MLC leakage

Leakage from MLCs has two broad sources: the leaf banks themselves (intraleaf leakage, interleaf leakage, and leaf-end leakage) and the upstream support structure that shields the outsides of the leaf banks. The MLCs in proton therapy nozzles are typically not backed up by moveable secondary jaws in the same way as they are in photon linear accelerator heads. Consequently, verifying the continuing integrity of the shielding support structure is of utmost importance and must be performed with each leaf bank, in turn, fully extended across the central axis. In addition, because the MLC in a proton system resides in the retractable snout, at a minimum, it is necessary to check all sources of leakage at the two extremes of the snout's travel range. Tests for all sources of leakage aside from intraleaf leakage should be made annually. These tests should use the highest-energy (i.e., deepest range) clinical beam and the largest field size, and the results should be compared to baseline measurements made during MLC acceptance testing. The QA values should be similar to leakage levels observed with photon MLCs (~1–2%).[46,129,130]

Intraleaf leakage is dominated by neutrons produced by protons in the leaf material and upstream devices and must be assessed during commissioning.[43] Intraleaf leakage will not change with time. Therefore, it does not need to be reassessed as part of routine MLC QA checks.

Interleaf leakage and leaf-end leakage are susceptible to the force of gravity and must be checked against baseline measurements for different gantry (for fully rotating gantries) and collimator angles. These characteristics may change with the aging of the MLC and as the mechanisms that control the trajectories of the leaves across the field wear with use.

5.A.13. MLC activation

Radiation levels from radionuclides in the treatment nozzle must be assessed during commissioning and checked annually by monitoring radiation levels at appropriate locations near the treatment nozzle.[131] Although the location of measurement should be an institutional adopted policy to protect the staff, we point out that the maximum distance of measurement should not exceed 30 cm from the surface MLC based on the NCRP 151 report.[132] This test should be performed after delivering a clinically relevant proton dose fluence (e.g., the equivalent of an hour's worth of patient treatment) using the highest energy (range), largest SOBP width, and largest clinically available field size. Regulatory restrictions (federal and state) should be observed if excess radiation is detected.[133]

5.B. Mechanical

Annual mechanical QA tests should include all the translational and rotational movements for the couch, gantry, nozzles, imaging systems, and, if applicable, MLC accuracy. These tests should verify not only the range of motion for the clinical setups but also the maximum permissible ranges of motion for all equipment and agreement with angle and position indicators. There may be challenges for a full range of motion of all the axes of a positioner with 6 degrees of freedom, in which case a clinically appropriate range of motion should be factored into the QA procedure. Most of the annual QA checks should be performed with high-precision devices. For example, gantry isocentricity should be checked with high-precision tools, such as a theodolite[113,134] or precise digital front pointers[22,135] or film.[136]

Verification of light field versus kV x-ray field and proton fields may be required at some proton therapy centers. The methods of verifying these coincidences depend on the availability of QA equipment and devices located in the nozzle. Verification of kV x-ray and proton beam isocentricity needs to be performed to ensure the correct coincidence of target alignment and irradiation for all cardinal gantry angles.

5.B.1. MLC leaf positioning

This is a similar requirement as in photon MLC QA and readers are referred to TG 50 and TG 142.

5.C. Imaging

Several components of the imaging system should be checked annually (TG 179[13], TG 142[12]) and must comply with state and federal regulations.[12] The imaging dose, operating tests (kV, mAs), and exposure tests, including dose for pediatric protocols should be reviewed against baseline values (TG 179[13], TG 142[12]). Required tests for CBCT should be performed if the treatment rooms are equipped with such devices. TG 179[13],TG 142[12], and MPPG 2a[14] recommend the required QA checks for CBCT imaging. All safety interlocks

should be checked on the imaging devices. These include, but are not limited to, "dead-man" switches, 5-minute fluoroscopy timer warning, radiation warning lights, and door interlocks.

When imaging for patient positioning is performed outside of the treatment space (e.g., with the use of CT-on-rails) comprehensive checks are needed to validate the mapping between the patient positioning space and the treatment space.

5.D. Safety

In addition to daily and monthly QA safety checks, an extensive safety check should be performed annually. Some of these safety checks may require the assistance from other staff, such as engineers, accelerator operators, and therapists. For example, an accelerator emergency shutdown may be intertwined with other systems that may affect the operation of the accelerator, such as a facility shutdown. For proton therapy systems offering an integrated CBCT solution that uses unified controls for the CBCT, the gantry, and the (robotic) couch, the collision-avoidance models for various equipment arrangement scenarios need to be tested as well.

Proton therapy beams activate material they come in contact with through a variety of inelastic processes. The materials involved can be considered to be permanent system components or patient-specific consumables or recyclables. Annual radiation safety checks of the activation of selected RMWs, beam collimators, and apertures should be carried out to ensure that their activation levels are not changed beyond the expected values measured during acceptance testing and commissioning. The activation levels of these devices might change because the increased use of the facility to treat patients can produce values different from those measured during acceptance testing and commissioning. In such situations, new baseline values should be established and assessed for compliance with radiation safety standards. A more complete discussion of activation hazards from proton therapy is found in the forthcoming TG 136: "Potential Hazard due to Induced Radioactivity Secondary to Radiotherapy." If a workroom or storage area is designed for patient-device decay, a physicist or radiation safety officer should ensure the environment does not have exposures above regulatory limits.

5.E. Visual inspections

The gantry and proton beam delivery accessories and devices should be visually inspected annually to detect wear and tear of the systems, where possible. For example, the modulator wheels, the apertures and compensator door interlocks on the nozzle, and any other mechanically moving parts may wear from normal use. If a vendor performs these inspections and preventative maintenance, the physicist should keep documentation of the vendor's QA activities. It is also recommended that the couch tops and any other immobilization devices that are used for patient treatments be checked for damage or wear that could impact on the accuracy of the beam delivery.

6. DEVICES AND INSTRUMENTATION

Dosimetric measurements for radiation therapy beams can be divided into absolute dosimetry and relative dosimetry. Measurement accuracy depends on the equipment for collecting particular data, as well as on the training of personnel who use the equipment and analyze the results.

Overall, the combined accuracy for all dosimetry measurement uncertainties should be below 3%.[21] The desirable precision is 1% or less for absolute dosimetry and 2% or less or 1 mm or less for relative dosimetry. However, every effort should be made to ensure that the uncertainties remain as low as possible in order to achieve the overall measurement uncertainty of 3% or less.

Measurements of proton beams are in many instances similar to those for external photon beams. However, in some cases, proton beam properties have tighter tolerances because of the physical characteristics of the beams. Although proton beam dosimetry and external photon beam dosimetry have many similarities, proton beams have potentially higher linear energy transfer, a finite range, and dynamic beam motion in the case of scanning. Some general references on the topic are available.[137,138] Task Group 106[139] provides some important guidelines for photon beam commissioning measurements, which are also necessary for proton beams to obtain a precision of 1% or below. Typically, during the annual QA tests, proton beam dosimetry parameters are measured in water phantoms. However, for daily and monthly D/MU and range checks, solid plastic phantoms with similar water-equivalent thickness and proton stopping power ratios[93] are recommended because they are easier and more reproducible to set up. The specific requirements for choosing a radiation detector for particular QA measurements, such as depth-dose, range verification, and beam profile measurements, are governed by the specific characteristics of each proton beam delivery technique. When measuring depth-dose distributions along the central axis or near the beam edge, lateral equilibrium can be lost with depth for pencil beams and beams collimated to less than 2 cm in diameter. A large diameter parallel plate chamber with a wide active area is recommended because it can capture locally scattered components of the beam; however, an additional correction[122,140] may be required to capture the dose from nuclear reactions.

An optimal detector to measure proton depth-dose distributions accurately, while capturing all scatter components, depends on the proton beam delivery modality. For scattering, measuring depth-dose distributions and range with a plane-parallel chamber will be suitable because it provides high spatial resolution along the beam axis.[122] For pencil beam range verification, a Markus plane-parallel chamber may be used if a large field is delivered.

Narrow, point-like ionization chambers are suitable for measuring scattered and scanned beam profiles. Acquiring a beam profile for pencil beams with an ionization chamber

can be tedious; film dosimetry with high spatial resolution is an alternative. However, caution is required, considering the LET and energy-dependent responses of film (i.e., quenching effect).[141–144] Devices that use a scintillating screen viewed through a CCD camera[120,122,145] efficiently collect large amounts of data during clinical commissioning and at yearly and monthly QA tests. These devices (e.g., Lynx, IBA Dosimetry) can measure the lateral field geometry, the lateral homogeneity of dose distributions, the lateral penumbra and, in the case of scanning beams, the lateral beam width of individual pencil beams and the beam position. The electronic read-out of such devices allows online data analysis. Solutions for coping with the problem of quenching effects[122] have been proposed.[146–148] Karger et al.[149] and Farr et al.[126] have reviewed the literature[122] on detectors for absorbed dose measurements in ion beam radiotherapy. For quality assurance, two-dimensional ionization chambers (such as the MatriXX, IBA Dosimetry) can be used for monthly and annual consistency checks of beam output and for lateral profiles at different gantry angles.[19]

Multi-channel devices, such as multi-layer ion chambers (e.g., Zebra, IBA Dosimetry), can efficiently measure and verify the range of a large number of beam energies and can be used for routine QA (e.g., daily QA for scanning) after cross-calibration with depth-dose measurements in water.

Strip chambers (e.g., DE.TEC.TOR. S.r.l.-Devices & Technology, Torino, Italy), and perhaps amorphous silicon detectors in the near future, can measure the relative and absolute position of pencil beams and can be part of daily QA.

The daily D/MU is normally verified for either a single maximum range (cyclotron or synchro-cyclotron), or for multiple energies (synchrotron) with different ranges and SOBP widths. In either case, an ionization chamber, which is positioned at the center of modulation, is the most suitable for such measurements because it provides a large signal-to-background ratio. Building a solid phantom-chamber assembly for beam range measurements as part of daily QA tests is also recommended. This assembly could be used for higher energies with large ranges by adding more material in the beam path. The daily QA devices could be part of a single dedicated phantom. For example, in the case of scanning beams, an MLIC (for range verification), a small strip chamber (for beam width and beam position verification) and a calibrated cylindrical ion chamber in PMMA (for dose verification) could be part of a single phantom fulfilling the requirement for daily dosimetry quality checks.

Daily verification of patient positioning components can be performed with devices used in the photon clinic for IGRT.[12] A variety of QA devices can verify the lasers (if applicable), couch translation, and IGRT isocenter coincidence.[22]

Dosimetry equipment used for absolute proton dosimetry must be traceable to NIST standards to maintain as low an uncertainty as possible. For example, beam calibration should be performed with a system calibrated by an ADCL where the absolute dose is measured using the IAEA TRS-398 calibration protocol.[18] The calibration system should be reviewed by an ADCL at least every 2 years. Subsequently, systems used for monthly D/MU checks and daily quality assurance must be compared with the ADCL-calibrated system, ideally every year.

7. INDEPENDENT AUDITS

For proton therapy centers that are cooperative group members interested in participating in NCI-funded clinical trials, several independent audit services provided by the Imaging and Radiation Oncology Core (IROC) Houston QA Center (formerly RPC) can act as a second-check of a proton center's QA program. The first is the IROC Houston's annual remote beam output verification. This process uses thermoluminescent dosimeters (TLD) and optically stimulated luminescent dosimeters (OSLD) to check an institution's beam calibration. IROC Houston also performs onsite dosimetry review visits as part of the approval process required to participate in clinical trials.[150] A separate site visit procedure is offered for scattered, uniform scanning, and PBS beam delivery methods. The onsite visit combines a comprehensive review of a proton center's QA procedures and documentation of results with a review of dosimetric measurements of many beam delivery parameters, including beam calibration, lateral profile dose distributions, and depth-dose distributions. After the audit, IROC Houston generates a site visit document that includes results of the review and recommendations to improve the proton center's QA program. Lastly, IROC Houston also has anthropomorphic phantoms that can be used as an end-to-end check of a proton center's treatment simulation, planning, and beam delivery process.

For centers not enrolled in NCI trials, having an independent review by an independent physicist with independent equipment is highly recommended. IROC Houston offers audit services (output verification, phantoms, and onsite audits) for fee for institutions that are not clinical trial participants.

[a)]Author to whom correspondence should be addressed. Electronic mail: arjomandy_2000@yahoo.com.

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