Task Group 142 report: Quality assurance of medical accelerators[a)]

Eric E. Klein[b)]
Washington University, St. Louis, Missouri

Joseph Hanley
Hackensack University Medical Center, Hackensack, New Jersey

John Bayouth
University of Iowa, Iowa City, Iowa

Fang-Fang Yin
Duke University, Durham, North Carolina

William Simon
Sun Nuclear Corp., Melbourne, Florida

Sean Dresser
Northside Hospital, Atlanta, Georgia

Christopher Serago
Mayo Clinic, Jacksonville, Florida

Francisco Aguirre
M. D. Anderson Cancer Center, Houston, Texas

Lijun Ma
University of California, San Francisco, San Francisco, California

Bijan Arjomandy
M. D. Anderson Cancer Center, Houston, Texas

Chihray Liu
University of Florida, Gainesville, Florida

Consultants:

Carlos Sandin
Elekta Oncology, Crawley, United Kingdom

Todd Holmes
Varian Medical Systems, Palo Alto, California

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The task group (TG) for quality assurance of medical accelerators was constituted by the American Association of Physicists in Medicine's Science Council under the direction of the Radiation Therapy Committee and the Quality Assurance and Outcome Improvement Subcommittee. The task group (TG-142) had two main charges. First to update, as needed, recommendations of Table II of the AAPM TG-40 report on quality assurance and second, to add recommendations for asymmetric jaws, multileaf collimation (MLC), and dynamic/virtual wedges. The TG accomplished the update to TG-40, specifying new test and tolerances, and has added recommendations for not only the new ancillary delivery technologies but also for imaging devices that are part of the linear accelerator. The imaging devices include x-ray imaging, photon portal imaging, and cone-beam CT. The TG report was designed to account for the types of treatments delivered with the particular machine. For example, machines that are used for radiosurgery treatments or intensity-modulated radiotherapy (IMRT) require different tests and/or tolerances. There are specific recommendations for MLC quality assurance for machines performing IMRT. The report also gives recommendations as to action levels for the physicists to implement particular actions, whether they are inspection, scheduled action, or immediate and corrective action. The report is geared to be flexible for the physicist to customize the QA program depending on clinical utility. There are specific tables according to daily, monthly, and annual reviews, along with unique tables for wedge systems, MLC, and imaging checks. The report also gives specific recommendations regarding setup of a QA program by the physicist in regards to building a QA team, establishing procedures, training of personnel, documentation, and end-to-end system checks. The tabulated items of this report have

been considerably expanded as compared with the original TG-40 report and the recommended tolerances accommodate differences in the intended use of the machine functionality (non-IMRT, IMRT, and stereotactic delivery). © *2009 American Association of Physicists in Medicine*.
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Key words: accelerator, QA, quality assurance, radiotherapy

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I. INTRODUCTION

I.A. Purpose

The AAPM TG-40[1] report published in 1994 is a widely used and referenced document which includes recommendations for general quality assurance (QA) tests for medical linear accelerators. Since the publication of TG-40, several new technologies have been developed and are now commonly used in clinical practice. These technologies include multileaf collimation (MLC), asymmetric jaws, dynamic and virtual wedges, and electronic portal imaging devices (EPIDs). Image guidance devices such as cone-beam CT (CBCT), static kilovoltage (kV) imaging, and respiratory gating were rarely used in 1994. In addition, TG-40 did not consider the demands placed on an accelerator by procedures such as stereotactic radiosurgery (SRS), stereotactic body radiation therapy (SBRT), total body photon irradiation (TBI), and intensity-modulated radiotherapy (IMRT) treatment. Also, the quality of linear accelerators in terms of accuracy and precision has improved in recent years, allowing for procedures such as SRS, SBRT, and IMRT.

The purpose of this report is to build upon the recommendations of TG-40 for QA of medical linear accelerators including the before mentioned technologies (MLC, newer wedge systems, asymmetric jaws, imaging systems, and respiratory systems) and procedures such as SRS, SBRT, TBI, and IMRT. During the development of this report, investigation of technologies that deliver MLC-based IMRT with simultaneous gantry rotation had just begun, and therefore QA for these technologies is not included in the report.

The recommendations of this task group are not intended to be used as regulations. These recommendations are guidelines for QMPs to use and appropriately interpret for their individual institution and clinical setting. Each institution may have site-specific or state mandated needs and requirements which may modify their usage of these recommendations.

I.B. Background

The underlying principle behind TG-40 was the International Commission on Radiation Units and Measurements[2] (ICRU) recommendation that the dose delivered to the patient be within ±5% of the prescribed dose. Taking into consideration the many steps involved in delivering dose to a target volume in a patient, each step must be performed with accuracy better than 5% to achieve this recommendation.

The goal of a QA program for linear accelerators is to assure that the machine characteristics do not deviate significantly from their baseline values acquired at the time of acceptance and commissioning.[3] There are several publications that describe procedures and conditions for acceptance testing and commissioning, and the reader is referred to these: The International Electrotechnical Commission[4,5] (IEC), American Association of Physicists in Medicine[3,6,7] (AAPM), and American College of Medical Physics[8] (ACMP). Many of these baseline values are entered into treatment planning systems to characterize and/or model the treatment machine, and therefore can directly affect treatment plans calculated for every patient treated on that machine. Deviation from the baseline values could thus result in suboptimal treatment of patients. Machine parameters can deviate from their baseline values as a result of many reasons. There can be unexpected changes in machine performance due to machine malfunction, mechanical breakdown, physical accidents, or component failure. Major component replacement (waveguide, bending magnet, etc.) may also alter machine performance from the original parameters. In addition there can be gradual changes as a result of aging of the machine components. These patterns of failure must be considered when establishing a periodic QA program.

It is not the goal of this report to describe the experimental techniques for performing QA tests, as these tests are described in a number of publications.[9–35] We also realize the increased demands on staff in the current healthcare environ-

TABLE I. Daily.

Procedure	Machine-type tolerance		
	Non-IMRT	IMRT	SRS/SBRT
Dosimetry			
X-ray output constancy (all energies)			
Electron output constancy (weekly, except for machines with unique e-monitoring requiring daily)		3%	
Mechanical			
Laser localization	2 mm	1.5 mm	1 mm
Distance indicator (ODI) @ iso	2 mm	2 mm	2 mm
Collimator size indicator	2 mm	2 mm	1 mm
Safety			
Door interlock (beam off)		Functional	
Door closing safety		Functional	
Audiovisual monitor(s)		Functional	
Stereotactic interlocks (lockout)	NA	NA	Functional
Radiation area monitor (if used)		Functional	
Beam on indicator		Functional	

ment and recognize the fact that the tests should be simple, rapid, and reproducible. Since the publication of TG-40 there have been many QA products designed around the TG-40 table that make execution of these tests more efficient. TG-40 stated that the test procedures should be able to distinguish parameter changes smaller than tolerance or action levels. A definition of *repeatability* is included in Sec. II C.

As noted in TG-40, the QA program for linear accelerators is very much a team effort, and the responsibilities of performing various tasks are typically divided among physicists, dosimetrists, therapists, and accelerator engineers. However, we reiterate the recommendation that the overall responsibility for a linear accelerator QA program be assigned to one individual: The qualified medical physicist (QMP).

The foundation of linear accelerator based QA lies in Table II of TG-40. Since its publication linear accelerators have changed not only with respect to their physical construction but also in their role as treatment devices. Asymmetric jaws, dynamic/virtual wedges, and multileaf collimators have been added. Intensity-modulated radiation therapy and image-guided radiation therapy (IGRT) have increased demands on the accuracy required of the linear accelerator for precise dose delivery. The types of treatments delivered with the machine should also have a role in determining the QA program that is appropriate for that treatment machine. For example, machines that are used for SRS/SBRT treatments, TBI, or IMRT require different tests and/or tolerances. Some older machines may be upgraded (MLCs, portal vision) in order to perform IMRT or stereotactic radiotherapy. This will change the machine category for testing requirements. Solid compensator based IMRT is an option for some machines that are not IMRT capable. Many of the mechanical and dosimetric tests that apply to IMRT machines will therefore be applied to these machines and in most cases, specific for the particular manufacturer.

And finally, this report does give recommendations in regards to imaging devices that are connected to the accelerator and with gating as the accelerators operation can be tied to the respiratory system's signals. This was necessary as safety, mechanical, and operational attributes of imaging and gating are tied to the accelerator.

II. QUALITY ASSURANCE OF MEDICAL ACCELARATORS

II.A. General

The recommendations of this report are summarized in six tables. The first three tables, Table I (daily), Table II (monthly), and Table III (annual), essentially replace Table II of TG-40. However, as is evident, the scope of testing and the number of variables have increased compared to TG-40. Each table has specific recommendations based on the nature of the treatments delivered on the individual machine. The tables are differentiated into non-IMRT or nonstereotactic machines, IMRT machines, and IMRT/stereotactic machines. There are also explicit recommendations based on the equipment manufacturer as a result of the design characteristics of those machines. The recommendations in each table utilize the QA categories used in Table II of TG-40, dosimetry, mechanical, and safety, while adding a new category: Respiratory gating. The tests for asymmetric jaws and TBI/total skin electron therapy (TSET) are contained in Tables II and III. Three additional tables were created for dynamic/virtual/universal wedges (Table IV), MLC (Table V), and imaging (Table VI). All of these ancillary devices not covered in TG-40 are discussed in Sec. II D. Test frequencies for each test are listed in the tables and the rationale for them is dis-

TABLE II. Monthly.

Procedure	Machine-type tolerance		
	Non-IMRT	IMRT	SRS/SBRT
Dosimetry			
X-ray output constancy			
Electron output constancy		2%	
Backup monitor chamber constancy			
Typical dose rate[a] output constancy	NA	2% (@ IMRT dose rate)	2% (@ stereo dose rate, MU)
Photon beam profile constancy		1%	
Electron beam profile constancy		1%	
Electron beam energy constancy		2%/2 mm	
Mechanical			
Light/radiation field coincidence[b]		2 mm or 1% on a side	
Light/radiation field coincidence[b] (asymmetric)		1 mm or 1% on a side	
Distance check device for lasers compared with front pointer		1mm	
Gantry/collimator angle indicators (@ cardinal angles) (digital only)		1.0°	
Accessory trays (i.e., port film graticle tray)		2 mm	
Jaw position indicators (symmetric)[c]		2 mm	
Jaw position indicators (asymmetric)[d]		1 mm	
Cross-hair centering (walkout)		1 mm	
Treatment couch position indicators[e]	2 mm/1°	2 mm/1°	1 mm/0.5°
Wedge placement accuracy		2 mm	
Compensator placement accuracy[f]		1 mm	
Latching of wedges, blocking tray[g]		Functional	
Localizing lasers	±2 mm	±1 mm	< ± 1 mm
Safety			
Laser guard-interlock test		Functional	
Respiratory gating			
Beam output constancy		2%	
Phase, amplitude beam control		Functional	
In-room respiratory monitoring system		Functional	
Gating interlock		Functional	

[a]Dose monitoring as a function of dose rate.
[b]Light/radiation field coincidence need only be checked monthly if light field is used for clinical setups.
[c]Tolerance is summation of total for each width or length.
[d]Asymmetric jaws should be checked at settings of 0.0 and 10.0.
[e]Lateral, longitudinal, and rotational.
[f]Compensator based IMRT (solid compensators) require a quantitative value for tray position (wedge or blocking tray slot) set at a maximum deviation of 1.0 mm from the center of the compensator tray mount and the cross hairs.
[g]Check at collimator/gantry angle combination that places the latch toward the floor.

cussed in Sec. II C. This task group (TG) considers that all of the tests included in the tables are important for ensuring the equipment to be suitable for high quality and safe radiation treatments. For example, in reference to physical wedge placement accuracy, Table II notes a monthly placement test with an accuracy of 2 mm. Deviations greater than 2 mm could result in errors as much as 2% at clinically relevant depths.

A *consistent beam profile* is an important quantity for accurate and reproducible dose delivery in radiotherapy. *Beam uniformity* was addressed in TG-40 Table II with flatness constancy, i.e., consistent flatness and symmetry tolerance levels. Constancy is specifically associated with flatness; however, symmetry tolerance can be interpreted as either absolute, regardless of reflection reference, or as constant values, taking into account the reflection reference, i.e., left to right or right to left. We believe this needs further interpretation in order to detect excessive changes in relative symmetry via sign change that would still fall within the tolerance of absolute symmetry value. For example, a cross-plane right/left symmetry drift from +3% to −3% is within the tolerance of TG-40 Table II but constitutes a beam shape change of 6%. Therefore, the monthly and annual tolerance values have been edited to take this into account and still

TABLE III. Annual.

Procedure	Machine-type tolerance		
	Non-IMRT	IMRT	SRS/SBRT
Dosimetry			
X-ray flatness change from baseline		1%	
X-ray symmetry change from baseline		±1%	
Electron flatness change from baseline		1%	
Electron symmetry change from baseline		±1%	
SRS arc rotation mode (range: 0.5–10 MU/deg)	NA	NA	Monitor units set vs delivered: 1.0 MU or 2% (whichever is greater) Gantry arc set vs delivered: 1.0° or 2% (whichever is greater)
X-ray/electron output calibration (TG-51)		±1% (absolute)	
Spot check of field size dependent output factors for x ray (two or more FSs)		2% for field size $<4\times4$ cm^2, 1% $\geq4\times4$ cm^2	
Output factors for electron applicators (spot check of one applicator/energy)		±2% from baseline	
X-ray beam quality (PDD_{10} or TMR_{10}^{20})		±1% from baseline	
Electron beam quality (R_{50})		±1 mm	
Physical wedge transmission factor constancy		±2%	
X-ray monitor unit linearity (output constancy)	±2% ≥5 MU	±5% (2–4 MU), ±2% ≥5 MU	±5% (2–4 MU), ±2% ≥5 MU
Electron monitor unit linearity (output constancy)		±2% ≥5 MU	
X-ray output constancy vs dose rate		±2% from baseline	
X-ray output constancy vs gantry angle		±1% from baseline	
Electron output constancy vs gantry angle		±1% from baseline	
Electron and x-ray off-axis factor constancy vs gantry angle		±1% from baseline	
Arc mode (expected MU, degrees)		±1% from baseline	
TBI/TSET mode		Functional	
PDD or TMR and OAF constancy		1% (TBI) or 1 mm PDD shift (TSET) from baseline	
TBI/TSET output calibration		2% from baseline	
TBI/TSET accessories		2% from baseline	
Mechanical			
Collimator rotation isocenter		±1 mm from baseline	
Gantry rotation isocenter		±1 mm from baseline	
Couch rotation isocenter		±1 mm from baseline	
Electron applicator interlocks		Functional	
Coincidence of radiation and mechanical isocenter	±2 mm from baseline	±2 mm from baseline	±1 mm from baseline
Table top sag		2 mm from baseline	
Table angle		1°	
Table travel maximum range movement in all directions		±2 mm	
Stereotactic accessories, lockouts, etc.	NA	NA	Functional
Safety			
Follow manufacturer's test procedures		Functional	
Respiratory gating			
Beam energy constancy		2%	
Temporal accuracy of phase/amplitude gate on		100 ms of expected	
Calibration of surrogate for respiratory phase/amplitude		100 ms of expected	
Interlock testing		Functional	

TABLE IV. Dynamic/universal/virtual wedges.

Dynamic-including EDW (Varian), virtual (Siemens), universal (Elekta) wedge quality assurance				
		Tolerance		
Frequency	Procedure	Dynamic	Universal	Virtual
Daily	Morning check-out run for one angle		Functional	
Monthly	Wedge factor for all energies	C.A. axis 45° or 60° WF (within 2%)[a]	C.A. axis 45° or 60° WF (within 2%)[a]	5% from unity, otherwise 2%
Annual	Check of wedge angle for 60°, full field and spot check for intermediate angle, field size	Check of off-center ratios @ 80% field width @ 10 cm to be within 2%		

[a]Recommendation to check 45° if angles other than 60° are used.

maintain the TG-40 intent. The tolerance values are also stated such that new developments in treating beams without flattening filters are considered.

In our updated tolerance table, the monthly tolerance values are specific to a consistent beam shape, where baseline off-axis factors (OAFs) were measured with a QA device immediately following beam commissioning or updated by the annual review. Ongoing QA measurements are compared to the baseline off-axis factors. Chosen point locations that fall within the core of the field [as an example four points off axis in multiple directions within 80% of an agreed upon field size (FS)] should have an average of their absolute values within the tolerance value in Table II. This is expressed as

$$\frac{1}{N}\cdot\sum_{L=1}^{N}\left|\frac{\mathrm{TP}_L-\mathrm{BP}_L}{\mathrm{BP}_L}\right|\cdot 100\%\leq \text{tolerance}\%,$$

where TP_L and BP_L are off-axis ratios at test and baseline points, respectively, at off-axis point L, N is the number of off-axis points, and $\mathrm{TP}_L=(\mathrm{MP}_L/\mathrm{MP}_C)$ where M represents the measurement value and C is the central axis measurement. Similarly, the baseline points are represented by $\mathrm{BP}_L=(\mathrm{MBP}_L/\mathrm{MBP}_C)$

The annual table in TG-40 included a 2% tolerance for "off-axis factor constancy," with recommended testing at various gantry angles, but there was no mention of flatness or symmetry. We have added this as a profile comparison to baseline commissioning data in a large field size; this increases the sensitivity to detect beam shape changes that result from a beam energy change or target change that may be due to long term aging effects. The recommended field size is 30×30 cm^2 or greater for conventional x rays; the largest field size for special x-ray applications if $<30\times30$ cm^2 and the largest applicator for electrons. The flatness and symmetry values in the center 80% FS of the measured profile, as defined during machine commissioning, should not deviate from the baseline by more than the tolerance values in Table III. We believe that this test expansion is justified since the

TABLE V. Multileaf collimation (with differentiation of IMRT vs non-IMRT machines).

Procedure	Tolerance
Weekly (IMRT machines)	
Qualitative test (i.e., matched segments, aka "picket fence")	Visual inspection for discernable deviations such as an increase in interleaf transmission
Monthly	
Setting vs radiation field for two patterns (non-IMRT)	2 mm
Backup diaphragm settings (Elekta only)	2 mm
Travel speed (IMRT)	Loss of leaf speed >0.5 cm/s
Leaf position accuracy (IMRT)	1 mm for leaf positions of an IMRT field for four cardinal gantry angles. (*Picket fence* test may be used, test depends on clinical planning-segment size)
Annually	
MLC transmission (average of leaf and interleaf transmission), all energies	±0.5% from baseline
Leaf position repeatability	±1.0 mm
MLC spoke shot	≤1.0 mm radius
Coincidence of light field and x-ray field (all energies)	±2.0 mm
Segmental IMRT (step and shoot) test	<0.35 cm max. error RMS, 95% of error counts <0.35 cm
Moving window IMRT (four cardinal gantry angles)	<0.35 cm max. error RMS, 95% of error counts <0.35 cm

TABLE VI. Imaging.

Procedure	Application-type tolerance: non-SRS/SBRT	Application-type tolerance: SRS/SBRT
Daily[a]		
Planar kV and MV (EPID) imaging		
Collision interlocks	Functional	Functional
Positioning/repositioning	≤2 mm	≤1 mm
Imaging and treatment coordinate coincidence (single gantry angle)	≤2 mm	≤1 mm
Cone-beam CT (kV and MV)		
Collision interlocks	Functional	Functional
Imaging and treatment coordinate coincidence	≤2 mm	≤1 mm
Positioning/repositioning	≤1 mm	≤1 mm
Monthly		
Planar MV imaging (EPID)		
Imaging and treatment coordinate coincidence (four cardinal angles)	≤2 mm	≤1 mm
Scaling[b]	≤2 mm	≤2 mm
Spatial resolution	Baseline[c]	Baseline
Contrast	Baseline	Baseline
Uniformity and noise	Baseline	Baseline
Planar kV imaging[d]		
Imaging and treatment coordinate coincidence (four cardinal angles)	≤2 mm	≤1 mm
Scaling	≤2 mm	≤1 mm
Spatial resolution	Baseline	Baseline
Contrast	Baseline	Baseline
Uniformity and noise	Baseline	Baseline
Cone-beam CT (kV and MV)		
Geometric distortion	≤2 mm	≤1 mm
Spatial resolution	Baseline	Baseline
Contrast	Baseline	Baseline
HU constancy	Baseline	Baseline
Uniformity and noise	Baseline	Baseline
Annual (A)		
Planar MV imaging (EPID)		
Full range of travel SDD	±5 mm	±5 mm
Imaging dose[e]	Baseline	Baseline
Planar kV imaging		
Beam quality/energy	Baseline	Baseline
Imaging dose	Baseline	Baseline
Cone-beam CT (kV and MV)		
Imaging dose	Baseline	Baseline

[a]Or at a minimum when devices are to be used during treatment day.
[b]Scaling measured at SSD typically used for imaging.
[c]Baseline means that the measured data are consistent with or better than ATP data.
[d]kV imaging refers to both 2D fluoroscopic and radiographic imaging.
[e]Imaging dose to be reported as effective dose for measured doses per TG 75[36].

annual test is more comprehensive, intended to uncover changes that may have remained undetected during more frequent but less rigorous testing throughout the year. Note that the tolerance value is not absolute in that it should not be interpreted as a comparison to the machine specification; instead it is a tolerance value from the baseline. The expansion of tests is also justifiable due to the fact that since TG-40 and post-IMRT, the selection of available QA tools makes annual testing less burdensome; these tools range from 3D water scanning tanks to large area detector arrays. The proper tools should be chosen by matching the detectors and software to the needs and sensitivity requirements.

II.B. Test frequencies

As with TG-40, testing is distributed among daily, monthly, and annual QA frequencies. The underlying principles for test frequency follow those of TG-40 and attempt to balance cost and effort with accuracy. In this report there are additional factors that affect the frequency of the tests, specifically the type of treatments delivered on the machine and the inherent design of the machine. For example, some linacs are designed with independent photon and electron monitor chamber systems (e.g., Siemens). It is recommended that each independent monitor chamber system should be checked daily.

The daily (or in some cases weekly) tests include parameters that can affect dose to the patient by dosimetric (output constancy) or geometric (lasers, optical distance indicator, field size) means. The daily safety tests still include audiovisual monitoring of the patient and testing of the door interlock. With respect to EPID and kV imaging, the operation and functionality are tested daily, as well as collision interlocks. The daily tests are typically performed by the morning warm-up therapist, who should be trained by a qualified medical physicist with a well defined policy and procedure to follow if any of the tests are found to be out of tolerance. Monthly tests include those that have a lower likelihood of changing over a month (e.g., tray position or profile consistency—which also serves as an energy check for photons). Monthly tests for respiratory gating have been added as well as more quantitative tests for EPIDs and kV imaging. These tests are typically more involved and are generally performed by the QMP. The annual tests are a subset of the tests performed during acceptance testing and commissioning procedures. During the annual review of dosimetry systems, constancy factors are either established, reconfirmed, or updated.

Several authors have attempted to develop a systematic approach to developing QA frequencies and action levels.[37–39] More recently the work being performed by Task Group 100[40] of the AAPM. TG 100—A method for evaluating QA needs in radiation therapy [based on "Failure modes and effects analysis (FMEA)"]—promotes individual departments to be responsible for development of unique QA programs based on procedures and resources performed at individual institutions. Institutional deviations from some of these recommendations are expected based upon the institution's policy and procedures; the clinical significance of these deviations may be mitigated by other control methods that are not anticipated in this document. In the case of decreasing the frequency of a particular test, the results of the test must be examined and be validated with an appreciable history of that test and based on sound statistical principles. That decision must also be correlated with the documented analysis of the potential impact of catastrophic results in the event of an occurrence. By FMEA analysis, an institution can estimate the degree of harm due to a failure along with (lack of) detection and occurrence probabilities. We reiterate the recommendations of TG-40[1] that the QA program should be flexible enough to take into account quality, costs, equipment condition, available test equipment, and institutional needs. However, we do recommend using the tests and frequencies outlined in the tables that follow until methods such as TG-100 supersede this report.

II.C. Guidelines for tolerance values

The original tolerance values in TG-40 were adapted from AAPM Report 13. Report 13 used the method of quadratic summation to set tolerance values for individual machine parameters. These values were intended to make it possible to achieve an overall dosimetric uncertainty of $\pm 5\%$ and an overall spatial uncertainty of ± 5 mm. These tolerances are further refined in this report and those quoted in the tables are specific to the type of treatments delivered with the treatment unit. For example, the coincidence of collimator, gantry, and couch axes with the isocenter is recommended to be within 1 mm for a stereotactic machine and within 2 mm for other machines.

To clarify the relationship of tolerance values with variations from dosimetric baseline values or deviations from absolute mechanical values established during acceptance testing, we provide the following definitions.

II.C.1. Acceptance testing procedure standards

During the process of acceptance of equipment the supplier demonstrates its performance to the satisfaction of the customer against specifications, which should be part of the agreed contract. The dosimetric and mechanical measurements should satisfy the agreed upon specification values. Acceptance testing and commissioning set the *baseline* for future dosimetric measurements for beam performance *constancy* and verifies that the equipment is mechanically functional and operates within certain tolerances from absolute specified values.

II.C.2. Commissioning baseline values

Upon acceptance of the equipment, treatment beam characteristics needed for clinical use are established by the commissioning process. Often some of the beam characteristics may have been already acquired during the acceptance testing procedures. These beam characteristics establish the baseline values to be checked relative to constancy during future dosimetric quality assurance measurements.

II.C.3. Tolerances and action levels

The spirit and intent of TG 40 are maintained and further clarified; the tolerances listed in the tables should be interpreted to mean that if either a baseline parameter measured during AT exceeds the tabulated value or the change in the baseline parameter exceeds the tabulated value, then an action is required. Therefore, if ongoing QA measurements fall outside the tolerance levels (allowed deviation) in the tables, the equipment should be adjusted to bring the measured values back into compliance: the tolerances are action levels [a hierarchy of steps taken by the medical physicist (MP) and QA staff]. However, if certain baseline parameters barely satisfy the tolerance value repeatedly, an appropriate action should be taken to correct the equipment. These actions should be set by the MP in terms of the level of action (inspection, scheduled, or immediate stoppage) to be taken and under what circumstances. The actions should be well known by all personnel involved in the QA process.

It is not our intention to make prescriptive recommendations on the type of action but rather provide guidance as to the types of actions that are needed in the QA process. We believe there are three types of actions, with an action priority ranking from lowest to highest, as follows.

- Level 1: Inspection action. From repeated QA procedures, there are measurement values that become expected under normal operating conditions. A sudden and significant deviation from the expected value should be called to the attention of the MP, even if the measurement itself does not exceed the table tolerance value. Some measured values may be affected due to intervention outside of the normal linac operation or measurement. For example, a change in personnel, setup, or maintenance event may cause a measurement shift. The change may also be indicative of a machine problem that is not yet out of tolerance QA but a change nonetheless. Treatments should continue, but the cause should be investigated during routine QA.
- Level 2: Scheduled action. We present two examples which could require scheduled action. First, consecutive results of a QA procedure that are at or near the tolerance value should cause investigation or scheduled maintenance into the problem within one to two working days. Second, a single result that exceeds the tolerance value, but not excessively, should cause investigation or scheduled maintenance. Under these conditions, deviations may slightly exceed the tolerance, but the clinical impact over the course of a few days (<1 week) may not be significant. Treatment may continue, but mitigation of the cause should be scheduled to take place within one to two working days.
- Level 3: Immediate action or stop treatment action or corrective action. A measurement result could require an immediate suspension of the treatment function related to the dosimetric parameter measured. Examples for complete suspended use of the linear accelerator could be as simple as nonfunctional safety interlocks or as extreme as an excessive error in a dosimetry parameter. Specified treatment functions should not continue until the problem is corrected.

With these three action levels, there is an institutional need to specify the deviations from baseline values and tolerances associated with levels 2 and 3. This should be carried out by the QA committee as discussed in the TG-40 report (Sec. B.I.C). The level 1 parameters' thresholds cannot be specified by the committee; these thresholds evolve from the QA data. The level 1 threshold is not a critical requirement but it can lead to significant improvements in the QA program. The report from TG-100 is expected to address some of these issues.

II.C.4. Uncertainties, repeatability, and precision

The TG-40 report[1] stated that test procedures should be capable of distinguishing parameter changes that are smaller than tolerance or action levels. Here we attempt to further clarify this requirement and offer some examples. There is an associated measurement uncertainty that depends upon the technique used, the measuring device, and the person using the device and recording the measurement.

- Measurement uncertainty (or accuracy) is in reference to an expected error of the measurement result with respect to a defined standard (baseline value).
- Measurement repeatability is in reference to the device's measurement statistics, i.e., with no change in the quantity being measured and no change in the measurement setup, the recorded values from repeated measurements will have a standard deviation about the mean.
- Measurement precision is in reference to the measuring device's scale resolution of the display.

For example, a dosimetry chamber/electrometer may have a measurement precision of 0.01% on a full scale four digit display, measurement repeatability with a deviation of the mean of 0.05% after ten repeated measurements, and a measurement uncertainty of 1.5% absolute dose. Many of the tolerance values in the tables are with respect to baseline values from the QA measuring device, measured at the time of commissioning. The measurement repeatability of the device and technique must be less than the tolerance level for the parameter being measured. We recommend that the measurement system and procedure repeatability be such that two standard deviations for three or more repeated consecutive measurements are less than the tolerance value.

The tolerance values in the tables have an interdependence with test frequency. Devices used for daily QA output constancy may provide data for tests normally performed on a monthly basis. However, the monthly tests are expected to be performed at a higher level of skill and with a higher level of test equipment and therefore those measurements carry a tighter tolerance value. Therefore, when a procedure is performed on a more frequent schedule than required, the QA committee may include the more frequent measurements with a different tolerance value as listed in this report's tables. This will become apparent when establishing the level

1 action level. However, the tolerance values in this report should be rigorously maintained for the specified procedure frequency.

II.D. Ancillary treatment devices not in TG-40

The AAPM TG-40 report made it clear that new devices coming on-line during this time period (1994) would be beyond the scope of the report. The TG-40 report did not address asymmetric jaws, dynamic/virtual wedging, or multileaf collimation. However, task groups addressing each of these new technologies never formed, or the final reports were written after TG-40 was published, for example, the multileaf collimation TG-50[41] report. Klein *et al.*[15] published a manuscript on a QA program for ancillary high technology devices on a dual-energy linear accelerator that included asymmetric jaws, dynamic and virtual wedges, multileaf collimation, and electronic portal imaging. This paper was based on one institution's equipment and process for QA. In addition, the technologies themselves have manifested into more modern and complicated devices, especially the use of multileaf collimation for IMRT.

This section addresses these ancillary devices/options in terms of QA processes required to support them. We have incorporated asymmetric jaws within the revised Table II (TG-40) recommendations, while separate tables have been created for MLC and dynamic/virtual wedges. This task group makes specific recommendations for asymmetric jaws, jaw based wedge delivery systems, and multileaf collimation that are both vendor specific and operation specific. This was necessary due to the differences among the systems. The following sections outline these specific recommendations.

II.D.1. Asymmetric jaws

Slessinger *et al.*[42] published one of the earliest papers on implementation of asymmetric jaws including calculation schemes and QA. For asymmetric jaws, there should be additional scrutiny for beam matching and the accuracy of dynamic/virtual wedge delivery which depends strongly on jaw positioning accuracy. For example, Klein *et al.*[43] published a paper using a single isocentric technique relying on asymmetric jaws with beam matching at the isocentric plane for breast irradiation. To address this, the recommendation was to perform monthly light-radiation coincidence and asymmetric jaw positional accuracy for each jaw used clinically at 0.0 cm (for beam matching) and also at 10.0 cm (retracted from central axis). The testing of the jaws positioned at 0.0 can be performed with a single film to demonstrate nondivergent field matching.

II.D.2. Dynamic/virtual/universal wedge

Before IMRT, modulation of the beam during treatment was accomplished by computer controlled movement of the collimating jaw while the beam was on using computer control.[44] These technologies, dynamic (later enhanced dynamic wedge) and virtual wedges, were clinically introduced by Varian and Siemens, respectively. Jaw accuracy for the dynamic wedge-type delivery published by Klein *et al.*[45] showed that very small changes in jaw position could affect the dynamic wedge factor. The dynamic wedge reports (Klein,[15] Liu,[46,47] and Beavis[48]) all pointed to individual institution recommendations for dynamic jaw delivery to deliver a wedge field. Zhu *et al.*[49] published similar recommendations for virtual wedge. As these technologies rely on computer delivery of jaw position in a given instant or percentage of monitor units (MUs), there should be scrutiny of the embedded tables that map the location of jaw position in relationship to time (fraction of MU to be delivered). In this report, we include the Elekta universal wedge within this category (described by Phillips *et al.*[50]), as computer control moves the fixed internal 60° wedge in place to yield an effective wedge angle when combined with an open field. The recommendations in Table IV include some simple daily systematic tests, operational tests of the computer control on a monthly basis, and annual dosimetric tests. We recommend that tests be performed with a 45° wedge delivery for systems that deliver an "effective" wedge angle by using a combination of 60° and open beam. If, however, a facility opts to deliver a 60° wedge as a unique field, then the 60° wedge angle should be checked.

II.D.3. MLC

Early implementations of multileaf collimation[51–53] were limited to tests and tolerance recommendations for early Varian MLC machines. Soon afterward, Jordan and Williams[54] published a paper for Elekta machines and Das *et al.*[55] for Siemens machines. Mubata *et al.*[21] published a paper dedicated to QA for Varian machines following these initial papers. In 1998, the AAPM formed a task group (AAPM TG-50[41]) to address multileaf collimation, including extensive sections on multileaf collimator QA. This publication recommended a scope limited QA program. Although the task group report was published during initial IMRT implementations using multileaf collimation, it did not make recommendations specific for MLCs as used for IMRT. Subsequent publications,[9,30,56–61] particularly those by Cosgrove *et al.*[62] and Chang *et al.*,[63] pointed to tests for MLC QA along with tools for such tests. We have subsequently recommended testing (Table V) that depends on whether or not the MLC system is used for IMRT. With regards to the impact of MLC on IMRT, publications have documented the impact of leaf positioning accuracy and interleaf or abutted leaf transmission on the accuracy of delivered IMRT fields.[64–66] Therefore additional tests of multileaf collimators that are used for IMRT are recommended. Some of the leaf parameters that affect dose delivery for IMRT include leaf positional accuracy and transmission values. Simple tests, such as the picket fence test described by LoSasso,[66] can assess positional accuracy qualitatively (by the matching of sequential segments and leaf transmission, particularly interleaf). We recommend the picket fence test be performed weekly with a careful examination of the image acquired by static film or on-line portal image. On a monthly basis, we recommend expansion of the leaf position accuracy test to account

for gantry rotation which may affect leaf motion due to gravitational effects imposed on the leaf carriage system. Loss of travel speed can result in increased beam holds or gap width errors.[66] MLC travel speed is evaluated with vendor software or by MLC log file evaluation. As an example, Varian offers a tool for such analysis.[67,68] The software takes data and creates a series of tables and plots, specifically an error histogram showing all the leaf position deviations, error RMS showing the calculated root mean square error for leaf deviations, and beam hold off and beam on plots. As per manufacturer specifications, the error histogram is deemed acceptable if 95% of the leaf deviations are less than 0.35 cm and the maximum error RMS for either carriage is less than 0.35 cm. We have incorporated use of this analysis in Table V for multileaf collimation for Varian MLCs and recommend repeating the customer acceptance test procedures on an annual basis. Similar types of analysis software can be developed for other systems if the leaf and time dependent data can be extracted.

On an annual basis we recommend enhancing the transmission test to include quantitative analysis of the leaf transmission. Recent development of tools utilizing EPID devices allow for subpixel precision to detect changes in discrete locations of an acquired image.[69,70] As treatment planning parametrization seeks a global value for leaf transmission, it is important that the leaf body, side, and end characteristics do not change over time, the most vulnerable being the leaf side rigidity due to leaf inderdigitation, as it may affect interleaf leakage, hence the close attention needed. Leaf position repeatability, MLC spoke shot, and coincidence of light field and x-ray field all are tests intended to check the alignment of the MLCs. Vendor-specific tests are also recommended depending on the model of MLC used. Each vendor has unique preventative maintenance program recommendations and therefore replacement of MLC motors and leaves may vary in frequency. Therefore physicists must be aware of the replacement schedule as post-testing is required. All tests should reflect the types of treatments delivered in the department. The method of testing (film, solid state detectors, software, EPID) shall be sensitive enough to detect errors less than the tolerance level and have the ability to analyze all MLC leaves.

II.D.4. TBI/TSET

For either TBI or TSET QA tests chosen by a qualified medical physicist are a subset of the commissioning data sufficient to assure continued proper operation of the accelerator. QA tests should replicate test conditions performed during the commissioning of the technique. *In vivo* patient-specific dosimetry should be considered for both TBI and TSET.

TBI requires very large treatment fields to encompass the entirety of the patient. Some health care facilities have treatment units specifically designed for total body irradiation, but it is more common for conventional radiotherapy linear accelerators to be used. AAPM Report 17 [71] is a general reference describing TBI techniques. Report 17 describes phantom and patient dosimetry considerations for TBI. It is common for the linear accelerator to operate in a special dose rate mode for TBI treatment. The treatment distance is normally much greater than the standard 100 cm source-to-axis distance (SAD). TBI beam modifiers may be employed. Thus, measurements at extended distance with the accelerator in the TBI mode and with TBI modifiers must be made when this modality is commissioned. Table III recommends annual tests of TBI modifiers' transmission constancy if used, tissue-phantom ratio (TPR), OAF constancy, and measurement of output constancy ($\pm 2\%$) in the TBI mode for the clinical MU range at clinical dose rates (MU/min). Measurement at two depths is sufficient for confirmation of beam energy, and a limited number of off-axis measurements suffice for confirmation of OAFs. Some accelerators operate in a special TBI mode that has identical operating parameters as the normal non-TBI mode. In this case, annual measurements of the beam energy [percentage-depth dose (PDD) or TMR] and beam profile (OAF) at the isocenter are sufficient.

TSET is a specialized electron beam technique normally at energies from 3 to 7 MeV at the patient. TSET is described in detail in an AAPM Task Group Report.[72] This report describes irradiation techniques for TSET as well as dosimetric considerations specific to the technique. The linear accelerator operating parameters, such as dose rate, collimating device, and perhaps the beam scatterer, differ for TSET from standard electron beam operating parameters. QA tests should replicate test conditions done during the commissioning of the technique. Table III recommends annual tests of TSET modifiers' transmission constancy if used, PDD or other energy check, OAF constancy, and measurement of output constancy in the TSET mode for the clinical MU range. Measurement at two depths is sufficient for confirmation of beam energy, and a limited number of off-axis measurements suffice for confirmation of OAFs.

II.D.5. Radiographic imaging

This section covers radiographic imaging systems commonly integrated with medical accelerators: Megavoltage (MV) planar imaging, kV planar imaging, and MV or kV computed tomographic imaging (both serial and cone beam). Table VI contains QA recommendations for the imaging systems. Each radiographic imaging device, either 2D or 3D, has its own geometric coordinate system, similar to the delivery system. Even for the 2D portal imaging device which uses the treatment beam as the imaging source, the manual methods or software used to manipulate images could cause some discrepancies with treatment coordinates. Typically, the imaging coordinate system is correlated with the delivery coordinate system through a calibration process. It is, therefore, critical to ensure the coincidence of these two coordinate systems for different clinical needs of image-guided radiation therapy procedures. The QA item "imaging and treatment coordinate coincidence" is aimed to test this coincidence and is applicable for each of the imaging systems considered. In addition, each system performing patient positioning and/or repositioning based on in-room imaging sys-

tems, either 2D or 3D, relies upon vendor software that compares and registers on-board images and reference images. Quality assurance of this process could be easily done by a phantom study[73] with known shifts and is recommended for each system used clinically. The accuracy of this process should be tested on the daily basis, especially for SRS/SBRT.

Clinical use of kV imaging devices is being systematically summarized in TG104,[73] although there are no specific recommendations for the QA tolerances in that report. In this report, we set basic recommendations for the use of in-room kV imaging systems. The fundamental goals for kV imaging in radiation oncology target localization are different from those in diagnostic imaging. In radiation oncology there is greater emphasis on the localization accuracy. However, the localization accuracy is dependent on the visibility of the anatomic structures to be localized. Better image quality typically leads to better visibility of anatomical structures but is also proportional to higher imaging dose. It is understandable that the localization accuracy of some treatment sites (such as breast portals) may be less sensitive to image quality than others (such as head and neck). Therefore, it is critical to carefully balance the desire of image quality and imaging dose without compromising the localization accuracy. A variety of kV imaging systems was recently introduced. Applications of these kV imaging systems include 2D radiographic imaging, 2D fluoroscopic imaging, and 3D tomographic imaging as well as 4D imaging associated with organ motions. Acceptance testing criteria for each imaging system should be established between the manufacturer and the user. These acceptance testing criteria should include parameters related to safety, image quality, imaging dose, and localization accuracy. The baseline data (including both means and ranges or measured values and their upper and lower limits) established during the acceptance testing should be used for the QA criteria.

II.D.5.a. Planar MV imaging (portal imagers). Clinical use of electronic portal imaging devices has been addressed by TG58[74] and is described widely in the literature.[17,75–77] Recommended QA tests from the TG-58 report are incorporated in Table VI, though updated to account for on-board-imaging tests. However, details of the test contents, such as the dose rate to be checked for imaging quality, the energy, and the calibration distances, should be determined specifically for each type of EPID and for each individual institution. It is important to note that image quality checks (contrast, resolution, and noise) should be done for all calibration modes and energies to be used for imaging.

II.D.5.b. Planar kV imaging. The basic QA for planar kV imaging system mainly handles 2D x-ray imaging, either with radiographic imaging (single shot of a planar image) or continuous fluoroscopic imaging. Radiographic 2D imaging is very powerful in localizing bone structures and internal/implanted markers with higher density. It is also fast with negligible imaging dose. Fluoroscopic imaging is useful in monitoring organ motion but caution should be paid for imaging dose. The baseline data from acceptance testing are recommended as criteria for imaging quality QA. The user should maintain the image quality not poorer than those data. The criteria for the SRS/SBRT should be based on rigid-body phantom tests.

II.D.5.c. Serial and cone-beam CT. Basic recommendations for the QA of axial and CBCT systems, including both kV[78] and MV,[79] are found in Table VI. These tools are primarily used for target localization, which provides excellent soft tissue and volumetric information. In this report, serial CT should include both axial and helical CT and mainly refers to the CT-on-rail system. The positioning and repositioning accuracy should include couch movement from the treatment position to the imaging position. The QA for tomotherapy which uses helical serial MV CT, will be discussed in a separate AAPM report (TG-148). Although spatial accuracy of image reconstruction is paramount and most heavily emphasized, image quality parameters (e.g., contrast, noise, uniformity, and spatial resolution) are important aspects that should also be considered. Additionally, manufacturer's recommendations for imaging systems recalibration procedures should be followed unless the user has shown in extensive studies that the procedure frequency can be reduced. Since such imaging systems are often used daily and are capable of delivering significant radiation dose, a direct measure of imaging dose and beam quality/energy is recommended at least annually. As with the recommendations for kV imaging, the baseline data (including both means and ranges or measured values and their upper and lower limits) established during the acceptance testing should be used for QA criteria. Consistent with recommendations of TG-75[36] ("Management of imaging dose during IGRT"), the tolerance for variation of imaging dose and beam energy from baseline measurements identified during acceptance testing should be established such that the patient experiences clinically insignificant increases in stochastic and deterministic risk while maintaining image quality parameters. We believe that an annual review of imaging dose is sufficient due to minimal impact on overall dose and by virtue of existing daily/monthly reviews of many parameters that would detect changes that could potentially affect dose. For the Siemens MV CBCT the beam calibration parameters are typically very similar to the treatment beam, yet they are unique and independent, so the calibration of dose should be specifically checked for the MV CBCT beam. The frequency of measuring dose and beam quality/energy depends on the likely system stability and details of clinical utilization; for example, if the imaging dose is included in the treatment plan but represents $<10\%$ of the prescribed dose, a 20% variation in imaging dose will still only result in a 2% dose error. This report recommends annual assessment of imaging dose, which may be deemed to be required more frequently by the individual user based on clinical utilization and observed system stability.

II.D.6. Respiratory gating

Respiratory gating, at the time of the report, is an emerging technology. As such, QA methods will need to evolve in tandem with the technology. AAPM Report 91[80] (TG-76),

published in 2006, described all aspects of the management of respiratory motion in radiation oncology, including imaging, treatment planning, and radiation delivery. Various configurations and techniques for implementation of respiratory gating are described in TG-76. The TG-76 report also contains technology-specific QA recommendations. Though there are different avenues of implementation, all respiratory techniques fundamentally require a synchronization of the radiation beam with the patient's respiratory cycle. Characterization of the accelerator beam under respiratory gating conditions is done during commissioning of this modality. Dynamic phantoms which simulate human organ motions associated with respiration are recommended to test target localization and respiratory gated treatment accuracy. Tables II and III include tests for respiratory gated accelerator operation, including measurement of beam energy constancy, beam output constancy, temporal accuracy of phase/amplitude gating windows used, calibration of surrogate for respiratory phase/amplitude (detailed below), and interlock testing. One approach to performing these measurements was described by Bayouth *et al.*,[81] where gating windows from 250 to 1500 ms were considered. Beam energy and output constancy were quantified with a pair of ion chambers (10 and 20 cm depths) measuring simultaneously for each gated period; it was found that all dosimetric parameters were within $\pm 2\%$ for gating windows ≥ 500 ms on a Siemens accelerator. The relationship between temporal accuracy and phase/amplitude gate used was established by gated treatment delivery exposing the radio-opaque target attached to motion phantom, where the geometric center of a radio-opaque target was known at each phase/amplitude relative to the beam central axis. These images were acquired on radiographic film but could also be acquired on an EPID. Table III provides tolerance values to be verified during annual QA; the 100 ms tolerance for temporal accuracy assumes the moving object travels at speeds no greater than 20 mm/s, which would result in 2 mm of positional uncertainty. The QMP should maintain a tolerance consistent with spatial uncertainty values accounted for in the treatment planning process. Site-specific and technique-specific tests should be used to supplement these general recommendations. For example, several different types of surrogates of respiratory pattern may be used clinically (e.g., optical, strain-gauge belts with pressure sensors, and spirometry); the QMP should verify the phase and amplitude indicated by the surrogate do not change significantly over time as is relevant to how they are applied clinically. Calibration of the sensor for respiratory phase/amplitude, which has not been described in the literature, consists in validating constancy between a known location/movement of the surrogate and its response. An example test for the pressure sensor is placing a series of fixed weights on the sensor and determining the gain and offset values that produce a desired amplitude (e.g., 50%). For optical systems, this can be accomplished by placing a fiducially marked block (surrogate) at a series of fixed known locations within the field of view and comparing the reported displacements to the known values. Once spatial accuracy is confirmed, phase confirmation can be established with a periodic motion phantom.

III. SUMMARY OF RECOMMENDATIONS/ IMPLEMENTATION SCHEME

The tabulated items of this report have been considerably expanded as compared with the original TG 40 report[1] and the recommended tolerances accommodate differences in the intended use of the machine functionality (non-IMRT, IMRT, and stereotactic delivery).

(1) It is recommended that a departmental QA team be formed to support all the QA activities and draft necessary policies and procedures. These policies and procedures should be readily available to all members of the departmental QA team on hard copy and online. The policy should establish the roles and responsibilities of involved QA personnel. For QA measurements, detailed instructions on equipment use, cross calibration of these devices, measurement frequency, and documentation of the results should be provided. In case of suspected malfunction of the equipment, policies and procedures should also provide alternative methods for measurement.

(2) The first step in implementing the recommendations is to establish institution-specific baseline and absolute reference values for all QA measurements. The QA team needs to meet regularly and monitor the measurement results against the established values to (1) ensure the machine performance and (2) determine any significant dose deviations from the treatment planning calculations. There are many commercially available QA devices that could be used for daily, weekly, and monthly QA. The manufactures of these devices supply descriptive procedures that guide the user in utilizing these QA devices correctly. It is recommended that such devices be checked for accuracy and consistent performance prior to use for any specific QA procedures based on the manufacturer guidelines. These devices should also be evaluated for proper use and appropriateness of the particular QA test.

(3) A QMP should lead the QA team. It should be her/his responsibility to provide adequate training of the other team members, such as the therapists and the dosimetrists, so that they clearly understand and follow policies and procedures. For example, training on the operation of the QA equipment may cover appropriate warm-up period, how to interpret the measured data, what to do when tolerance levels are exceeded, etc. It is recommended that the QMP provide the proper action level and methods of notification in the case tolerances are exceeded.

(4) In general, the daily QA tasks may be carried out by a radiation therapist using a cross-calibrated dosimetry system. For such tasks, we recommend using robust and easy-to-setup equipment. For example, a plastic phantom cube with a thimble ionization chamber insert may

be used for the checking output constancy. In most cases, the flat edge and the surface of the phantom can be also used to check the alignment of in-room lasers. Commercial flat-panel multidetector arrays with appropriate buildup material may be also used for daily QA. The advantage of such equipment is that it allows efficient check of other beam parameters such as the flatness and symmetry without repeated setup of the equipment. Due to frequent use of the daily QA equipment, correction factors influencing the detector response should be carefully documented. These may include temperature and pressure correction factors for a vented chamber, electrometer calibration factors, leakage corrections, etc. All results should be documented in either a permanent electronic or hardcopy format and should be readily available for inspection purposes. There should be clear guidelines for the personnel performing the tests as to the appropriate action to take if a test is out of tolerance. These guidelines would generally include notifying a physicist. In addition, the QMP should review and sign off on the reports at a minimum of once per month.

(5) Monthly QA tasks should be performed by a QMP or by individuals directly supervised by a QMP. It is recognized that there is overlap on some test items for daily, monthly, and annual. This overlap in frequency should have some level of independence such that the monthly check would not simply be a daily check. This can be achieved with independent measurement devices, but the full extent of monthly independence from the daily measurements is decided upon by the QMP. This involvement should include validation of devices through redundant measurements and validation of the daily process by examination of the records. For example, if a multidetector array is used for the daily output measurement and the monthly dosimetry measurements use the same multidetector array, then an ionization chamber with a phantom should be compared with the output measurement of the array on an annual basis, including reference to past baseline values. This provides confidence in the daily device and will identify trends that may otherwise go undetected over the course of a long period of time such as 1 year. Such comparison enables effective use of minimal equipment in institutions with limited resources. As for the daily QA tasks, all results should be documented in either a permanent electronic or hardcopy format and should be readily available for inspection purposes. It is important for the physicist to cross calibrate any equipment used with equivalent or surrogate systems. There should be clear guidelines for the personnel performing the tests as to the appropriate action to take if a test is out of tolerance. These guidelines would generally include secondary checks and notification to the QMP. In addition, the QMP should review and sign off on the reports within 15 days of completion.

(6) The annual QA items in the report represent the most extensive tests on the machine performance. These checks are sometimes adopted by the city or state regulatory agencies to ensure adequate functionality of the linear accelerators for patient and environmental safety concerns. For this reason, it is recommended that the annual measurements be performed by a QMP with involvement of other QA team members. It is highly recommended that QA devices and equipment, such as ionization chambers and water scanning tank, should be adequately checked prior to any measurements. The measurements should be carried out using commissioning quality equipment as recommended by the forthcoming AAPM TG-106 report.[7]

(7) An end-to-end system check is recommended to ensure the fidelity of overall system delivery whenever a new or revised procedure is introduced. This can be done by creating a set of sample treatment plans typical of the facility's clinical caseload, transferring the plan data across the data network, and delivering them at the treatment machine. If the record and verify (R&V) system is a conduit for data, it must be included in the end-to-end testing. End-to-end tests are necessary whenever software changes occur with the treatment planning software, R&V software, or delivery system software. In particular, point dose measurements should be performed for treatment plans to ensure constancy between the dose calculation and the treatment delivery process. These end-to-end tests should be documented for the life of the various system components.

(8) During the annual QA review, absolute machine output should be calibrated as per the TG51 calibration protocol[82] using an ionization chamber with a NIST traceable calibration factor. Once the machine output has been calibrated, all secondary QA dosimeters including the daily QA and the monthly QA devices should be cross-checked against such calibrations. Although our report did not make specific recommendations regarding independent acceptance tests for a new machine, we promote the use of the annual QA tests recommended by this report to be used as a general guide when reviewing vendor-specific acceptance tests and tolerance values.

Upon completion of the measurements, it is recommended that an annual QA report be generated. The report should state significant findings based on the recommended table tolerance values. The report can be similarly divided into sections that include (1) dosimetry, (2) mechanical, (3) safety, (4) imaging, and (5) special devices/procedures. The QA report should be signed and reviewed by the QMP and filed for future machine maintenance and inspection needs.

[a]TG-142 was constituted by the AAPM—Science Council—Therapy Physics Committee—Quality Assurance and Outcome Improvement Subcommittee.
[b]Electronic mail: eklein@radonc.wustl.edu

[1]G. J. Kutcher, "Comprehensive QA for radiation oncology: Report of AAPM Radiation Therapy Committee Task Group 40," Med. Phys. **21**, 581–618 (1994).
[2]"Determination of absorbed dose in a patient irradiated by beams of x- or gamma-rays in radiotherapy procedures," International Commission on Radiation Units and Measurement Bethesda Report 24, 1976.

[3]R. Nath, P. J. Biggs, F. J. Bova, C. C. Ling, J. A. Purdy, J. van de Geijn, and M. S. Weinhous, "AAPM code of practice for radiotherapy accelerators: Report of AAPM Radiation Therapy Task Group No. 45," Med. Phys. **21**, 1093–1121 (1994).
[4]"Medical electron accelerators-functional performance characteristics," International Electrotechnical Commission Publication 976, 1989.
[5]"Medical electron accelerators in the range 1 MeV-50 MeV—Guidelines for functional performance characteristics," International Electrotechnical Commission Publication 977, 1989.
[6]"Physical aspects of quality assurance in radiation therapy," American Association of Physicists in Medicine Task Group Report 13 (American Institute of Physics, New York, 1984).
[7]I. Das, J. C. Cheng, R. J. Watts, A. Ahnesjo, J. P. Gibbons, X. A. Li, J. Lowenstein, R. K. Mitra, W. E. Simon, and T. C. Zhu, "Accelerator beam data commissioning equipment and procedures: Report of the TG-106 of the Therapy Physics Committee of the AAPM," Med. Phys. **35**, 4186–4215 (2008).
[8]"Radiation control and quality assurance in radiation oncology: A suggested protocol," American College of Medical Physics Report Series No. 2 (American College of Medical Physics, Reston, VA, 1986).
[9]J. E. Bayouth, D. Wendt, and S. M. Morrill, "MLC quality assurance techniques for IMRT applications," Med. Phys. **30**, 743–750 (2003).
[10]L. Berger, P. Francois, G. Gaboriaud, and J. C. Rosenwald, "Performance optimization of the Varian aS500 EPID system," J. Appl. Clin. Med. Phys. **7**, 105–114 (2006).
[11]H. Bouchard and J. Seuntjens, "Ionization chamber-based reference dosimetry of intensity modulated radiation beams," Med. Phys. **31**, 2454–2465 (2004).
[12]M. G. Davis, C. E. Nyerick, J. L. Horton, and K. R. Hogstrom, "Use of routine quality assurance procedures to detect the loss of a linear accelerator primary scattering foil," Med. Phys. **23**, 521–522 (1996).
[13]R. E. Drzymala, E. E. Klein, J. R. Simpson, K. M. Rich, T. H. Wasserman, and J. A. Purdy, "Assurance of high quality linac-based stereotactic radiosurgery," Int. J. Radiat. Oncol., Biol., Phys. **30**, 459–472 (1994).
[14]A. Gonzalez, I. Castro, and J. A. Martinez, "A procedure to determine the radiation isocenter size in a linear accelerator," Med. Phys. **31**, 1489–1493 (2004).
[15]E. E. Klein, D. A. Low, D. Maag, and J. A. Purdy, "A quality assurance program for ancillary high technology devices on a dual-energy accelerator," Radiother. Oncol. **38**, 51–60 (1996).
[16]T. LoSasso, C. S. Chui, and C. C. Ling, "Comprehensive quality assurance for the delivery of intensity modulated radiotherapy with a multileaf collimator used in the dynamic mode," Med. Phys. **28**, 2209–2219 (2001).
[17]D. A. Low, E. E. Klein, D. K. Maag, W. E. Umfleet, and J. A. Purdy, "Commissioning and periodic quality assurance of a clinical electronic portal imaging device," Int. J. Radiat. Oncol., Biol., Phys. **34**, 117–123 (1996).
[18]W. R. Lutz and B. E. Bjarngard, "A test object for evaluation of portal films," Int. J. Radiat. Oncol., Biol., Phys. **11**, 631–634 (1985).
[19]W. R. Lutz, R. D. Larsen, and B. E. Bjarngard, "Beam alignment tests for therapy accelerators," Int. J. Radiat. Oncol., Biol., Phys. **7**, 1727–1731 (1981).
[20]L. Ma, P. B. Geis, and A. L. Boyer, "Quality assurance for dynamic multileaf collimator modulated fields using a fast beam imaging system," Med. Phys. **24**, 1213–1220 (1997).
[21]C. D. Mubata, P. Childs, and A. M. Bidmead, "A quality assurance procedure for the Varian multi-leaf collimator," Phys. Med. Biol. **42**, 423–431 (1997).
[22]J. Rassow, "Quality control of radiation therapy equipment," Radiother. Oncol. **12**, 45–55 (1988).
[23]J. Rassow and E. Klieber, "Quality assurance procedures in radiotherapy—IEC specifications for equipment," Strahlenther. Onkol. **162**, 496–502 (1986).
[24]R. J. Watts, "Evaluation of a diode detector array for use as a linear accelerator QC device," Med. Phys. **25**, 247–250 (1998).
[25]M. S. Al-Ghazi, B. Arjune, J. A. Fiedler, and P. D. Sharma, "Dosimetric aspects of the therapeutic photon beams from a dual-energy linear accelerator," Med. Phys. **15**, 250–257 (1988).
[26]M. S. Al-Ghazi, D. Lingman, B. Arjune, L. D. Gilbert, and J. Thekkumthala, "Characteristic parameters of 6–21 MeV electron beams from a 21 MeV linear accelerator," Med. Phys. **18**, 821–828 (1991).
[27]C. Constantinou and E. S. Sternick, "Reduction of the 'horns' observed on the beam profiles of a 6-MV linear accelerator," Med. Phys. **11**, 840–842 (1984).
[28]P. B. Dunscombe and J. M. Nieminen, "On the field-size dependence of relative output from a linear accelerator," Med. Phys. **19**, 1441–1444 (1992).
[29]B. A. Faddegon, P. O'Brien, and D. L. Mason, "The flatness of Siemens linear accelerator x-ray fields," Med. Phys. **26**, 220–228 (1999).
[30]M. N. Graves, A. V. Thompson, M. K. Martel, D. L. McShan, and B. A. Fraass, "Calibration and quality assurance for rounded leaf-end MLC systems," Med. Phys. **28**, 2227–2233 (2001).
[31]S. W. Hadley and K. Lam, "Light field and crosshair quality assurance test using a simple lens system," Med. Phys. **33**, 930–932 (2006).
[32]Y. Mandelzweig and V. Feygelman, "Evaluation of electron-beam uniformity during commissioning of a linear accelerator," Med. Phys. **20**, 1233–1236 (1993).
[33]R. Rajapakshe and S. Shalev, "Output stability of a linear accelerator during the first three seconds," Med. Phys. **23**, 517–519 (1996).
[34]A. S. Shiu, S. S. Tung, C. E. Nyerick, T. G. Ochran, V. A. Otte, A. L. Boyer, and K. R. Hogstrom, "Comprehensive analysis of electron beam central axis dose for a radiotherapy linear accelerator," Med. Phys. **21**, 559–566 (1994).
[35]M. K. Woo, P. O'Brien, B. Gillies, and R. Etheridge, "Mechanical and radiation isocenter coincidence: An experience in linear accelerator alignment," Med. Phys. **19**, 357–359 (1992).
[36]M. J. Murphy, J. Balter, S. Balter, J. A. BenComo, Jr., I. J. Das, S. B. Jiang, C. M. Ma, G. H. Olivera, R. F. Rodebaugh, K. J. Ruchala, H. Shirato, and F. F. Yin, "The management of imaging dose during image-guided radiotherapy: Report of the AAPM Task Group 75," Med. Phys. **34**, 4041–4063 (2007).
[37]T. E. Schultheiss, A. L. Boyer, J. L. Horton, and R. J. Gastorf, "Calibration frequency as determined by analysis of machine stability," Med. Phys. **16**, 84–87 (1989).
[38]M. Rozenfeld and D. Jette, "Quality assurance of radiation dosage: Usefulness of redundancy," Radiology **150**, 241–244 (1984).
[39]T. Pawlicki, M. Whitaker, and A. L. Boyer, "Statistical process control for radiotherapy quality assurance," Med. Phys. **32**, 2777–2786 (2005).
[40]"Method for evaluating QA needs in radiation therapy," American Association of Physicists in Medicine Task Group Report 100, 2009 (unpublished).
[41]A. Boyer, P. Biggs, J. Galvin, E. Klein, T. LoSasso, D. Low, K. Mah, and C. Yu, "Basic applications of multileaf collimators," AAPM Radiation Therapy Committee Task Group No. 50 Report No. 72, 2001.
[42]E. D. Slessinger, R. L. Gerber, W. B. Harms, E. E. Klein, and J. A. Purdy, "Independent collimator dosimetry for a dual photon energy linear accelerator," Int. J. Radiat. Oncol., Biol., Phys. **27**, 681–687 (1993).
[43]E. E. Klein, M. Taylor, M. Michaletz-Lorenz, D. Zoeller, and W. Umfleet, "A mono isocentric technique for breast and regional nodal therapy using dual asymmetric jaws," Int. J. Radiat. Oncol., Biol., Phys. **28**, 753–760 (1994).
[44]P. K. Kijewski, L. M. Chin, and B. E. Bjarngard, "Wedge-shaped dose distributions by computer-controlled collimator motion," Med. Phys. **5**, 426–429 (1978).
[45]E. E. Klein, R. Gerber, X. R. Zhu, F. Oehmke, and J. A. Purdy, "Multiple machine implementation of enhanced dynamic wedge," Int. J. Radiat. Oncol., Biol., Phys. **40**, 977–985 (1998).
[46]C. Liu, Z. Li, and J. R. Palta, "Characterizing output for the Varian enhanced dynamic wedge field," Med. Phys. **25**, 64–70 (1998).
[47]C. Liu, T. C. Zhu, and J. R. Palta, "Characterizing output for dynamic wedges," Med. Phys. **23**, 1213–1218 (1996).
[48]A. W. Beavis, S. J. Weston, and V. J. Whitton, "Implementation of the Varian EDW into a commercial RTP system," Phys. Med. Biol. **41**, 1691–1704 (1996).
[49]X. R. Zhu, M. T. Gillin, P. A. Jursinic, F. Lopez, D. F. Grimm, and J. J. Rownd, "Comparison of dosimetric characteristics of Siemens virtual and physical wedges," Med. Phys. **27**, 2267–2277 (2000).
[50]M. H. Phillips, H. Parsaei, and P. S. Cho, "Dynamic and omni wedge implementation on an Elekta SL linac," Med. Phys. **27**, 1623–1634 (2000).
[51]E. E. Klein, W. B. Harms, D. A. Low, V. Willcut, and J. A. Purdy, "Clinical implementation of a commercial multileaf collimator: Dosimetry, networking, simulation, and quality assurance," Int. J. Radiat. Oncol., Biol., Phys. **33**, 1195–1208 (1995).
[52]J. M. Galvin *et al.*, "Evaluation of multileaf collimator design for a pho-

ton beam," Int. J. Radiat. Oncol., Biol., Phys. **23**, 789–801 (1992).
[53]J. M. Galvin, A. R. Smith, and B. Lally, "Characterization of a multi-leaf collimator system," Int. J. Radiat. Oncol., Biol., Phys. **25**, 181–192 (1993).
[54]T. J. Jordan and P. C. Williams, "The design and performance characteristics of a multileaf collimator," Phys. Med. Biol. **39**, 231–251 (1994).
[55]I. J. Das, G. E. Desobry, S. W. McNeeley, E. C. Cheng, and T. E. Schultheiss, "Beam characteristics of a retrofitted double-focused multileaf collimator," Med. Phys. **25**, 1676–1684 (1998).
[56]A. L. Boyer and S. Li, "Geometric analysis of light-field position of a multileaf collimator with curved ends," Med. Phys. **24**, 757–762 (1997).
[57]C. Burman, C. S. Chui, G. Kutcher, S. Leibel, M. Zelefsky, T. LoSasso, S. Spirou, Q. Wu, J. Yang, J. Stein, R. Mohan, Z. Fuks, and C. C. Ling, "Planning, delivery, and quality assurance of intensity-modulated radiotherapy using dynamic multileaf collimator: A strategy for large-scale implementation for the treatment of carcinoma of the prostate," Int. J. Radiat. Oncol., Biol., Phys. **39**, 863–873 (1997).
[58]S. C. Vieira, M. L. Dirkx, K. L. Pasma, and B. J. Heijmen, "Fast and accurate leaf verification for dynamic multileaf collimation using an electronic portal imaging device," Med. Phys. **29**, 2034–2040 (2002).
[59]M. Sastre-Padro, U. A. van der Heide, and H. Welleweerd, "An accurate calibration method of the multileaf collimator valid for conformal and intensity modulated radiation treatments," Phys. Med. Biol. **49**, 2631–2643 (2004).
[60]J. J. Sonke, L. S. Ploeger, B. Brand, M. H. Smitsmans, and M. van Herk, "Leaf trajectory verification during dynamic intensity modulated radiotherapy using an amorphous silicon flat panel imager," Med. Phys. **31**, 389–395 (2004).
[61]S. J. Baker, G. J. Budgell, and R. I. MacKay, "Use of an amorphous silicon electronic portal imaging device for multileaf collimator quality control and calibration," Phys. Med. Biol. **50**, 1377–1392 (2005).
[62]V. P. Cosgrove, U. Jahn, M. Pfaender, S. Bauer, V. Budach, and R. E. Wurm, "Commissioning of a micro multi-leaf collimator and planning system for stereotactic radiosurgery," Radiother. Oncol. **50**, 325–336 (1999).
[63]J. Chang, C. H. Obcemea, J. Sillanpaa, J. Mechalakos, and C. Burman, "Use of EPID for leaf position accuracy QA of dynamic multi-leaf collimator (DMLC) treatment," Med. Phys. **31**, 2091–2096 (2004).
[64]J. E. Bayouth and S. M. Morrill, "MLC dosimetric characteristics for small field and IMRT applications," Med. Phys. **30**, 2545–2552 (2003).
[65]E. E. Klein and D. A. Low, "Interleaf leakage for 5 and 10 mm dynamic multileaf collimation systems incorporating patient motion," Med. Phys. **28**, 1703–1710 (2001).
[66]T. Losasso, "IMRT delivery performance with a varian multileaf collimator," Int. J. Radiat. Oncol., Biol., Phys. **71**, S85–S88 (2008).
[67]C. D. Venencia and P. Besa, "Commissioning and quality assurance for intensity modulated radiotherapy with dynamic multileaf collimator: Experience of the Pontificia Universidad Catolica de Chile," J. Appl. Clin. Med. Phys. **5**, 37–54 (2004).
[68]A. M. Stell, J. G. Li, O. A. Zeidan, and J. F. Dempsey, "An extensive log-file analysis of step-and-shoot intensity modulated radiation therapy segment delivery errors," Med. Phys. **31**, 1593–1602 (2004).
[69]S. S. Samant, W. Zheng, N. A. Parra, J. Chandler, A. Gopal, J. Wu, J. Jain, Y. Zhu, and M. Sontag, "Verification of multileaf collimator leaf positions using an electronic portal imaging device," Med. Phys. **29**, 2900–2912 (2002).
[70]M. Mamalui-Hunter, H. Li, and D. A. Low, "MLC quality assurance using EPID: A fitting technique with subpixel precision," Med. Phys. **35**, 2347–2355 (2008).
[71]J. Van Dyk, J. M. Galvin, G. P. Glasgow, and E. B. Podgorsak, "The physical aspects of total and half body photon irradiation," AAPM Radiation Therapy Committee Task Group 29 Report No. 17, 1986.
[72]C. J. Karzmark, J. Anderson, A. Buffa, F. P, F. Khan, G. Svensson, K. Wright, P. Almond, F. B, K. Hogstrom, R. Loevinger, R. Morton, and B. Palos, "Total skin electron therapy: Technique and dosimetry," AAPM Radiation Therapy Committee Task Group 30 Report No. 23, 1987.
[73]"Kilo voltage localization in therapy," American Association of Physicists in Medicine Task Group Report 104, 2009 (unpublished).
[74]M. G. Herman, J. M. Balter, D. A. Jaffray, K. P. McGee, P. Munro, S. Shalev, M. Van Herk, and J. W. Wong, "Clinical use of electronic portal imaging: Report of AAPM Radiation Therapy Committee Task Group 58," Med. Phys. **28**, 712–737 (2001).
[75]R. Rajapakshe, K. Luchka, and S. Shalev, "A quality control test for electronic portal imaging devices," Med. Phys. **23**, 1237–1244 (1996).
[76]A. L. Boyer, L. Antonuk, A. Fenster, M. Van Herk, H. Meertens, P. Munro, L. E. Reinstein, and J. Wong, "A review of electronic portal imaging devices (EPIDs)," Med. Phys. **19**, 1–16 (1992).
[77]M. G. Herman, J. J. Kruse, and C. R. Hagness, "Guide to clinical use of electronic portal imaging," J. Appl. Clin. Med. Phys. **1**, 38–57 (2000).
[78]D. A. Jaffray, J. H. Siewerdsen, J. W. Wong, and A. A. Martinez, "Flat-panel cone-beam computed tomography for image-guided radiation therapy," Int. J. Radiat. Oncol,. Biol., Phys. **53**, 1337–1349 (2002).
[79]J. Pouliot, A. Bani-Hashemi, J. Chen, M. Svatos, F. Ghelmansarai, M. Mitschke, M. Aubin, P. Xia, O. Morin, K. Bucci, M. Roach, 3rd, P. Hernandez, Z. Zheng, D. Hristov, and L. Verhey, "Low-dose megavoltage cone-beam CT for radiation therapy," Int. J. Radiat. Oncol., Biol., Phys. **61**, 552–560 (2005).
[80]P. J. Keall, G. S. Mageras, J. M. Balter, R. S. Emery, K. M. Forster, S. B. Jiang, J. M. Kapatoes, D. A. Low, M. J. Murphy, B. R. Murray, C. R. Ramsey, M. B. Van Herk, S. S. Vedam, J. W. Wong, and E. Yorke, "The management of respiratory motion in radiation oncology report of AAPM Task Group 76," Med. Phys. **33**, 3874–3900 (2006).
[81]J. Bayouth, J. Sample, T. Waldron, and R. Siochi, "Evaluation of 4DRT: CT acquisition and gated delivery system," Med. Phys. **33**, 2188–2189 (2006).
[82]P. R. Almond, P. J. Biggs, B. M. Coursey, W. F. Hanson, M. S. Huq, R. Nath, and D. W. Rogers, "AAPM's TG-51 protocol for clinical reference dosimetry of high-energy photon and electron beams," Med. Phys. **26**, 1847–1870 (1999).