



ACPSEM guideline: commissioning and quality assurance of Magnetic Resonance Imaging Linear Accelerators

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Abstract

MRI-guided radiotherapy introduces unique quality assurance (QA) requirements due to magnetic field effects on dose delivery, imaging-dependent workflows, adaptive planning and system specific considerations. Consistent, vendor agnostic guidance is needed to support safe commissioning, clinical implementation, and ongoing performance monitoring across MRI-Linac platforms. This guideline defines minimum recommended MRI-Linac commissioning and QA practices to support consistent and safe clinical operation across services. It was developed by the MRI-Linac QA sub-group of the Magnetic Resonance Imaging Linac Working Group using an evidence-informed, consensus-based approach. Key international standards, task group reports, vendor documentation, and peer-reviewed literature relevant to the MRI-Linac were reviewed. Candidate QA tests were mapped to clinical risks and system functions, then organized into commissioning and routine QA domains with suggested cadence. Recommendations were refined through iterative working group review, with emphasis on implementation and auditability. The resulting commissioning recommendations are grouped into domains addressing key performance and safety areas for MRI-Linacs. Additionally, a minimum test set is proposed with suggested frequencies and tolerances where supported by evidence. Adoption of this guideline supports harmonized MRI-Linac QA practice, improved reproducibility across sites, and enhanced patient safety. The framework is designed to be implementable across platforms and evolve as MRI-guided radiotherapy workflows, vendor capabilities, and the evidence matures.

Keywords MRI · MRI-Linac · Quality assurance · Acceptance · Commissioning

Abbreviations

AAPM	American Association of Physicists in Medicine	ESE	Electron streaming effect
ACPSEM	Australian College of Physical Scientists and Engineers in Medicine	FFF	Flattening filter-free
ACR	American College of Radiology	FOV	Field of view
ARPANSA	Australian Radiation Protection and Nuclear Safety Agency	IMRT	Intensity-modulated radiation therapy
ASTM	American Society for testing and materials	MLC	Multi-leaf Collimator
DSV	Diameter of spherical volume	MRIL	Magnetic Resonance Imaging Linac
EPID	Electronic portal imaging device	MRIGRT	Magnetic Resonance Imaging Guided Radiation Therapy
ERE	Electron return effect	NCRP	National Council on Radiation Protection & Measurements
		NEMA	National Electrical Manufacturers Association

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PSQA	Patient Specific Quality Assurance
QA	Quality assurance
RF	Radiofrequency
RT	Radiation therapy
ROMP	Radiation Oncology Medical Physicist
TPS	Treatment planning system

Introduction

Magnetic Resonance Imaging Linear Accelerators (MRI-Linac) represent an important development in the delivery of radiotherapy. By integrating magnetic resonance imaging (MRI) with radiation delivery, these systems provide superior soft tissue contrast and enable acquisition of dynamic and functional information in real time. This supports improved visualisation of tumour and normal tissue anatomy, and facilitates adaptive treatment with the potential to improve target coverage while reducing dose to organs at risk [1, 2].

MRI-Linac technology also introduces important technical, operational, and clinical challenges across facility planning, acceptance, commissioning, and ongoing quality assurance (QA). The MR environment affects beam behaviour, dosimetry, imaging, workflow, and safety, and these factors must be considered within the commissioning and QA framework.

This guideline provides vendor neutral recommendations for the acceptance, commissioning and routine QA of MRI-Linac systems. It is intended to support registered radiation medical physicists (ROMP), physicists in training, and other professionals involved in the implementation, commissioning and maintenance of MRI-Linac services. Specifically, this guideline aims to:

1. Outline key site and system preparation considerations relevant to commissioning and QA;
2. Provide vendor-neutral recommendations for commissioning tests;
3. Summarize current QA devices and their applications; and
4. Recommend routine QA tests with daily, monthly, and annual frequencies.

As acceptance, commissioning, and QA program management are safety-critical activities, they require appropriate expertise, training, and professional judgement [3]. The working group recommends that a registered ROMP retain overall responsibility for the oversight, interpretation, and completion of relevant tests and assessments, and for the development and review of QA procedures in accordance with best practice and regulatory requirements [4]. Specific

tasks may be delegated to non-registered ROMPs or other trained personnel, provided appropriate training, supervision and review processes are in place [5].

Methodology

This guideline was developed by the QA working group of the ACPSEM MRI-Linac working group. Evidence was generated from professional task group reports, vendor documentation, and peer-reviewed literature relevant to MR-Linac commissioning, imaging QA, dosimetry in magnetic fields, and safety. Where formal evidence was limited, recommendations were informed by practical experience and published multi-institutional approaches. Recommendations were grouped into commissioning tests, periodic QA, and implementation and safety considerations.

Key references by Roberts et al. [6], longitudinal studies of the Elekta Unity (Elekta AB, Stockholm, Sweden) and ViewRay MRIdian (MRIdian™, ViewRay Inc., Cleveland, OH, USA) systems [7–10], the acceptance and commissioning work of Woodings et al. [11], Valdenaire et al. [12], and the ESTRO-ACROP consensus guideline [13].

Draft recommendations were refined through iterative working group review to define minimum recommended test sets, suggested frequencies, and action levels. External stakeholder feedback was incorporated where feasible. This guideline should be reviewed periodically and updated as MRI-Linac technology, clinical workflows, and the supporting evidence evolve.

Machine overview

Machine configuration

MRI-linac systems can be broadly grouped into two configurations based on the orientation of the static magnetic field (B_0) relative to the treatment beam: perpendicular (transverse) and parallel (inline). In perpendicular systems, such as the Elekta Unity and ViewRay MRIdian, B_0 is oriented orthogonally to the radiation beam. This configuration gives rise to the Electron Return Effect (ERE), which can increase dose at tissue interfaces, and the Electron Streaming Effect (ESE), in which electrons are guided along the magnetic field and may alter dose deposition away from the primary beam path [14].

In parallel systems, such as the Aurora RT and the Australian MRI-Linac, B_0 is aligned with the treatment beam. This reduces ERE-related interface dose perturbations, narrows the beam penumbra, and results in more predictable electron transport with reduced ESE effects [15]. These

characteristics may simplify treatment planning and improve dosimetric predictability. Key characteristics of these clinical and developmental systems are summarized in Table 1, providing insights into their advantages and challenges for different clinical applications. More detailed descriptions of MRI-Linac technology, platform design, and clinical implementation are available in prior overview papers [16–19].

Current commercial machines

At the time of publication, the Elekta Unity and ViewRay MRIdian were the two commercial MRI-Linac systems available in the Australian and New Zealand market (Fig. 1). Both systems combine MRI and radiation delivery within platform-specific shielding designs and use flattening

filter-free photon beams with a perpendicular B0-beam configuration. Additional technical details, including multileaf collimator characteristics, are available elsewhere [21, 22].

First generation systems

First generation systems are ones that are yet to be commercially available or in the final steps towards clinical release at the time of this publication (Fig. 2).

Australian MRI-Linac

The Australian MRI-Linac is a prototype system that can deliver 4 and 6 MV photons through a Varian Millennium MLC mounted on a rail system [20]. The 1 T magnet is open, superconductive, and the system can have parallel or perpendicular MR-to-beam orientations [19].

Aurora system

The Aurora RT system (Fig. 3) employs a 6 MV Linac and 0.6 T MRI, where the Linac can be positioned between open MR planes (perpendicular), or alternatively through a central opening of one of the planes (parallel) [23].

Commissioning

MRI-linac acceptance and commissioning include both vendor-led and site-specific components. Site physicists should participate to ensure tests are appropriate for local equipment and workflows. The commissioning tests summarized in Table 2 draw on the ESTRO-ACROP recommendations [13], the Unity and MRIdian commissioning reports [11, 12], and the hybrid MRI-Linac interaction tests described by Tijssen et al. [24]. Additional rationale and selected test descriptions are provided in the following sections.

Site preparation

An MRI-Linac shares commonalities with conventional linear accelerators for radiation shielding, with the added complexity of an MR environment. Users need to be cognisant during the early stages of site design to provide or assess network requirements, RF shielding and isolation, quench vent and exhaust, excessive mechanical vibration (whether steady state or transient) acoustic management, and magnetic shielding. The working group recommends close consultation with vendors during the planning process.

Design aspects that improve safety and general site planning have been detailed by Hu et al. [43]. A critical point is the necessity of dedicated storage for QA and immobilization

Table 1 Configuration details of current MRI-Linac systems [20]

Feature	Elekta Unity	ViewRay MRIdian	Australian MRI	Aurora MagnetTx
Nominal Energy (MV)	7 FFF	6 FFF	4 & 6 FFF	6 FFF
SAD (cm)	143.5	90	190—330	122
MLC	Single stack 160 leaves, effective 7.175 mm width	Double stack 138 leaves, effective 4.15 mm width	Single stack 120 leaves, effective 9.5—16.5 mm width *	120 leaves effective 5.0 mm width
MLC speed (mm/s)	60	40	30	35
Max field size (cm)	57.4 × 22 cm ²	27.4 × 24.1 cm ²	30 to 50 cm ²	28.5 × 28.5 cm ²
Delivery method	Step and shoot IMRT	Step and shoot IMRT	Sliding window Step and shoot IMRT	Sliding window Step and shoot IMRT
360-degree delivery	No	Yes	Yes * with patient rotation	Yes
Bore diameter (cm)	70	70	62	110W x 60H
B ₀ strength (T)	1.5	0.35	1.0	0.55
Magnet type	Closed superconductor	Split superconductor	Open superconductor	Open room temperature
Orientation	Perpendicular	Perpendicular	Parallel and perpendicular	Parallel and perpendicular
Gradient strength (mT.m ⁻¹) / Slew rate (T.m ⁻¹ s ⁻¹)	34 / 120	10 / 200	10 / 370	45 / 200

*(SID dependent)



Fig. 1 **A** the Elekta Unity and **B** the ViewRay MRIdian

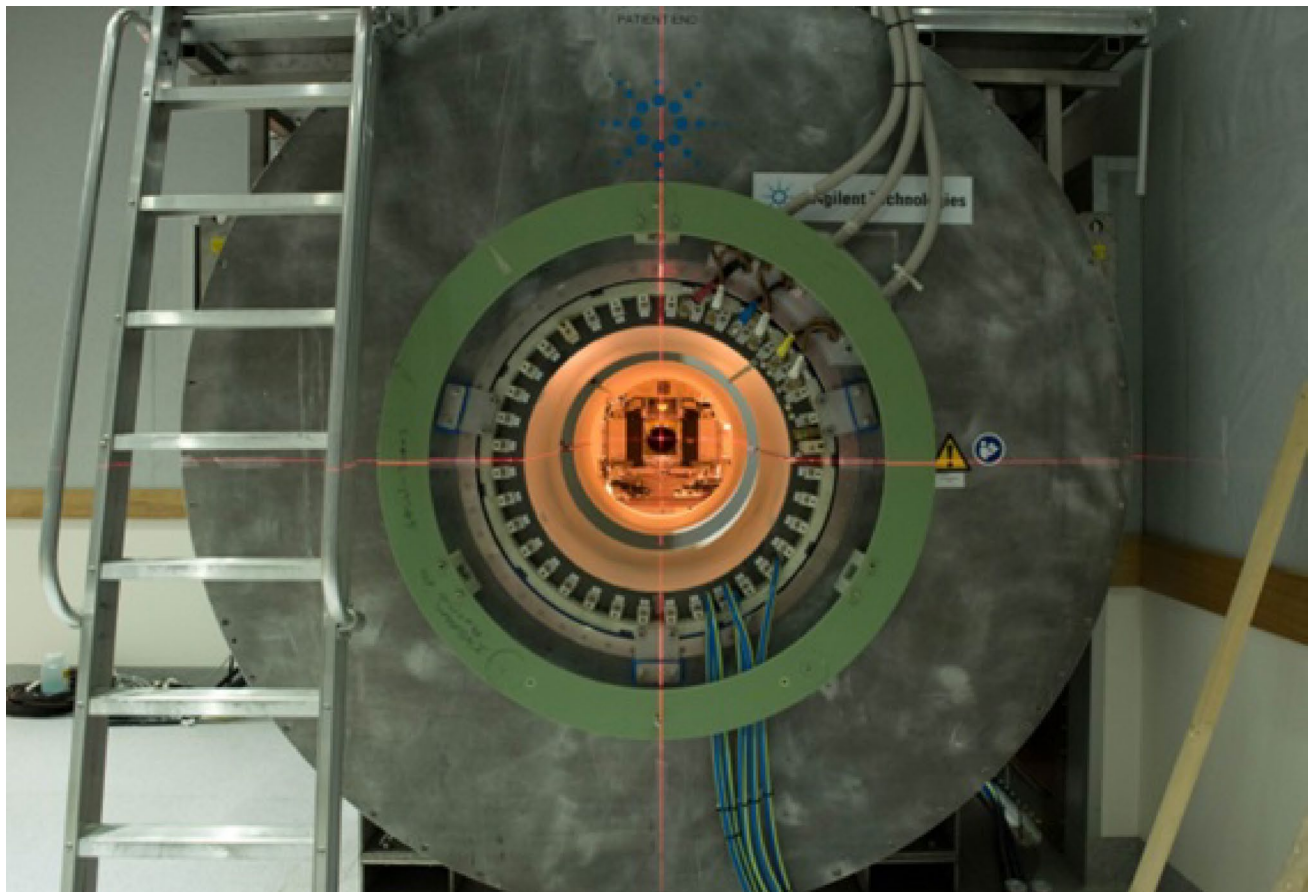


Fig. 2 The Australian MRI-Linac (photo courtesy of Jarrad Begg)

equipment, to limit the misuse of the MR-unsafe equipment from conventional Linacs.

Internationally accepted shielding design standards and guidelines can be used to determine the most suitable material and attenuation level required, with minor modifications. The working group recommends NCRP 151 [44], for

tenth-value layer (TVL) values due to their inherent conservatism, ensuring that the shielding calculations are robust and provide an added safety margin. Differences in shielding between the conventional and MRI-Linac are summarized in Table 3, and each item for consideration is explained in following sections. For currently available clinical MRI-Linac

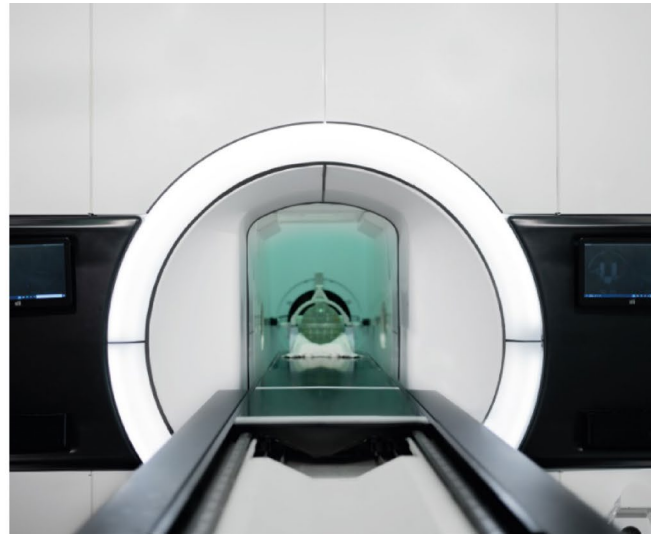


Fig. 3 The Aurora MagnetTx system

platforms, neutron shielding is not expected to be a primary design consideration, as these systems generally use 6–7 MV FFF beams. Neutron production is principally associated with higher-energy photon beams, particularly around 10 MV and above [25].

Source to isocentre distance

Current MRI-Linac systems do not have 100.0 cm source-to-axis distance (d_{iso}). As all distances are normalized to 100.0 cm in NCRP 151 [44], d_{iso} must be explicitly included.

Maximum field size and primary collimator angle

Conventional accelerators must consider the maximum field size to be defined by the jaws and MLCs at the collimator rotation that produces the greatest lateral dimension. As commercial MRI-Linacs have fixed collimators, this consideration is not required, and the field size can be simply projected onto the primary barrier. It is common to define the maximum field size by considering the primary collimator angle as this impacts the projection of the field. Note that the projection is maximized at the intersection of the ceiling and wall barriers, as described in NCRP 151 [25]. It is still recommended to add 30 cm to either side of the largest beam projection to determine the width of the primary barrier.

Primary beam transmission

The primary beam transmission characteristics of MRI-Linacs differ from those of conventional as the beam may pass through substantial machine structures, this can include the cryostat, magnet, shielding components and beam stopper

before reaching the bunker barrier [45]. As a result, the primary transmission and leakage should be evaluated using platform specific data provided by the vendor, and validated using measurements referenced to the stated measurement locations [45].

Where transmission is specified at the machine cover or other defined distance, it may be converted to an isocentre equivalent quantity for shielding calculations using an inverse square correction. As the transmitted spectrum may be modified by passage through machine structures, a conservative barrier design approach using both T_{VL_1} and T_{VL_c} is appropriate where platform specific spectral data are unavailable. Any use of steel or other conductive structural material near the MRI-Linac should be reviewed with the vendor, as ferromagnetic materials and poorly characterized components may affect the MR safety or system performance.

MRI-Linacs absorb much of the small-angle patient scatter because of their high energy. The scattering angles are typically limited to greater than 25° , which reduces the penetration and scatter fraction. Consequently, the requirement of the primary barrier to intercept at least the 20° scatter line is no longer crucial, providing the opportunity to use laminated or composite barriers.

Steel can be used to shield and reinforce the bunker, but its use must be approved by the vendor to ensure that the magnet can be adjusted to accommodate additional steel. Nonferrous materials are required in and around the magnet, and each vendor offers specific guidance in this regard.

The primary beam transmission in MRI-Linacs is affected by the presence of the magnet, cryostat, and beam blockers. Vendors provide values for maximum transmission, which are measured at the machine cover or specified distance. Owing to the inverse square law correction to the point,

Table 2 Vendor agnostic commissioning tests recommended by the MRI-Linac working group

Test/check category	Test/check description	Tolerances	References
<i>A. Site preparation</i>			
Bunker and surrounding environment considerations	Preliminary radiation survey completed post installation and first beam on	As per local regulatory requirements	[25]
	Complete magnetic fringe field assessment		[26]
	Validation of acoustic insulation of RF cage/bunker and headphones/hearing protection		[27]
	Cage and RF interference map	at least 100 dB of attenuation across a broad frequency range	[24]
	MRI safety considerations		[27]
	Beam profile and output stability on adjacent linacs (with gantry rotation) post MRI ramp up	$\pm 1\%$ from 0 T case	[12, 13, 28]
<i>B. Linear accelerator</i>			
Safety	Emergency stop buttons, door interlocks, and alarms functional	As per vendor specifications and regulatory requirements	[13, 28]
	Cryogen level monitoring	Must be stable, variance must trigger alerts	[13]
	Final radiation survey post beam tuning and machine calibration	As per local regulatory requirements	[25]
System configuration and connectivity	Individual coils and channels assessment	As per vendor specifications	
	System configuration checks and backups	As per vendor specifications	
	Coordinate systems and data integrity	As per vendor specifications	[11, 24]
Mechanical	Gantry angle calibration	$< 0.2^\circ$	[11]
	Couch calibration, orthogonality and alignment	± 1 mm	[11]
	MLC and jaw position accuracy	± 1 mm	[11, 28]
	Alignment of laser, MV panel, MRI, and beam/isocentre	± 1 mm	[11, 13, 28]
Beam data collection	Beam data required for creation of, and/or comparison against, beam model	As per vendor requirements	[29, 30]
Dosimetry	Monitor chamber output constancy, stability, accuracy, and precision	$\pm 1\%$	[11, 28]
	Radiation beam profile constancy	Within $\pm 1\%$ across the beam	[11, 13]
	Radiation dose profiles	Agreement with TPS simulations within 1.5%	[11, 13]
	Magnetic correction factors for dosimetry	Verified	[11, 13]
	Gantry angle dependent dose delivery	Variation $< 1.5\%$ across all gantry angles	[13]
	Cryostat attenuation	Uniform attenuation, must be calibrated and compensated	[13]
	Transmission through coils and bridge	No attenuation artifacts	[12]
	Table transmission test	Verified	[13]
	Output factor validation across clinically relevant field sizes	$\pm 1\%$ for standard fields; $\pm 2\%$ for small fields	[11, 13]
	ERE/ESE testing	Verified	[11]
	MU timer accuracy and system latency for gating	$\pm 1\%$ or ± 50 ms	[11, 13]
	MU linearity	$\pm 2\%$ for > 5 MU	[11, 13]
	Beam quality determination and baselining	As per clinical protocols	[11, 13]
	Dose rate stability, linearity, reproducibility – short and long term	$\pm 2\%$	[11, 13]
	Dose output with gantry variation	$\pm 0.5\%$ (if not accounted for in TPS) or $\pm 2\%$ (if considered in TPS)	[11, 13]
	MLC and jaw transmission	$\pm 0.5\%$ from baseline, example baseline = 1.5%, tolerance range = 1–2%	[11, 13]
	Immobilisation device commissioning	As per clinical protocols	
Ancillary imaging systems	MV imager geometric accuracy	As per vendor specifications	[28]
	MV image quality (spatial resolution, contrast)	As per vendor specifications	
	MV dosimetry		
	MV panel pixel scale	As per vendor specifications	[11]
<i>C. MRI scanner</i>			

Table 2 (continued)

Test/check category	Test/check description	Tolerances	References
MRI and linear accelerator interplay	Imaging during radiation	Validate MR image quality under active beam irradiation	[12]
	B ₀ homogeneity (with gantry rotation)	<0.5 ppm volume root mean square (VRMS) across a 35 cm DSV or as specified by MRI manufacturer across a given DSV	[11, 24]
Image quality measures	Table alignment with B ₀	± 0.3°	[11]
	High contrast resolution	≤1.0 mm	[26]
	Signal ghosting	Ghosting ratio ≤ 2.5%	[26]
	Slice position accuracy	± 2 mm	[26]
	Slice thickness accuracy	Within ±0.5 mm or ±10% of the nominal slice thickness, whichever is greater	[26]
	Image intensity uniformity	Head coil ≥ 87.5% for < 3 T Body coil ≥ 82.0% for < 3 T	[26]
	Low contrast detectability	Total number of discernible spokes for four slices 21 (0.3 T) to 36 (1.5 T)	[26]
	Signal-to-noise ratio	≥ baseline from acceptance testing. SNR must remain consistent over time for comparable protocols	[26]
Geometric distortion assessment	RF coil evaluation	SNR within 5% for all coils used	[11, 24]
	Combined geometric distortion in an MRI	Must not exceed 1 mm in a 20 cm diameter spherical volume (DSV) and 2 mm in a 40 cm diameter spherical volume	[11, 24]
Sequence assessment	Magnetic field drift (B ₀ stability)	< 1 ppm/day during < 0.25 ppm/day for first 1–2 months operation	[25]
	Transmitter gain calibration	No visible artifacts, manual transmit gain within 5% of automatic, manual centre frequency within 10 Hz of automatic	[25]
	Transmitter gain stability	Vendor specified minimum amplitude, frequency, and phase stability levels unless otherwise agreed upon	[25]
	Image quality and geometric distortion for all MRI sequences	Baseline	[25]
	Orientation of the MRI images for the sequences transferred to the TPS during commissioning	Verified	[24]
	Geometric fidelity and geometric consistency of all modes of acquisition of scanner i.e. Cine mode, navigated scan, localizer scan, fast and slow scans	Baseline	
	MR contrast and MR marker validation and protocol development	As per vendor specifications	
	MR to MV baseline determination	± 1 mm from baseline value including multiple gantry angles impact on MR isocentre	[26]
MRI to MV isocentre coincidence	Gradient non-linearity	±1 mm for distances less than 10 cm of isocentre, ±2 mm between 10 and 20 cm from isocentre	[26]
	External laser offset from MV isocentre	<1 mm (where essential for patient positioning)	[8, 10]
	Baseline and QA with appropriate phantoms and sequences to isolate system variation from patient response	Baseline	
Diffusion weighted and quantitative imaging	Recommendations for DWI scanning parameters	b-values established	
<i>D. Treatment planning system</i>			
System configuration and connectivity	Connectivity and acceptance testing to record and verify system	Error free, functional, and/or as per vendor specifications	[24]
	Coordinate systems and data integrity	Verification within ±1 mm for positional accuracy and coordinate consistency according to vendor specifications	[24]
Dose calculation accuracy	Homogeneous and heterogeneous phantom validation with increasing complexity	Scenario-specific tolerances (2–5%)	[31, 32]

Table 2 (continued)

Test/check category	Test/check description	Tolerances	References
Magnetic field effects on dose deposition	ERE/ESE modelling (simple and anthropomorphic cases)	Verified	[33]
Patient positioning devices	Couch and MR coil modelling validation	within $\pm 1\%$ of measurements realistically, with some exceptions being couch corners	[34]
	Ancillary patient aid modelling e.g., headboard, masks, wing board	within $\pm 1\%$ of measurements realistically, with some exceptions being couch corners	[35]
Plan generation and assessment tools	Density conversion method and layering accuracy (including equivalency during adaptations)	Verified	[36]
	DVH validation	Verified	[36]
	Validation and equivalency of adaption techniques	As per clinical protocols	[37]
	Clinical planning protocol or template commissioning	As per clinical protocols	[38]
	Plan reconciling tool validation	Verified	[39]
<i>E. Clinical workflows</i>			
Patient specific QA	Secondary MU check program commissioning for simple and complex fields	As per clinical protocols	[40]
	Measurement-based QA commissioning	As per clinical protocols	[41]
End-to-end	End-to-end testing for clinical workflows (adaptive and non-adaptive), complex and simple clinical case validation	As per clinical protocols, suggested γ as per AAPM TG218	[37, 42]
Motion management assessment	Full end-to-end testing including motion management	As per clinical protocols and local regulations	
	Gating and beam hold functionality	As per vendor specifications	[28]
	Gating and beam hold latency	As per vendor specifications	[28]
Audits	Absolute dosimetry audit by regulatory body or nearby MRI-Linac centre	As per regulatory requirements	

Table 3 Comparison of the pertinent machine characteristics for radiation shielding between conventional Linacs and MRI-Linacs

Machine characteristic	Affected parameter	Conventional Linac	Elekta unity	ViewRay MRIdian
Source to isocentre distance	d_{SAD}	100.0 cm	143.5 cm	90.0 cm
Maximum field size	Primary barrier width	$40 \times 40 \text{ cm}^2$	$57.4 \times 22.0 \text{ cm}^2$	$27.4 \times 24.1 \text{ cm}^2$
Primary collimator angle	Primary barrier width	$\approx 28^\circ$ full divergence ($\approx 14^\circ$ half-angle)*	8°	18°
Maximum field area	F	1600 cm^2	1263 cm^2	743 cm^2
Primary beam transmission	D_t	100%	0.5% at covers (2130 mm from isocentre)	Assume 100%
Average leakage	L_f	0.1%	0.15%	0.1%
Nominal dose rate	D_0	6–24 Gy/min	7 Gy/min	6 Gy/min

*For conventional Linacs, NCRP 151 notes that the maximum primary field is typically limited to $\sim 50 \text{ cm}$ diameter at 100 cm SSD, equivalent to a half-angle of 14° ; the corresponding full divergence angle is therefore $\sim 28^\circ$

these values can be misleading regarding the overall amount of shielding provided. It is recommended to scale the maximum transmission value back to the isocentre. While the beam spectra have already been altered by transmission through the machine, it is advisable to use both TVL_1 and TVL_e to determine the primary barrier thickness, as specific alterations to the beam spectrum are not well documented.

Leakage radiation

Some MRI-Linac systems may exhibit higher leakage radiation than conventional Linacs. Leakage should therefore be explicitly included in shielding calculations using an appropriate leakage factor (L_p). Other shielding parameters may follow the definitions in NCRP 151 [25].

Bunker and surrounding environment considerations

Conduits for QA cabling should be designed to preserve both radiation shielding and RF integrity [45]. Conductive cabling passing through RF waveguides may introduce image artefacts, so conduit arrangement should be planned in consultation with MR physicists and vendors.

The surrounding environment may also affect MRI-Linac performance. Adjacent construction, large ferromagnetic

sources, nearby MRI systems, and neighbouring linacs can influence B0, image distortion, or machine performance [46]. MR image quality may also be affected by transient or steady-state mechanical vibration. For high-field MRI-Linacs located near other linacs, beam flatness and symmetry on adjacent systems should be confirmed after B0 ramp-up or ramp-down.

Cooling and environmental control are also important. Helium, cryostat, and cabinet systems require reliable cooling to maintain vendor-specified operating conditions. Inadequate cooling or high ambient temperatures may increase humidity and condensation risk in cryostat cabinet rooms. Monitoring of temperature, humidity, water ingress, and linac performance may assist with early fault detection and maintenance planning. Clear escalation and response processes should be established for disruptions to cooling or environmental control.

Acoustic noise should also be considered in bunker design. MRI procedures may generate moderate-to-high acoustic noise levels that affect patient comfort and safety [47–49]. Appropriate bunker construction and acoustic isolation can reduce this impact [50], and local standards should be followed [27].

Linear accelerator

Safety

Standard safety tests include electrical, mechanical and dosimetric tests. Tests and tolerances designed by the AAPM TG-142 [28], updated in TG-198 [51], and those within IEC 60976 [52], and IEC 60601 [53], remain relevant as guidelines for acceptance testing.

A robust MRI safety program should also be established with reference to ACR guidance [54], and the recommendations of the MRI-Linac Safety Working Group [27].

System configuration and connectivity

Acceptance and commissioning should verify DICOM imaging and connectivity to the picture archiving and communication system (PACS), record and verify system (RVS), and other nodes required for adaptive workflows. Tijssen et al. [24], provides a useful list of recommended system connections and configuration checks.

Mechanical

The concept of mechanical isocentre is less directly applicable to current commercial MRI-Linacs than to conventional C-arm linacs because the collimator and couch do not rotate [11, 55, 56]. Radiation isocentre size in the plane of gantry

rotation can be assessed using star-shot imaging with film, as described by Roberts et al. [6], and Palacios et al. [57]. Where available, an MV imager and radiopaque marker may also be used in a Winston–Lutz approach. Powers et al. [58], provides a practical overview of linac commissioning tests for the Elekta Unity, including methods that do not require dedicated specialised equipment.

MLC and jaw alignment with gantry rotation and treatment beams are key components of machine characterisation. Each MLC bank should be independently verified for position accuracy and transmission. This is particularly important for the MRIdian system, where two MLC banks are stacked in a tessellated configuration. Because both commercial systems use fixed collimator positions, unintended rotations should also be assessed [11]. Users should understand the vendor's jaw and MLC calibration process and independently verify alignment, interleaf and intraleaf leakage, and performance over the full range of travel [21, 22]. Picket fence testing with film or EPID may be used for verification, and Tsuneda et al. [59], describes practical approaches for the Elekta Unity.

Beam data collection

AAPM TG-106 [29], remains a useful reference for acquisition of baseline beam data during commissioning. In MRI-Linacs, detector response in a scanning water tank depends on depth, off-axis position, field size, detector type, magnetic field strength, and detector orientation. Important considerations include beam profile offsets, shifts in effective point of measurement [60], and orientation-dependent detector response [61]. These effects influence both linac calibration and TPS commissioning. In particular, vertical shifts affect beam quality and tissue maximum ratio determination, while lateral shifts affect ion chamber positioning and profile measurement.

The availability and scope of vendor-supplied reference or “golden” beam data varies between platforms. During acceptance and commissioning, centres should confirm whether such data are provided, determine whether they are intended for beam-model generation, independent comparison, or constancy assessment, and document any limitations. Where vendor reference data are unavailable or incomplete, locally acquired baseline data should be used as the primary reference for commissioning and future QA. Baseline profile data can be acquired using films, planar arrays, or portal dosimetry where available. According to Roberts et al. [6], chamber response in an array can be variable if they are closely packed, owing to differences in the average density around the chambers. Planar arrays are commonly used for relative profile measurements during QA, but

cross-calibration against water tank data is recommended to account for detector sensitivity and magnetic field effects.

Air gaps in phantoms should also be considered, as magnetic-field effects may alter dose distribution in air-filled regions. Where appropriate, these gaps may be filled with water to reduce this effect [30, 62].

Detector selection should consider MR compatibility, detector-specific magnetic field response, intended use for scanned or non-scanned beam data, and the required measurement accuracy. Where possible, use of a single detector type is preferred to minimise differences arising from detector-specific magnetic field response. If multiple detector types are required, cross-comparison measurements should be performed under clinically relevant conditions.

For output factor measurements, particular attention should be given to detector positioning, field-size dependence, and off-axis profile shifts. Where profile shifts are present, output factors should be measured at the point of peak intensity for each field size before applying lateral profile shift corrections. Detector positioning reproducibility should be verified using the onboard MV imager or another suitable method, particularly for small fields or measurements sensitive to detector alignment.

Dosimetry

The QA working group endorses the use of the MRI-Linac WG dosimetry paper for reference and recommendations when completing absolute dosimetry [63]. Relative dosimetry considerations were discussed above in section “[Beam data collection](#)”.

Patient support and immobilisation devices used during treatment should be appropriately represented in the TPS, particularly for adaptive workflows. The working group recommends that transmission through the treatment table and immobilisation devices be assessed during acceptance and commissioning [64]. Hu et al. [20], provides useful recommendations for such devices.

For the MRIdian system, the movable fiberglass couch top may affect surface and depth dose depending on patient position. For the Elekta Unity, high-density couch support struts are present and should be avoided during treatment where possible, although this is not prevented by an interlock.

Radiation transmission through receiver coils should also be verified during commissioning for each clinically used coil. Liney et al. [17], Ghila et al. [65], and Raaymakers et al. [66], evidenced the effect of an RF receiver coil impacting dosimetry. Powers et al. [58], pointed out that no work to date has been published on anterior coil attenuation characterization for the Elekta Unity, nor does it form part of the device acceptance test; rather, a factory default structure and

relative electron density (RED) are applied in the TPS. The authors of this guideline recognize the early work by Hoogcarpsel et al. [67], which showed a decrease in dose of up to 2.2% as a result of the posterior coil (0.4% for the anterior), suggesting that modelling of the dosimetric impact must be considered in planning.

At the time of writing, Elekta provide a model in Monaco of a standard patient coil (anterior and posterior) to account for the dosimetric impact of the device. The position and orientation of these coils may not be guaranteed by all vendors. As such, extensive validation of coil modelling should be performed to understand the dosimetric impact of height above the patient’s surface, longitudinal positioning, and any tilting that could occur between fractions. For the Elekta Unity anterior coil, Powers et al. [68], found good agreement between measured and Monaco-calculated attenuation, with a maximum difference of 0.5% across the lateral extent of the coil. However, the associated out-of-field dose from ESE was more substantial. These findings support explicit validation of coil modelling and positioning during commissioning.

Ancillary imaging systems

The implementation of a robust QA program relies on ancillary imaging systems provided by a platform [58]. The working group recommends the use of AAPM physics practice guideline 2b [69], for commissioning of the MV imager.

MRI scanner

Several MRI performance factors affect treatment planning and therefore require appropriate QA. Of these, geometric fidelity is the most critical.

MRI and linear accelerator interplay

In commercial MRI-Linac systems, linac rotation may alter the imaging magnet fringe field and produce gantry-angle-dependent changes in B0 homogeneity and linac performance. In systems with a fixed linac, or where the magnet rotates with the linac, active shimming may reduce these effects, but ongoing monitoring is required to confirm adequate compensation. TG-284 recommends magnetic field drift testing during the initial two months of acceptance as an indicator of system stability [26].

Radiation-induced currents in RF coils may also produce image artefacts [70, 71]. These effects can be assessed using methods described by Buckley et al. [72], Hoogcarpsel et al. [67], and Burke et al. [70]. As some artefacts are position-dependent while others are more static, their potential

impact on online imaging and motion monitoring should be understood during commissioning.

Image quality measures

MRI image quality should be assessed consistently. Routine QA should include image uniformity, signal-to-noise ratio, and spatial resolution, typically using vendor-provided phantoms. Performance of individual coils and channels should also be checked in accordance with vendor guidance, including long-term stability assessment [24]. ACR MRI quality control methods provide a useful framework for sequence-specific assessment of MRI-Linac systems [24].

RF coil position over the treatment region can affect image quality, with signal degrading as coil-to-surface distance increases. Commissioning should therefore assess image quality not only in the nominal setup, but also with clinically relevant variations in coil height, position, and tilt. Lee et al. [73], provides one such assessment method.

Geometric distortion assessment

Geometric distortion arises from B_0 inhomogeneity, gradient nonlinearity, chemical shift, and susceptibility effects. These distortions generally increase with distance from MRI isocentre and may vary with magnetic field strength, tissue interface, and sequence parameters [67]. Increasing readout bandwidth may reduce susceptibility and chemical shift distortion, although sequence-dependent effects may remain.

Geometric fidelity testing should be matched to the tolerances required for the intended clinical application, particularly for small targets or off-axis anatomy. Walker et al. [74], proposed a vendor-neutral MRIGRT geometry-fidelity workflow. B_0 inhomogeneity and gradient nonlinearity should be assessed separately and re-evaluated after gradient calibration or service. Residual distortion may persist despite shimming, gradient compensation, and software correction, and should be considered in treatment applications [26, 75].

Sequence assessment

MRI sequences used for treatment should be assessed for both image quality and geometric distortion to estimate the resulting dosimetric uncertainty. MRI datasets transferred to the TPS should also be checked for correct image orientation using a phantom with directional features [24].

MRI to MV isocentre coincidence

MRI-Linac systems require verification of alignment between the MRI and radiation isocentres. Each manufacturer provides phantoms and procedures for this purpose. Baseline isocentre coincidence should be established at installation and monitored during routine QA, with the goal of minimising and maintaining the residual offset [6].

Diffusion weighted and quantitative imaging

Quantitative MRI measures such as T1, T2, DWI, and ADC may support response assessment during treatment [76]. Different parameters, such as longitudinal relaxation rate (T1), transverse relaxation rate (T2), diffusion-weighted imaging (DWI), and apparent diffusion coefficient (ADC), have the potential to enhance clinical findings. The accuracy of the results for both quantitative measures and ADC values can vary based on the magnet model, sequence implementation, and magnet characterization [77, 78], as such QA with appropriate phantoms and sequences are recommended to isolate the system variation from patient response. Platform-specific recommendations for DWI parameters, including b-values, are available [79]. QA methods for quantitative imaging on current MRI-Linac systems have also been reported [8, 76].

Treatment planning system

Magnetic field effects on dose deposition

A magnetic field alters dose deposition in both patient tissues and ancillary support devices, with potential effects on target and non-target dose [33]. Readers are referred to existing recommendations [18, 80], and the MRI-Linac WG dosimetry paper [63], for more information. The ability of a TPS to account for the ERE and ESE should be investigated during commissioning. It is important to consider these influences carefully and thoroughly understand their impact for routine clinical planning [33]. Hall et al. [16], demonstrated both effects in the same clinical setting using perpendicular MRI-Linacs.

Patient positioning devices

For accurate dose calculation, ancillary components should be appropriately characterized within the TPS [58]. Initial modelling should establish planning guidance for devices used under clinically representative loading, setup and immobilization conditions.

MRI-Linac systems present particular challenges for immobilisation and support devices [43]. These may include

fiberglass or carbon fibre couches, bolus, compression belts, breast boards, head and neck masks, foam pillows, and vacuum bags. As many of these devices are not directly visualised on MR images, their position and deformation may be difficult to define reproducibly at each fraction. Some centres have therefore adopted custom virtual TPS models [81], or MRI-visible marking systems for daily localisation. Where these devices have relevant dosimetric effect, CT-based or virtual CT – based modelling approaches should be considered. Evaluation should include device attenuation, assigned density, positional reproducibility and deformation or deflection under expected clinical loading conditions.

Clinical workflows

End-to-end validation of online adaptive workflows should be performed using equipment suitable for the MR environment. Vendor-supplied devices and quasi-3D detectors such as ArcCHECK or PTW Ruby may be used for this purpose, provided their performance in magnetic fields has been verified [82, 59].

Where MR-safe or MR-conditional commercial equipment is unavailable, appropriately validated in-house solutions may be used [83, 84]. Powers et al. [58], described an end-to-end commissioning process on the Unity system using a combination of commercial and non-commercial tools.

True 3D dosimetry using radiochromic polymer gel also offers a method for machine QA and end-to-end verification [85, 86]. Similar approaches have been described for 4D verification of accumulated dose [87, 88]. Although modular phantom-based methods remain more common, gel dosimetry is a promising alternative [89].

Motion management assessment

Intrafraction motion remains an important consideration in MRI-guided radiotherapy [90, 91]. Motion-managed imaging, cine imaging, or 4D MRI workflows should be assessed using a motion phantom with a known waveform, frequency, and amplitude to characterise system limitations and benchmark latency [26]. Respiratory-gated and breath-hold workflows are available on some systems, while ECG-gated workflows remain under development.

Audits

Independent end-to-end validation of treatment processes is recommended as routine during upgrades and updates where relevant, and particularly for emerging technologies. Centres should implement independent fit-for-purpose audit or intercomparison processes that are appropriate to

their clinical scope, available resources and local regulatory requirements. Where formal audit programs are unavailable, centres should undertake independent measurement-based assessments appropriate to their departmental needs. This may include dosimetric intercomparisons using accredited suppliers, and independent review or evaluation of treatment workflows by experienced or accredited external facilities. The audit approach should be documented, justified, and reviewed periodically as national or state dosimetric audit frameworks evolve.

QA devices and their requirements

Influences of MR on dosimetry tools

This guideline does not review all effects of magnetic fields on dosimeter performance [18, 92–94]. However, users should understand the relevant corrections and limitations before using any detector on an MRI-Linac. Hu et al. [43], identified four key considerations when assessing QA equipment for the MR environment: ferromagnetic projectile risk, susceptibility of electronic components to magnetic, RF, and gradient fields, effects on measurement accuracy, and image artefacts or distortion caused by the device. Additional guidance on detector testing and limitations has been provided by Roberts et al. [6], Jelen and Begg [18].

Table 4 lists devices used for specific QA. The working group recommends to use equipment that vendors establish as MR-safe or MR-conditional, and to ensure it is labelled properly as defined by American Society for Testing and Materials (ASTM) requirements [95].

MR-safe and MR-conditional equipment

Commissioning and QA in the MR environment require the use of MR-safe or MR-conditional equipment. Because each centre may use a mixture of commercial, locally manufactured, legacy, or otherwise unverified devices, all equipment should be assessed in accordance with the MRI-Linac Safety Working Group recommendations [27]. An equipment register should be maintained to document MR safety status, labelling, and functionality checks.

Validation of software

Software used in the patient pathway should be subject to strict quality control [96]. Version changes, bug fixes, and software updates may affect system performance, so centres should maintain clear records of software versions and communicate closely with vendors regarding updates. Where

Table 4 MRI equipment for routine quality assurance

QA device type	Device manufacturer/name	Potential use cases
Planar array devices	SNC Daily QA MR SNC IC Profiler-MR PTW STARCHECK maxi ® MR PTW Octavius 1500 MR, 1600 MR	Output measurement Flatness and symmetry Field size
1D detectors	PTW Semiflex 3D MR PTW PinPoint® 3D MR PTW microdiamond PTW Semiflex Exradin A1SL Exradin A19 IBA cc13 IBA cc04 Farmer type NE2571, IBA FC65, PTW30013 OSLD	Absolute/relative dosimetry Beam data collection Output factors Beam model validation Dose calibration Surface dose
Water tank	PTW MP1 MR Manual Water Phantom PTW BEAMSCAN® MR In house solutions	Absolute dose measurements Relative dose measurements Beam data collection
Film	Gafchromic film—Ashland EBT3 or EBT4 Ashland EBT-XD	Absolute dose measurements Relative dose measurements Beam data collection MLC/Jaw calibration Patient specific plan QA
MRI QA devices	Modus MRID(3D) geometric distortion phantom Philips geometric distortion phantom PIQT phantom ACR MR-MV test phantom (Vendor Supplied) CIRS Abdo 4D phantom SNC SRS MR Distortion Phantom SNC ZEUS: MRgRT Motion Management QA Phantom Modus Motion MR Platform or MRI Motion phantom 3DONE phantom	Image quality Isocentre offset Motion assessment validation Sequence testing
Patient specific QA/Quasi 3D and true 3D	SNC ArcCHECK®-MR OCTAVIUS® 4D PTW Octavius 1500 MR, 1600 MR DELTA4 Gel dosimeters	Patient specific plan QA Output with gantry rotation
MV imager	Integrated MV imager	Image quality Phantom setup Isocentre MLC/jaw calibration
End-to-End testing	CIRS STEEV CIRS Freepoint CIRS IMRT thorax PTW Ruby CIRS Abdo 4D phantom CIRS ZEUS MRgRT phantom Gel dosimeters Inhouse designed phantoms	Patient specific plan QA Beam model validation Gating
Software	AQUA RIT PyLinac MU2Net RadCalc ClearCalc/ClearCheck Inhouse software Vendor supplied software	Isocentre MLC/jaw calibration Secondary dose check Data transfer validation

Table 4 (continued)

QA device type	Device manufacturer/name	Potential use cases
Others	MV alignment phantom	MV isocentre
	LasVegas phantom	MV images quality
	Solid water	Absolute and relative dosimetry
	Setup jigs	
	MRI markers	
	MR safe thermometer	
	MR safe rulers	
	CT/MR compatible markers	

possible, test environments should be used to assess pre-clinical releases before clinical deployment.

Periodic QA

Routine QA

Routine QA should be a focused subset of commissioning tests designed to identify clinically relevant deviations from baseline [28]. The registered ROMP is responsible for implementing a program that is comprehensive, practical, and appropriate to local workflows. A risk-based framework such as AAPM TG-100 [97], may assist in selecting and prioritising tests. Recommended daily, monthly, and annual QA tasks are summarised in Tables 5, 6 and 7. Experimental methods are not described here; readers should refer to the cited literature for implementation details. For adaptive workflows, Chen et al. [98], provides a useful daily end-to-end QA example for the Unity system.

Future developments and challenges in MRI-Linac Technology

Adaptive radiotherapy strategies involving emerging technologies present challenges for the workforce, particularly in training and credentialing, which are essential for the safe and effective use of MRI-Linac systems. There are several developments underway in MRI-Linac platforms, including advanced gated delivery [99], improved treatment workflow optimization, and helical delivery [100]. As commercial MRI-Linac platforms continue to evolve, guidance in these areas should be reviewed and updated periodically to reflect contemporary evidence, technology and practice. Finally, the use of automation and artificial intelligence in plan preparation is a viable option for workflow optimization, as detailed by Künzel et al. [101, and Spieler et al. [102].

Table 5 Daily quality assurance tests

Category / procedure	Tolerance and references
<i>Dosimetry</i>	
X-ray output constancy (all energies)	±3% [25, 46]
Backup dose monitor	±3% [3]
<i>Mechanical</i>	
Lasers	≤ 1 mm [25, 46]
Collimator size indicator	≤ 1 mm [25, 46]
<i>Safety</i>	
Door interlock	Functional [25, 46]
Door closing safety	Functional [25, 46]
AV systems	Functional [25, 46]
Beam ready and on indicator	Functional [3, 25, 46]
Table emergency stop	Functional [3]
Patient emergency call	Functional [3, 26]
Emergency trolley check	Present [26]
Emergency couch release	Functional [26]
MR safety signage	Present [26]
Check bore for presence of foreign metal objects	Not present [26]
Damage to equipment	Not present [3]
<i>MR imaging</i>	
MR SNR	Manufacturer defined [3, 26]
MR image scaling TRA and COR / basic spatial fidelity check	Manufacturer defined [3, 26]
Central frequency	Manufacturer defined [26]
Transmit gain	< 5% change from baseline [26]
<i>Misc</i>	
Connectivity and data transfer end-to-end test	Local tolerances in dedicated phantom [96]

Implementation considerations

Implementation of this guideline depends on local workforce capability, access to MRI-compatible QA equipment, vendor support, training, and regulatory requirements. Centres should adapt these recommendations to their platform,

Table 6 Monthly quality assurance tests

Category / procedure	Tolerance and references
<i>Dosimetry</i>	
Output constancy	$\pm 2\%$ [25, 46]
Backup monitor chamber constancy	$\pm 2\%$ [25, 46]
Beam profile constancy	$\pm 1\%$ [25, 46], $\pm 2\%$ [3]
Beam quality	$\pm 1\%$ [3]
<i>Mechanical</i>	
Gantry angle indicators	$\leq 1^\circ$ [25, 46]
MLC and Jaw position indicators / field size check	≤ 1 mm [25, 46]
Couch position indicators	≤ 1 mm [25, 46]
Lasers	≤ 1 mm [25, 46]
Radiation isocentre size	≤ 0.5 mm radius [3]
<i>Safety</i>	
Safety interlocks	Functional [3]
<i>MR imaging</i>	
Geometric distortion	200 mm ≤ 1 mm, 300 mm ≤ 2 mm, 400 mm ≤ 4 mm [3] 2 mm across 25 cm FOV [26]
MR imaging and treatment isocentre coincidence	Translation: ≤ 0.5 mm, Rotation: $\leq 0.3^\circ$ from baseline, RMS error < 1 mm [3]
MR image quality: flood field uniformity, spatial linearity, slice profile, spatial resolution	Manufacturer defined [3, 26]
Room temperature and humidity	[26]
Cold head operation	[26]
Helium level check	Baseline [3, 26]
Central frequency	Manufacturer specified [26]
Transmitter gain	$\pm 5\%$ from baseline [26]
High contrast spatial resolution	≤ 1 mm [26]
Low contrast detectability	21 (0.3 T) to 36 (1.5 T) spokes [26]
Artifact evaluation	Not present [26]
Percent signal ghosting	$\leq 2.5\%$ [26]
<i>Misc</i>	
Patient specific QA	Passing according to TG-218 [98]

resources, and clinical workflows while maintaining a risk-based, quality-focused approach. Ongoing monitoring, local audit, and periodic review are recommended to keep QA programs aligned with technological developments and the evolving evidence base.

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Table 7 Annual quality assurance tests

Category / procedure	Tolerance and references
<i>Dosimetry</i>	
Profile flatness / symmetry	$\pm 1\%$ from baseline [3, 25, 46]
Output calibration	$\pm 1\%$ [3, 25, 46]
Output factors spot check	$\pm 2\% < 4 \times 4$ cm ² and $\pm 1\% \geq 4 \times 4$ cm ² [3, 25, 46]
Beam quality	$\pm 1\%$ from baseline [3, 25, 46]
Monitor unit linearity	$\pm 5\%$ for 2–4 MU and $\pm 2\% \geq 5$ MU [3, 25, 46]
Output constancy vs. gantry angle	$\pm 1\%$ from calibration angle [25, 46]
Off-axis factor constancy vs. gantry angle	$\pm 1\%$ from gantry 0 [25, 46], $\pm 2\%$ from baseline [3]
MLC transmission	$\pm 0.5\%$ from baseline [3, 25, 46]
<i>Mechanical</i>	
Max. couch travel	≤ 2 mm [25, 46]
Leaf position repeatability	≤ 1 mm [25, 46]
<i>Safety</i>	
Manufacturers safety tests	Functional [25, 46]
<i>MV imaging</i>	
MV image scaling	≤ 1 mm [25, 46]
MV image quality (spatial resolution, contrast, uniformity, noise)	Baseline [25, 46]
<i>MR imaging</i>	
Transmitter gain stability	$\pm 5\%$ from baseline [26]
Magnetic field homogeneity	≤ 0.5 ppm volume root mean square across a 35 cm diameter spherical volume or as specified by MRI manufacturer across a specified DSV [26]
Radiofrequency coil evaluation	Coil dependent, action limit of one standard deviation determined by via several baseline measurements [26]
High performance imaging*	[26]
<i>Misc</i>	
PSQA	Pass rate 2% from baseline and within tolerance [46]
PSQA – interruption test	Pass rate 1% from uninterrupted [46]

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Declarations

Conflict of interest The authors declare no conflict of interests in the subject matter detailed.

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