ACPSEM position paper: Commissioning, and quality assurance of Magnetic Resonance Imaging Linear Accelerators

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Contents

1. Abstract

The Magnetic Resonance Imaging Linac Working Group (MRILWG) present a position statement on the commissioning and quality assurance (QA) tests for linear accelerators coupled with Magnetic Resonance Imaging. The core objective of the MRI-Linac quality assurance (QA) sub-group was to curate a set of critical performance tests to assist physicists in establishing and maintaining a safe and effective treatment program.

The commitment to a vendor neutral approach was made to delineate recommendations towards site preparation, commissioning assessments, QA tests and their frequency. The foundational and longitudinal studies referenced in this endeavour emphasized a broad spectrum of sources to provide a comprehensive guidance. Tests presented aim to reflect clinical use patterns and intend to be sensitive and relevant to detecting errors related to the specific use of an MRI-Linac. A certified ROMP is responsible for authorising return of the radiation therapy equipment to clinical use following any repair, adjustment, upgrade or modification to the equipment that affects patient safety.

2. Introduction

The MRI-Linac presents an advancement in the precise delivery of radiotherapy. Utilizing MR imaging, there is enhanced distinction of soft tissue, with the added capability of procuring dynamic and functional tissue data in real-time. An improved understanding of the tumour microenvironment [1] provides the potential for true treatment adaptation, leading to further escalation of dose to target tissues and optimized organ at risk and normal tissue sparing [2].

The integration of new technologies presents opportunities and challenges, spanning facility planning, acceptance and commissioning and quality assurance (QA). To understand the impact of an MR environment on beam generation and its interaction within and around a patient, physicists determine which tests are pertinent at the time of acceptance and commissioning and on-going QA. In this pursuit, references were made to foundational studies like Roberts et al [3], longitudinal studies pertaining from both Elekta Unity (Elekta AB, Stockholm, Sweden) and ViewRay MRIdian (MRIdianTM, ViewRay Inc., Cleveland, OH,

USA), have been incorporated for this purpose [4-7]. Further insights from Woodings et. al. [8] and the ESTRO-ACROP consensus opinion [9] augmented this work to ensure a comprehensive guidance.

This position paper aims at:

- describing a comprehensive set of vendor agnostic recommendations on acceptance and commissioning tests, supplemented by justification.
- detailing site preparation considerations.
- listing current QA devices
- recommendations on routine QA tests for daily, monthly and yearly frequencies.

As commercial MRI-Linac platforms evolve to add functionality and features, requirements for acceptance, commissioning and QA should be reviewed in light of these changes.

3. Scope of practice

The purpose of this position statement is to address the commissioning and quality assurance (QA) of MRI-Linacs. In view of the critical nature of acceptance, commissioning, and the ongoing management of the QA program, specialized knowledge and training is required [10]. As such the working group recommend that the certified ROMP assumes the ultimate responsibility for overseeing and executing the appropriate completion of tests, evaluations, and assessments. They will also provide guidance on QA procedures and protocols, ensuring that they adhere to best practices and regulatory standards [11]. Delegation of specific tests to non-certified ROMPs should be completed with specific training, oversight and review of QA results [12].

4. Definitions and Abbreviations

AAPM	American Association of Physicists in Medicine
ACPSEM	Australian College of Physical Scientists and Engineers in Medicine
ACR	American College of Radiology
ARPANSA	Australian Radiation Protection and Nuclear Safety Agency
DAT	Device Acceptance Test
DIMP	Diagnostic Imaging Medical Physicist
DSV	Diameter of Spherical Volume

EPID	Electronic Portal Imaging Device
ERE	Electron Return Effect
ESE	Electron Streaming Effect
FFF	Flattening Filter-Free
FOV	Field of View
IMRT	Intensity-Modulated Radiotherapy
MLC	Multi-leaf Collimator
MRIL	Magnetic Resonance Imaging Linac
NCRP	National Council on Radiation Protection & Measurements
PSQA	Patient Specific Quality Assurance
QA	Quality Assurance
RF	Radiofrequency
ROMP	Radiation Oncology Medical Physicist
TPS	Treatment Planning System

5. Machine overview

5.1 Current commercial machines

Currently two commercial systems are available to the Australian and New Zealand market, the Elekta Unity (Elekta AB, Stockholm, Sweden) and the ViewRay MRIdian (ViewRay Technologies Inc, Cleveland, OH, USA) Figure 1A and 1B respectively. Details of their characteristics are summarised in Table 1. Both employ an S-band linac delivering flattening filter free (FFF) photon beams perpendicular to the static magnetic field. Delivery is completed via step-and-shoot intensity-modulated radiotherapy (IMRT) on both platforms that facilitate adaptive treatment workflows.

The MR hardware and technology architecture at the heart of these devices overcome the engineering challenge presented to adequately isolate both systems from each other and find synergy to leverage their composite benefit. To achieve the challenges of high spatiotemporal resolution for real time imaging that satisfies the requirements for adaptation [13]. This is dependent on having good gradient performance, along with high slew rates that influence the minimum attainable TR and TE for imaging [14].

Each MRI-Linac design approaches the integration of systems differently using a combination of active and passive magnetic shielding. For the Elekta Unity, active shielding that isolates the MRI system from the linac component is used to provide a low-field toroid for the linac beam and sensitive components [15], and a central 15 cm gap in coils plus shimming is

employed to deliver the photon beam [16]. The MRIdian utilises split coils leaving a 28 cm gap and linac components are mounted in ferromagnetic compartments around a ring of ferromagnetic shields forming a magnetically shielded volume around the linac [17].

Another notable difference between the two systems is that the Unity employs the Agility multileaf collimator (MLC) while the MRIdian uses a double stack and double focus MLC without additional jaws, reducing the effective leaf with to half the physical width and further reducing an interleaf leakage. Refer to Zhang et al [18] and Latifi et al [15] for further details on each respective system. The two clinical systems provide translational treatment couches, the Elekta Unity provides only longitudinal movements in the direction of the magnetic field, whereas the ViewRay MIRIdian system allows lateral, longitudinal and vertical translations, allowing for corrections due to initial patient alignment.

Figure 1 – A) Elekta Unity and B) ViewRay MRIdian

5.2 First Generation Systems

5.2.1 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 employing an open bore 1 T magnet [19]. The magnet is a split superconductive magnet with the ability to have the in-line or

perpendicular beam field orientation which is similar to the Aurora design [20].

Figure 2 - Australian MRI-Linac

5.2.2 Aurora System

The Aroura RT (MagnetTx Oncology Solutions, Canada) system [21] employs a 6MV linac and 0.6 T MR, where the linac can be positioned between open MR planes (perpendicular), or alternatively through a central opening of one of the planes (in-line) (Figure 3).

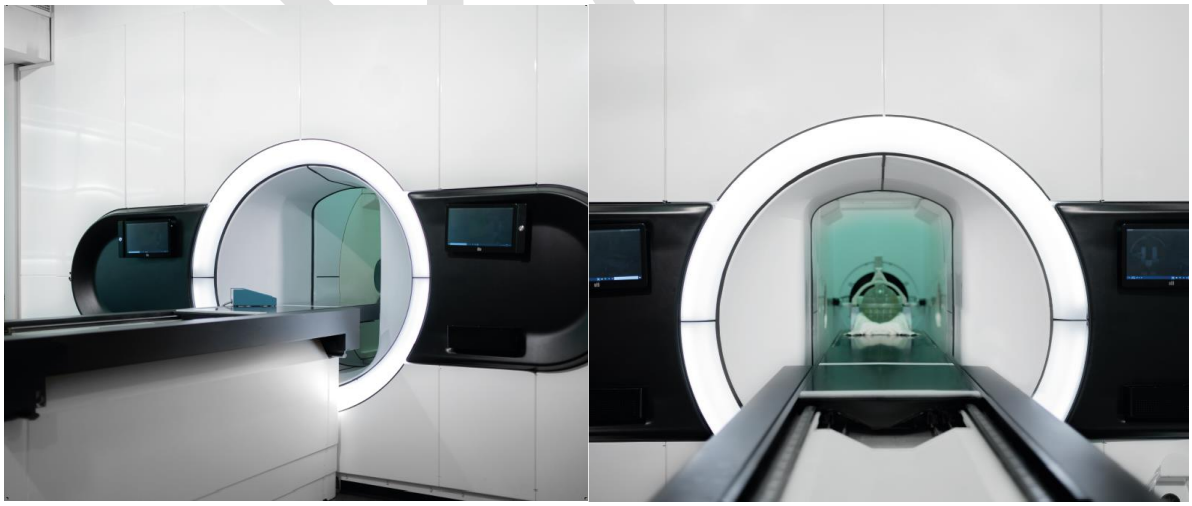

Figure 3 - Aurora MagnetTx system

Table 1. Configuration details of current MRI-Linac systems

Feature	Elekta Unity	MRIdian ViewRay	Australian MRI	Aurora MagnetTx
Nominal Energy (MV)	7 FFF	6 FFF	4 & 6 FFF	6 FFF
B0 strength (T)	1.5	0.35	1.0	0.55
SAD (cm)	143.5	90	190 - 330	122
MLC	Single stack 160 leaves	Double stack 138 leaves	Single stack 120 leaves	Single stack 120 leaves
MLC speed (mm/s)	86	40	-	35
Max field size (cm)	57.4 x 22 cm^2	27.4 x 24.1 cm^2	30 cm^2 to 50cm^2	28.5 cm x 28.5 cm^2
Bore diameter (cm)	70	70	82	110W x 60H
Magnet type	Closed superconductor	Split superconductor	Open superconductor	Open Room temperature MR
Orientation	Perpendicular	Perpendicular	Inline and perpendicular	Inline
Delivery method	Step and shoot IMRT	Step and shoot IMRT	Step and shoot IMRT	Sliding window Step and shoot IMRT
360-degree delivery	No	Yes	Yes * with patient rotation	Yes
MRI Characteristics	gradient strength (GS) of 34 $mT.m^{-1}$ and slew rate of 120 $T.m^{-1}.s^{-1}$	GS 10 $mT.m^{-1}$ and a slew rate of 200 $T.m^{-1}.s^{-1}$	???	GS 45 $mT.m^{-1}$ and a slew rate of 200 $T.m^{-1}.s^{-1}$

6. WG position on acceptance and commissioning of an MRI-Linac

MRI-Linac device acceptance tests are conducted with a vendor and customer component. Site physicists should participate during this process to ensure a level of accuracy and consistency commensurate with their local equipment. Recommended commissioning tests found in Table 3 find synergy with ESTRO-ACROP recommendations detailed by Tanadini-Lang et al. [9], Woodings et al. (Unity) [8] and Valdenaire et. al. (MRIdian) [22]. Hybrid tests provided by Tijssen et al assess the interactions between linac and MRI system. Test descriptions are not provided in subsequent sections however, justification and expanded descriptions on some of the recommended tests are provided. Sections will be lettered accordingly.

Table 2 – Vendor agnostic recommended commissioning tests endorsed by the MRI linac working group.

Test/Check Category	Test/Check Description	Tolerances	References
A. Site preparation			
	Radiation Survey - Preliminary survey competed post installation and first beam on	As per local regulatory requirements	
	Final survey post beam tuning and machine calibration	As per local regulatory requirements	
MR survey	Complete magnetic fringe field assessment		[23]
Acoustic survey	Validation of acoustic insulation of RF cage/bunker and headphones/ hearing protection		[24]
MRI safety	Installation of metal detectors ferromagnetic detection system		[9],[24]
MRI infrastructure	Safe installation of quench pipe		
MRI influence on surrounding devices	Beam profile and output stability on adjacent linacs with MRI-linac gantry rotation pre and post magnet ramp	± 1% (TG142 tolerances)	[9, 22]
B. Acceptance tests (vendor performed)	Safety – Inhibit systems including emergency off, audio-visual, two-way communication system, interlocks, door, lights, beam stability	As per vendor specifications As per local regulatory requirements	
	Coordinate systems and data integrity	As per vendor specifications	[8, 25]
	Helium fill		
	Radiation isocentre – beam alignment and locus	± 1 mm	
	MV panel rigidity, alignment, pixel scale, isocentre and image quality	As per vendor specifications	[8]
	Beam quality	± 1%	[26]
	Dose output without gantry variation - MRL systems without specific TPS characterisation	≤ 1% (CCT usually 0.98 - 1.02)	
	Dose output with gantry rotation - MRL systems with specific TPS characterisation	± 2%	
	Dose rate stability with/without gantry rotation	± 2%	IEC 976 specify that the monitor chamber should have less than 2% variation to dose rate?

	MU linearity	2% > 5 MU	TG 142 and IEC 976 and IEC 977
	MU reproducibility	COV < 0.5	<IEC 976>
	Beam profile with gantry rotation	± 1%	[26]
	Beam limiting device calibration - MLC only or and MLC and jaw calibration	± 1 mm	[26]
	Gating and beam hold functionality	As per vendor specifications	
	Gating and beam hold latency	As per vendor specifications	
	MR to MV alignment	± 1 mm	TG284
	Individual coils and channels assessment	As per vendor specifications	
	Effect of MV beam on MR image quality	As per vendor specifications	
	Effect of gantry on MR image quality, and B0 homogeneity	As per vendor specifications	
	MR geometric accuracy	± 1 mm	
	System config checks and backups	As per vendor specifications	
C. Mechanical	Gantry angle calibration – rotation and readout	< 0.2º± 1°	
	Couch calibration, orthogonality and alignment	± 1 mm	TG 142 IEC 976
	MLC and jaw calibration, orthogonality, and sag	± 1 mm	IEC 976 AAPM TG 142
	QA support system calibration and alignment	± 1 mm	
	Alignment of all isocentres (laser, MV panel, beam, MRI)	± 1 mm	TG 142
D. Beam data collection	Beam data required for creation of, and/or comparison against, beam model	As per vendor requirements	
	Additional data collected for site specific TPS commissioning and ongoing routine QA.	As per clinical protocols and local regulatory requirements	
E. Dosimetry	Monitor chamber output constancy, stability, accuracy, and precision	± 1%	IEC 976
	MU Timer accuracy and system latency for gating	± 1% or ± 50 ms	IEC 976
	Beam quality and baseline	As per clinical protocols	TG 142

	Dose rate stability, linearity, reproducibility – short and long term	± 1%	IEC 976
	Cryostat/ high density MR element characterisation	As per vendor specifications	
	Output with gantry angle	± 1%	TG 142
	Flatness and Symmetry	± 2%	TG 142
	Beam profile stability with gantry rotation	± 1%	TG 142
	MLC and jaw transmission	< 1%	TG119
	Couch transmission	As per clinical protocols	
	Coil transmission	As per vendor specifications	
	Immobilisation device commissioning	As per clinical protocols	
F. Ancillary Imaging	MV imager Central pixel location and subsequent geometric accuracy based on pixel size and mag factors	± 1%	
	MV imager image quality	As per clinical protocols	TG 142
G. MRI Scanner	Cage and RF interference map	>=100dB from Marlin 1.5T	
	MR to MV alignment and baselining, including multiple gantry angles	± 1 mm	
	MR uniformity and SNR measurement	acquired using all three coils (body, torso, H&N) in the transversal, sagittal, and coronal planes using the NEMA protocol for analysis	
	Magnetic field drift (B0 stability)	< 1 ppm/day during < 0.25 ppm / day for first 1-2 months operation	TG 284
	Transmitter and Gain Calibration	No visible artefacts Manual transmit gain within 5% of automatic Manual centre frequency within 10 Hz of automatic	TG 284
	Transmitter Gain Stability	Vendor specified minimum amplitude, frequency, and phase stability levels unless otherwise agreed upon	TG 284
	Magnetic field homogeneity (B0)	0.5 ppm volume root mean square (VRMS) across a 35cm DSV or as specified by MRI manufacturer across a specified DSV	TG 284

	Gradient Non-linearity	≤1 mm (within 10 cm radial distance of isocentre) ≤2mm (<20 cm radial distance away from magnet isocentre)	TG 284
	RF coil evaluation		TG 284
	External laser offset from MR isocentre	≤1 mm (where essential for patient positioning)	TG 284
	Table alignment with B0	0 ± 0.3°	TG 284
	Informatics/ connectivity/ Data transfer/ orientation	Site specific	TG 284 & TG 248
	MR spurious noise assessment	As per clinical protocols	[27]
	MR geometric distortion assessment and baselining	Acquire baseline for routine QA ≤ 2mm across 25 cm FOV	TG 284
	Effect of linac states on MR Image quality	As per vendor specifications	[27, 28]
	MR image quality and distortion with gantry rotation	As per vendor specifications	[29]
	MR image quality and distortion with MV beam on	As per vendor specifications	[29]
	MR image quality and distortion with MLC movement (single stack and double stack)	As per vendor specifications	[29]
	MR image quality and distortion with jaw (secondary MLC bank) movement	As per vendor specifications	[29]
	MR spatial integrity in cine mode	As per vendor specifications	[9]
	MR contrast and MR marker validation and protocol development	As per vendor specifications	
	Motion management assessment (gating)	As per vendor specifications	
	DWI and quantitative MRI assessment	As per vendor specifications	
H. TPS	Connectivity and acceptance testing to record and verify system	As per vendor specifications	
	Coordinate systems and data integrity	As per vendor specifications	[8]
	Basic field validation including output and symmetry	± 2%	
	Heterogeneous field validation	As per clinical protocols	
	Couch and MR coil modelling validation	As per clinical protocols	
	Complex and simple clinical case validation	As per clinical protocols	
	Ancillary patient aid modelling e.g., headboard, masks, wing board	As per clinical protocols	
	ERE/ESE/ EF modelling in simple and anthropomorphic cases	As per clinical protocols	

	Density conversion method accuracy and equivalency during adaptations	As per clinical protocols	[9]
	DVH validation	As per clinical protocols	
	Density information layering (where appropriate) accuracy	As per clinical protocols	
	Contouring tool equivalency	As per clinical protocols	
	Validation and equivalency of adaption techniques	As per clinical protocols	
	End to end system tests, including dosimetry of simple and complex plans	As per clinical protocols	
	Clinical planning protocol or template commissioning	As per clinical protocols	
	Plan reconciling tool validation	As per clinical protocols	
I. End-To-End	End to end testing for clinical workflows	As per local regulatory requirements	
J. Patient plan specific QA	Secondary MU check program commissioning for simple and complex fields	As per clinical protocols	
	Measurement-based QA tool commissioning e.g., ArcCheck, phantom with film	As per clinical protocols	
Adaptive end-to-end test	Phantom studies for specific adaptive workflows	As per clinical protocols, suggested γ (5%/2mm), 10% threshold, >90% pixels passed	[8]
Non-adaptive end-to-end	Full end-to-end testing static targets	Townsville Paper – MRIL, Powers et al	
	Full end-to-end testing including motion management		
	Geometric fidelity and geometric consistency of all modes of acquisition of scanner i.e. Cine mode, navigated scan, localizer scan, fast and slow scans	4DMR sim/4DCT sim	R.A.
J. Audit	Absolute dosimetry audit by regulatory body or nearby MR linac centre	As per local regulatory requirements	

6A MRI-Linac shielding and site preparation

An MRI-Linac shares commonalities with conventional linear accelerators for radiation shielding with the added complexity of an MR environment. Optimal site setup should make provision to consider network requirements, RF shielding and isolation, quench vent and exhaust, excessive mechanical vibrations (whether steady state or transient) acoustic management and magnetic shielding which can impact an MRI-Linac system.

Site preparation guides are provided by vendors for standard configurations, the working group recommends close consultation with vendors during the planning process. Design aspects that improve safety and general site planning are detailed by Hu et. al. [30]. Of note is the need for dedicated storage for QA and immobilization equipment to limit misuse of unsafe equipment used for conventional linac treatment.

Internationally accepted shielding design protocols can be used to determine the most suitable material and attenuation level required with minor modifications. The MRI-Linac WG recommend NCRP 151 [31] as the values for tenth value layer (TVL) are more conservative. The differences as applicable to shielding between conventional and MRI-Linac are summarised in Table 3, each item for consideration is explained in detail in the paragraphs that follow. When considering neutron emission, standard photon shields within MRI linacs are adequate to safeguard against these neutrons at every available energy configuration.

Table 3 2 Comparison of the pertinent machine characteristics for radiation shielding between conventional linacs and MR linac vendors.

Section	**Machine Characteristic**	**Parameter Affected**	**Conventional Linac**	**Elekta Unity**	**ViewRay MRIdian**
T1	Source to isocentre distance	d_{SAD}	1000 mm	1435 mm	900 mm
	Primary collimator angle	*Primary barrier width*	27.8°	8°	18°
T2	Maximum field size	*Primary barrier width*	40 cm x 40 cm	57.4 cm x 22.0 cm	27.4 cm x 27.1 cm

	Maximum field area	*F*	1600 cm^2	1263 cm^2	743 cm^2
T3	Primary beam transmission	D_t	100%	0.5% at covers (2130 mm from iso)	Assume 100%
T4	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

T1. Primary Barrier Transmission and Source to Isocentre Distance

In C-arm linacs, which typically have a distance of 1000 mm between the source and the isocentre, the source-to-isocentre distance is vitally important. Current MRI-Linac systems do not adhere to this standard distance. As all distances are normalized to 1 m in NCRP 151, the source-to-axis distance (dSAD) must be explicitly included. As an example, the calculation for primary barrier transmission would be as follows:

$$B_{pri} = \frac{P\left(\frac{d_{pri}}{d_{SAD}}\right)^2}{WUT}$$

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 at a distance. Due to the inverse square law correction to the point, these values can be misleading about the overall amount of shielding provided. We recommend scaling back the maximum transmission value to isocentre, allowing it to be used in calculations of primary barrier thickness by scaling the workload or isocentric dose rate.

For example, considering the Elekta Unity:

$$Transmission = 0.5\% \times \frac{(1435 + 2130)^2}{1435^2} = 3.09\%$$

In spite of the fact that this value is significantly higher than the average leakage of the unit, it is still common to find primary barriers that are thicker than adjacent secondary barriers. While

the beam spectra have already been altered by transmission through the machine, it is advisable to use both TVL1 and TVLe for determining the primary barrier thickness, as the specific alterations to the beam spectrum are not well-documented.

T2 Maximum field size

Conventional accelerators must consider the maximum field size to be defined by the jaws and MLCs at a collimator rotation that produces the greatest lateral dimension. As Unity and MRIdian have fixed collimators this consideration is not needed and the field size in the superior and inferior direction can be simply projected onto the primary barrier. It is also common to define the maximum field size by the primary collimator angle. The correct maximum field size is therefore limited by the lower value of these two approaches.

T3 Primary barrier width

MRI-Linacs absorb much of the small-angle patient scatter due to their high energy. Scattering angles are typically limited to >25°, reducing penetration and scatter fraction. Consequently, the requirement for the primary barrier to intercept at least the 20° scatter line is no longer crucial, providing the opportunity to use laminated or composite barriers.

It is still recommended to add 30 cm either side of the largest beam projection to determine the width of the primary barrier. This projection is maximized at the intersection of the ceiling barrier and the wall barrier, as described in NCRP 151.

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 the additional steel. Non-ferrous materials are required in and around the magnet, and each vendor offers specific guidance in this regard.

T4 Leakage radiation

Some MR linear accelerator manufacturers report a higher percentage leakage than is observed in conventional linacs. Thus, it is important to include this explicitly in the equation for leakage transmission. We recommend this be denoted as the factor L_f, such that the leakage equation is written as:

$$B_L = \frac{P d_L^2}{L_f W T}$$

Conduits, Magnetic fields, ventilation, air-conditioning and acoustic management

Radiation therapy equipment typically requires conduits to facilitate cabling and dosimetry tool installation through radiation shielding. These conduits are designed to minimize scattered ionizing radiation outside the bunker [32]. Similarly, RF shielding allows for small "waveguides" within the RF cage to accommodate conduits. Their design ensures that the RF shield always remains effective, however, any conductive cabling that passes through a waveguide may introduce RF artifacts into the MR images. As a result, it is crucial to minimize the likelihood of stray RF signals interfering with the quality of MRI images. During commissioning works or daily quality assurance, it may not always be possible to fully close these waveguides. To determine the optimal arrangement, we recommend collaboration between physicists, MR physicists, and the vendor.

The impact of an MRI-Linac on the surrounding environment and vice versa is crucial for a successful build. It is important to monitor any major facility changes, such as construction in adjacent areas or large ferromagnetic sources like elevators or MRI systems (above and below), as they may affect the static field and distortions. MR image quality may be adversely affected by transient as well as steady-state mechanical vibrations. In addition, stray magnetic fields must be taken into account when high field MRI-Linacs are located near other linacs [33]. Particularly after static magnetic field ramp-up and any scheduled (or unscheduled) ramp-down, ensure flatness and symmetry of gantry position on adjacent linacs.

Heat dissipation and management are crucial to MRI-Linac operation. Helium systems require tight control of cooling, not just for cryostats but also for control cabinets. In order to meet the vendor's operational specifications, physicists should consult cooling engineers when designing MRI-Linac bunkers. Insufficient cooling for helium or high ambient temperatures may result in extreme humidity in cryostat cabinet rooms, resulting in excessive condensation in ancillary rooms, control consoles, and bunkers. It is recommended to establish robust cooling chain monitoring overseen by local subject matter experts who can rectify issues outside of regular hours. To address any disruptions to the cooling chain or ambient conditions, clear monitoring protocols and management plans are essential. Monitoring environmental conditions, such as temperature, humidity, water ingress, and linac performance, is useful for pre-emptive maintenance and outage monitoring.

Managing acoustics is another consideration. Certain MRI procedures can produce moderate to high levels of acoustic noise, affecting patient comfort and posing safety concerns for staff

and patients [34-36]. Through proper bunker construction, acoustic isolation can be achieved to reduce MRI bunker noise [37]. Acoustic noise levels should be confirmed by physicists and local standards should be followed [24].

Summary recommendations

- Vendor Consultation: Engage closely with vendors during the planning phase to understand specific requirements, ensuring the optimal performance of MRI-Linac systems.

- Shielding & Primary Barriers: Adopt the NCRP 151 protocol for conservative shielding design. Pay keen attention to the primary barrier transmission, especially concerning the differences in source-to-isocentre distances. For MRI-Linacs, prioritize the consideration of small-angle patient scatter absorption and adjust primary barrier width accordingly.

- Technical Specificities: Understand the nuances of maximum field sizes, especially with MRI-Linacs' fixed collimators. Remain vigilant about potential leakage, particularly focusing on the L_f factor that indicates higher leakage in MRI-Linacs.

- Setup & Environment: Minimize stray RF signals' interference with MR image quality, necessitating close collaboration with MR physicists and vendors. Monitor the surrounding environment of the MRI-Linac, including adjacent construction and major facility changes.

- Temperature & Acoustic Control: Collaborate with cooling engineers to ensure consistent temperature regulation vital for MRI-Linac operation. Emphasize acoustic isolation in bunker construction to mitigate MRI-procedure noises, adhering to local standards.

6B MRI-Linac acceptance testing

6.B.1 Safety

Standard safety tests include electrical, mechanical and dosimetric. Tests and tolerances designed by AAPM TG-142 updated in TG-198 and acceptance tests within IEC 60976 [38]

and IEC 60601 [39] remain relevant as references to establish baseline guidelines for acceptance tests.

A robust MRI safety program designed referencing ACR recommendations will ensure staff knowledgeable of the risks inherent in working in an MR environment [40]. The MRI-Linac WG endorses the recommendations presented by the MRI-Linac Safety WG [24].

6.B.2 System configuration and connectivity

Acceptance testing and commissioning for DICOM imaging and connectivity to the hospital PACS, record and verify system (RVS) and other required nodes is a paramount consideration for real-time adaptive workflows. Tijssen et al. provide a list of system connection and configuration tests recommended at the time of acceptance and commissioning [25]

6C Mechanical

6.C.1 Radiation isocentre

Mechanical isocentre is known to influence radiation isocentre in C-arm linacs, as collimator and couch do not rotate in current commercial MRI-Linac offerings, the concept of mechanical isocentre does not strictly apply. The validation of co-incidence of radiation and imaging isocentres has been verified to achieve a 1 mm tolerance by several groups across both commercial platforms [8, 41, 42].

The size of the radiation iso-centre can be assessed using a star-shot image using film sandwiched between copper plates as detailed by Roberts [3] or Palacios et al. [43], or alternatively using the MV portal dosimeter if one is provided. The position and the size can then be determined using a Winston-Lutz test, where any possible sag found in the beam limiting device [38]. Powers et al provide an overview of the linac commissioning tests performed on Elekta Unity along with their results, however with an emphasis on how to perform some of the tests when dedicated, specialized equipment is not available [44].

6.C.2 Considerations for the beam limiting device

MLC and jaw alignment with gantry rotation and treatment beam is a stalwart component of machine characterisation. Each MLC bank should be independently verified for the positioning and transmission, for the MRIdian system this is particularly important where there exists two sets of MLCs stacked in a tessellated configuration. Both systems have fixed collimator positions and validation of any possible rotation should be a consideration as detailed by Woodings [8]. Users are to familiarise themselves with the vendor's jaw and MLC calibration

processes, in using available detectors in the clinic independently verify alignment, interleaf leakage and intra-leaf leakage over full MLC bank and extent of travel [18, 45]. Picket fence tests using film or EPID can be completed for verification, Tsuneda et. al describes workflows in overcoming limitations with the Elekta Unity [46].

6D. Scanned and non-scanned data considerations

Considerations for beam scanning presented by AAPM-TG106 hold relevance for acquisition of baseline data for acceptance and commissioning [47]. For the acquisition of relative dosimetry, the effect of the magnetic field on a scanning detector within a scanning water tank may vary with depth, off axis position and field size, this effect should naturally be lower for low field strength systems like the ViewRay.

Key points of consideration for scanning under the influence of the static magnetic field include: profile offsets, changes in the effective points of measurement [48] and the influence of detector orientation [49]. The introduced shift in the effective point of measurement of ionization changes affects linac calibration and commissioning of the treatment planning system. Specifically, the vertical shift impacts beam quality and tissue maximum ratio determination, and the lateral shift affects ion chamber usage.

Baseline profile data can be acquired using film, planar array, or portal dosimetry if available. According to Roberts, chamber response can be variable when using closely packed ion chambers in an array due to differences in average density around the chambers. It is common to use planar arrays for relative profile measurements during quality assurance, so cross-calibration against water tank data would be necessary to account for device sensitivity and the B-field effect on profile measurements [3].

An additional consideration is the presence of air gaps in phantoms which can impact dosimetry measurements for the MRI-Linac, as the MRI's magnetic fields may influence dose distribution and accuracy due to altered electron return effect in the air-filled regions, one solution is to fill the gaps with water [50] [51].

Summary Recommendations:

- During validation of the beam data and acquisition of reference fields for constancy measurement, the working group emphasise checking with vendor requirements on which detectors are recommended for scanned and non-scanned beam data. This is to

ensure data acquired during the acceptance and commissioning period best emulates the data during the modelling process.

- Select detectors that are known to provide accurate results in the presence of a magnetic field, such as ionization chambers and diamond detectors. Avoid using shielded diodes, as they can produce misleading dose profiles.
- A single detector type should be used to acquire scanned and non-scanned data.
- Corrections for lateral shift in the beam profile should be applied after OPF are applied.
- If different detectors are required, OPF should be measured at the point of peak intensity.
- Consider the influence of the magnetic field on detector positioning: The magnetic field may cause shifts in the effective point of measurement for detectors. To ensure accurate measurements, use an on-board MV portal imaging system or another suitable method to verify the reproducibility of detector positioning within the magnetic field.

6E. Dosimetry - Absolute and Relative dose measurements

The QA working group endorses the use of the MRI-Linac WG – dosimetry paper for reference and recommendations when completing absolute dosimetry [52]. Relative dosimetry measurements will experience the same dependencies attributed to measurement within an MR environment.

6.E.1 Dosimetric characterization of patient support, immobilization and ancillary imaging equipment

A variety of immobilization and accessory devices are used to ensure positional repeatability during treatment, these devices must be correctly represented in the TPS for safe adaptive workflows. The working group recommends that transmission measurements of patient support hardware including the table and immobilization devices should be checked as part of the acceptance and commissioning process [53].

Hu et al [20] provides useful recommendations when considering such devices. For the MRIdian system this includes a fibreglass couch top which is moveable and the indexing and lateral placement of patients on top may impact dose both at the surface and at depths. For the Elekta Unity this includes the high-density couch support struts, it is recommended by the vendor to avoid treating through, however there is no interlock to prevent this occurring offline or online in the dedicated TPS.

The working group recommends that the receiver coils radiation beam transmission should also be verified at the time of commissioning for each coil available. Liney and Raaijmakers

foresaw and evidenced the effect of RF receiver coil impacting dosimetry respectively [54] [55], [56]. Powers et al [44] points out that no work to date had 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) is applied in the TPS. The authors of this paper recognise the early work by Hoogcarspel et al. [57] which showed a decrease in dose of up to 2.2% as a result of the coil, suggesting that modelling of the dosimetric impact of the coil must be considered in planning.

At the time of this paper, Elekta provided a model in Monaco of the standard body coil to predict the dosimetric impact of the device. The position and orientation of these coils may not be guaranteed for all vendors. As such, extensive validation of the coil modelling should be performed with care taken to understanding the impact of height above patient surface, longitudinal positioning above the isocentre and any tilting that may occur fraction to fraction. The Powers investigation addressed this for the Elekta Unity coil, finding only a maximum difference of only 0.5% between measured and calculated (in Monaco) attenuation across the lateral extent of the coil; however, the out of field dose due to ESE from the coil was found to be significant [58].

Radiation induced currents (RIC) may impact RF coils leading to image artefacts as detailed by [59, 60]. While Buckley et al [61], Hoogcarspel et al [57] and Burke et al [59] demonstrate methods for assessing the RIC using Fast Field Echo sequences and the ACR MRI accreditation phantom, as some of these artifacts may depend on the positioning, while others are static influences and may not vary with clinical use. The working group recommends understanding these influences which may lead to uncertainties during motion monitoring online.

6F. Ancillary imaging systems

The implementation of a robust QA program can rely on ancillary imaging systems provided with a platform [44]. The working group recommends the use of AAPM physics practice guideline 2b, for commissioning tests pursuant with desired outcomes [62].

6G. MRI-Linac considerations on MRI

There are several factors arising from the presence of an MR imaging system that can affect the accuracy of treatment planning, these need to be investigated and quantified for appropriate QA. The primary focus of MR performance for treatment planning is geometric fidelity. The Unity and MRIdian manage the fringe field in quite different ways: the Unity low-field toroid is designed to minimise the fringe field around sensitive components, and any potential beam

steering issues introduced from gantry or MV imager sag have been investigated to be within recommended tolerances provided in TG142 [41]. The MRIdian shielded ring contains large, unevenly distributed ferromagnetic components which are isolated from affecting the fringe field and static field homogeneity. Ginn et al. assessed the MRIdian and provides results to inform appropriate planning target volume (PTV) margins for 0.35 T MRI-guided radiotherapy [63].

6.G.1 Linac Gantry rotation and magnetic field homogeneity

The ring design employed by both commercial offerings allows for the potential modification of the fringe field of the imaging magnet as the linac rotates around the patient. This may cause rotation-dependent changes in the imaging field homogeneity, linac performance, and beam steering. For systems where the linac is fixed or where the magnet rotates with linac rotation, software active shimming can provide a viable solution to disturbances in the B_0 field homogeneity, however this requires active monitoring on the part of the physicist to ensure appropriate compensation is made for each image. As an indication of system performance, magnetic field drift tests in the initial 2 months of acceptance is recommended by TG 284 [23].

6.G.2 Image quality measures

Image quality of the MRI system in the MRI-Linac requires constant assessment. Image uniformity, signal-to-noise ratio and spatial resolution are usually assessed by vendor-provided phantoms during routine QA. It is also recommended to check the performance of individual coils and channels based on the vendor guidance, including monitoring of long-term stability [64]. Most MRI manufacturers provide semi-automated analysis phantoms and tools to meet NEMA standards.

The ACR MRI quality control tests are well established and widely adopted in diagnostic MRI. The same action levels and frequencies are recommended to be performed on the MR-Linac system for sequence specific assessment [25].

ACR recommended parameters to assess include:

- high contrast resolution,
- slice thickness accuracy,
- slice position accuracy,
- image intensity uniformity,
- signal ghosting,
- low contrast detectability, and
- signal-to-noise ratio.

RF coil placement over treatment areas significantly impacts image quality. It is crucial to understand the position and height of moveable RF coils above the patient, as signal degradation increases with distance. Image quality metrics should be assessed for all height variations, tilt, and longitudinal alignment over the intended target. Routine testing often assumes fixed height, position, and minimal tilt. Systematic investigation of these factors, such as assessing the impact of 2 cm shifts on image quality or the effect of key anatomy positioning near the central imaging plate, is recommended. Lee et al describes a method to assess the impact of coil tilt on image quality for reference [65].

6.G.3 Geometric Distortion assessment

No magnet is perfect, and the presence of a patient or phantom further disrupts the static field's homogeneity. Precession frequency determines spatial encoding and is directly related to local field strength. System-level geometric distortions in MRI result from static magnetic field inhomogeneity, gradient magnetic field nonlinearity, and patient-level chemical shifts and susceptibility distributions. System-level distortion increases with radial distance from the MRI isocentre, while susceptibility distortion increases with magnetic field strength at interfaces [67]. When commissioning the MRI-Linac system, both static magnetic field inhomogeneity and gradient nonlinearity should be assessed individually and baselined by medical physicists. They should also be checked during set frequencies and particularly following gradient calibration and services. This measurement can be done using reverse readout of gradient polarity technique, or by isolating the gradient nonlinearity distortion from B_0 homogeneity [23].

In addition, increasing gradient strength (i.e., increasing readout frequency bandwidth) can reduce susceptibility distortion and chemical shift effects. As recommended by AAPM TG284 [23], the 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. Walker et al. [66] propose a vendor neutral method for MRIGRT geometry distortion assessment. This allows physicists to assess any distortion that may be present on MRI sequences between MRI simulation and an MRI-Linac which could impinge on the effectiveness of the simulation process. Ensure geometric fidelity testing is appropriate and meets the tolerances used in treatments with off-axis targets or small organs.

Additional, sequence-dependent distortion is caused by induced eddy-currents resulting from rapid switching of gradients and gradient nonlinearities, which increase with distance from

isocentre. Non-homogeneity and gradient nonlinearity can be measured and are, to some extent, compensated for by shimming, gradient compensation, and software correction. These compensations, whilst usually sufficient in diagnostic radiology may give residual distortions that could severely impact the accuracy of RT [67].

6.G.4 Sequence Assessment

Since MRI images of the MR-Linac systems are the primary images for the adapted treatment of the patient, it is highly recommended that all MRI sequences in the MR-Linac system be evaluated for image quality and geometric distortion to provide better estimation for dosimetric uncertainty resulting from the MRI system. Also, the orientation of MRI images for the sequences transferred to the TPS must be checked during the commissioning process using a phantom with directional differences to confirm correct orientation is retained [25].

6.G.5 MRI to MV isocentre

Similar to all modern linear accelerators with onboard imaging system, MRI-Linac systems require characterization and minimisation of the offset between imaging isocentre and radiation isocentre. Each MRL vendor provides dedicated phantoms and processes for the MR-to-MV isocentre check. Baseline MR-to-MV isocentre information is acquired during commissioning and is frequently checked as part of the routine QA process [3].

6.G.7 Diffusion weighted and quantitative imaging

Monitoring tumour response during a course of treatment and adaptively modifying the treatment plan based on tumour biological feedback may represent a new paradigm for radiotherapy [68]. Different parameters like longitudinal relaxation rate (T1), transverse relaxation rate (T2), diffusion-weighted imaging (DWI) and apparent diffusion coefficient (ADC) have the potential to provide clinical findings. Since the accuracy of the results for both quantitative measures and ADC values can vary based on the magnet model, sequence implementation and magnet characterization, [69, 70] it is recommended to baseline and QA with recommended phantoms and sequences to isolate the system variation from patient response. Furthermore, as the design of each of the currently available systems differs from that of typical diagnostic systems, such as the split gradients in the 1.5T system and the low field of the 0.35 T system, recommendations exist for DWI scanning parameters such as b-values for both systems [71]. There are several studies on developing quality assurance process

for the quantitative measures on clinically available MR-Linacs [5, 68], QA of the technical performance of MRI for quantitative imaging is recommended to ensure metrics and factors affecting results are due to a physiological response and not measurement variability [72].

6H. MRI-Linac WG position on Treatment Planning System

6.H.1 Modelling ancillary components

For precise dosimetry during MRI-Linac commissioning, it's essential to characterize the ancillary components dosimetrically [44]. Initial modelling helps establish clear planning guidelines. Components like moveable imaging coils, headphones, and cabling that may influence radiation exposure are already well modelled, as highlighted by Powers[44, 58].

MRI-Linac systems pose unique challenge in imaging immobilization and support systems [30]. These include fibreglass or carbon fibre couches, bolus, compression belts, breast boards, head and neck masks, foam pillows, and vacuum bags. There are difficulties in positioning these support systems consistently for each fraction, as well as MRIs cannot show these components. To circumvent this, some centres have adopted custom virtual models in their TPS [73] or implemented MRI-visible marking systems for daily delineation. Considering their dosimetric influences, alternative modelling methodologies, such as CTs or virtual CTs, are pivotal. Physicists must be adept at understanding the implications of these systems across diverse clinical sequences.

6.H.2 Less familiar sources of radiation and accounting for them in the TPS

The imaging magnet alters dose distribution in the patient and ancillary support devices, potentially reducing dose delivered to the treatment volume or increasing dose to non-target organs [74]. Readers are referred to [75, 76] and the MRWG Dosimetry paper [52] for more information. The working group recommends testing the ability of a TPS to account for electron return effect and electron streaming effect. It is important to manage these influences carefully in the beam modelling and to understand them thoroughly for routine clinical planning [74]. Hall et al demonstrates both effects in the same clinical setting using perpendicular MRI-Linacs [77].

6I. End to End commissioning

Commercial vendors have provided several devices for end-to-end verification of online adaptive therapy workflows, these are detailed in Table 4. Quasi-3D detectors like the Sun Nuclear ArcCheck (Sun Nuclear Inc, Melbourne, FL, USA) or PTW Ruby (PTW, Freiburg, Germany) can be used as an end-to-end validation tool, and the use of dynamic motion to test

adaptation workflows is also recommended [78]. Before making clinical decisions based on device measurements, users should verify the device's accuracy [79], especially since measurement systems can be affected by magnetic fields, as highlighted by Ellefson et al. [59].

When MR-conditional or MR-safe commercial equipment isn't available, using in-house, non-commercial solutions is recommended [80, 81]. Without a quasi-3D device, Powers et al. detail an end-to-end commissioning process for IMRT treatment on the Unity system using a PTW 1500MR 2D array, Gafchromic EBT3/EBT-XD film, and the EPID. They assessed individual beam segments and analysed composite deliveries using film or detector arrays. For end-to-end tests, they used a water phantom with 3D-printed elements mimicking different target sizes [44].

True 3D dosimetry is possible with radiochromic polymer gel, providing solutions for machine QA and end-to-end verification [82, 83]; the use of gel dosimetry for 4-D verification of accumulated dose using gel dosimetry is similarly feasible [84, 85]. The advent of modular phantoms for end-to-end verification of treatment systems is well-documented, however the inclusion of gel dosimetry looks to be a promising validation tool for end-to-end [86] and routine QA [87] with interesting results.

6.I.1 Motion management assessment

Intrafraction motion from respiratory, musculoskeletal, cardiac and gastrointestinal systems is a known issue in modern radiotherapy and there are different imaging techniques and processes recommended in guidelines and publications [88, 89]. It is recommended to use a motion phantom with a known waveform, frequency and amplitude for testing the motion managed imaging, Cine imaging, 4DMRI process and identify and characterize the system limitations [23]. Some vendors already provide the necessary respiratory gated and breath-hold treatment workflows to process tumour tracking. We also anticipate ECG gated workflows which are currently in their development phase and will be available in future.

6J. System audit

The MRI-Linac QA working group recognise the added benefit of independent end-to-end validation for treatment processes. Especially in emerging technologies, where no formal auditing organisation offers end-to-end evaluation with the treatment processes available in your clinic we suggest working with nearby or established MIRL clinics to provide onsite

independent measurement-based testing. Audit programs by ARPANSA and IROC are also in development to ensure future recourse for level 1B and level III audits.

7. Recommendations on QA Devices and their requirements

7.1 Influences of MR on dosimetry tools

While it is not the purpose of this paper to discuss all aspects of dosimeter performance which may be affected by the presence of a low or high strength magnet [75, 90-92], physicists should familiarise themselves with the necessary corrections and considerations that should be made before using each detector with an MRI-Linac. Hu et. al. provides four for consideration when evaluating QA equipment for the MR environment: 1) projectile hazard effect due to ferromagnetic components, 2) electronic components that can be damaged by the magnet or interfered by the time-varying RF and gradient fields, 3) the impact on the measurement accuracy by the magnet and 4) image artifacts and distortion caused by the device [30]. Roberts et al provide guidelines for testing methods and detector limitations with perpendicular 1.5 T MRI-Linac [3].

Table 4 lists QA devices used by consortium members for all kinds of QA. The working group recommend users only use equipment that vendors establish as MR safe and are labelled properly as defined by ASTM requirements [93].

7.2 MRI conditional equipment

The presence of a magnetic field requires the use of MR conditional equipment to perform commissioning and quality assurance. Each site will have a unique assortment of QA equipment types and models, including devices verified as MR Conditional by the supplier, devices manufactured locally, and some unknown or legacy. In all cases, the safety of devices should be assessed according to the criteria in published guidance by the ACPSEM MR-Linac Safety Guidance [24]. It is recommended that an equipment register is established to record MR Safety status and functionality checks.

7.3 Validation of software

In their article [94] Salomons et al recommend medical physicists in radiation oncology apply strict quality control to their patient pathway software. Although vendors are careful to communicate major changes to software and describe which bugs have been resolved, these changes can (and do) have an impact on overall performance. We recommend keeping strict records of the software versions used and reporting on them, as well as maintaining strong

communication with vendors about software updates. Additionally, and more importantly, having test environments where a pre-clinical release is tested and vetted assures a smooth transition between updates to software.

Table 3 - 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	Ashland, EBT3, XD	Absolute dose measurements Relative dose measurements Beam data collection MLC/Jaw calibration
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 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 Elekta/Varian end to end phantoms including: • Gel • Inhouse designed phantoms • CIRS IMRT THORAX	Patient specific QA Beam model validation Gating
Software	AQUA	Isocentre

	RIT PyLinac MU2Net RadCalc ClearCalc/ClearCheck Inhouse software Vendor Supplied software	MLC/jaw calibration Secondary dose check Data transfer validation
Others	MV alignment phantom LasVegas phantom Solid water Setup jigs MR safe Thermometer MR safe Rulers CT/MR compatible markers	MV isocentre MV images quality Absolute and relative dosimetry

8. Working group position on Periodic QA

8.1 Routine QA

Routine QA is designed to be a subset of commissioning tests that aim to verify any actionable differences when comparing results to baseline [26]. The site physicist is challenged to ensure comprehensive testing without redundancy, critical performance tests and their tolerances must be relevant to clinical patterns and are likely to evolve as the MRI-linac platform continues to mature. By implementing resources such as TG 100, the physicist can ensure a robust QA program is established [95]. In Table 5-8, tests are grouped by class with recommendations for optional execution. The certified Radiation Medical Oncology Physics Specialist (ROMP) is responsible for implementing the appropriate tests.

Users are encouraged to use a testing cadence that builds confidence in the performance of the system. The experimental techniques for the recommended QA tests will not be described at length, where published work is recommended, the reader is encouraged to pursue a comprehensive understanding of required workflows.

The importance of QA of adaptive workflows cannot be emphasised enough, Chen et al [96] provide a comprehensive end-to-end for daily QA. This workflow ensures that performance checks and communication are verified on the Unity system.

671 Table 5. Daily quality assurance with suggested optional tests

Category	Procedure	Tolerance	Optional	Reference
Dosimetry	X-ray output constancy (all energies)	3%		AAPM TG-142 [26] / TG-198
Mechanical	MLC performance	Visual inspection of picket fence.		
Mechanical	Laser alignment	2mm		
Safety	Door Interlock	Functional		
Safety	Warning lights	Functional		
Safety	MRI regional specific safety checks • Low oxygen sensor • Compressor chirp • Ferromagnetic detectors	Functional		AAPM TG-284 [23]
Safety	• Patient duress alarm • AV system • Coils and patient accessories • MRI-Linac emergency trolley check	Functional		
Imaging	**EPID** Image quality - a SNR type test, especially if using EPID based PSQA or EPID for MLC tests **MRI – National Electrical Manufacturers' Association (NEMA) standards** Signal to noise Scaling Transverse and coronal Uniformity Spatial linearity Slice Profile Spatial Resolution Central Frequency		 ** ** ** ** **	AAPM TG-284 [23], ACR MRI QA [40, 97]
End to end	Routine patient for daily QA testing DICOM functionality and communication Adaptive online QA – Secondary MU check Testing workflow for scan, plan, transfer, QA and treat	Local tolerances in dedicated phantom		Chen et al. (Unity) [96]

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674 Table 6. Weekly quality assurance with suggested optional tests

Category	Procedure	Tolerance	Optional	Reference
Dosimetry	Beam quality (TPR 20,10) with gantry angle Backup monitor chamber constancy Photon beam profile MLC	±1% (TG-142) ±2% ±1% from baseline Visual inspection of picket fence	** ** ** **	[44] [98]
Imaging	MR to MV PIQT Geometric Distortion	Translations ±0.5 mm to baseline Rotations between the MR and MV coordinate systems: maximum rotation for each axis: ± 0.3 degrees Mean of the absolute value of the rotations about each axis: <=0.2 degrees	** ** **	Roberts et al. [1]

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676 Table 7. Monthly quality assurance with suggested optional tests.

Category	Procedure	Tolerance	Optional	Reference
Dosimetry	Output constancy	2%		AAPM TG-142 [26] TG 198
	Backup monitor chamber constancy	2%		
	Photon beam profile and energy measurement			
Mechanical	Setting vs radiation field for two patterns (non-IMRT)	2 mm		
Mechanical	Couch position accuracy	IMRT 2 mm SBRT/SRS 1 mm		
	Gantry angle accuracy and reproducibility	±1°		
	Picket fence/MLC position accuracy or leaf position accuracy	Visual observation of picket fence or 1 mm for IMRT		[26]

		field at 4 gantry angles		
	Radiation iso centre size WL	± 1 mm		[98]
Mechanical	Localization lasers	1mm		
Safety	Warning lights, interrupts and interlocks Safety inspection of console, magnet and equipment room Compressor chip Ferromagnetic detectors AV system MRI bore fan RF door Low oxygen sensor Helium level Receiver coil and accessories check Emergency power off switch	Functional		AAPM TG-284 [23]
Imaging	**MRI**			AAPM TG-284 [23], ACR MRI QA [40, 97]
	High contrast spatial resolution	≤ 1 mm		
	Low contrast detectability	Total number discernible spokes (for four slices) for fields < 3 T: 21 (0.3 T) to 36 (1.5 T), 40 for 3 T		
	RF coil testing	Functional		
	Large field of view 3D geometric distortion	Verify ≤ 2mm across 25 cm FOV		
	Percent image uniformity	Head coil: ≥ 87.5% for < 3 T		
	Signal to noise	Scan and B0 dependent		
	Spatial linearity	0.5%		
	Slice thickness accuracy	± 1.0 mm		
	Static field verification - Transverse B0 & B1 maps	ctr freq. < ± <1ppm/day during acceptance,		

		<0.25ppm/day for first 1-2 months operation		
	Central frequency drift	Manufacturer specified		
	MR and MV coincidence/isocentre shifts	Translations: 1 mm to baseline		
	Scaling Transverse and coronal	Within 1 mm		
	Transmitter gain stability	± 5% from baseline		
	Cryostat check (Helium level check)	Against baseline		
	Table check	± 1 mm from isocentre		
	Hardware check	Functional and without damage		
	MV			
	Positioning/repositioning	≤ 1 mm		
	Low contrast visibility – Las Vegas phantom	Baseline		
	Image quality – uniformity, artifact check (MV)	Baseline		
End to End	**End to End** TPS QA, routine patient for Annual QA Second check MU software audit	Baseline		Chen et al. (Unity) [96]

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678 Table 8. Yearly quality assurance with suggested optional tests

Category	Procedure	Tolerance	Optional	Reference
Dosimetry	Output constancy	1%		AAPM TG-142 [26] TG 198
	Backup monitor chamber constancy	2%		
	X-ray profile symmetry comparison from baseline	1%		
	Spot check of field size dependent output factors	2% for < 4x4cm^2 1% for ≥ 4x4cm^2		
	X-ray beam quality	1%		
	X-ray MU linearity (output constancy)	5% (2-4MU), 2% ≥ 5MU		
	X-ray output constancy vs dose rate	2%		
	X-ray output constancy vs gantry angle	1%		
Mechanical	Couch maximum travel range	1 mm		

	Couch position accuracy	IMRT 2 mm SBRT/SRS 1 mm		
	Gantry angle accuracy and reproducibility	±1°		
	Picket fence/MLC position accuracy or leaf position accuracy	Visual observation of picket fence or 1 mm for IMRT field at 4 gantry angles		[26]
	Radiation iso centre size WL	± 1 mm		[98]
	MLC Transmission	Verified against baseline		
	Localization lasers	1mm		
Safety	Review of MRI Safety Program Warning lights, interrupts and interlocks Safety inspection of console, magnet and equipment room Compressor chip Ferromagnetic detectors AV system MRI bore fan RF door Low oxygen sensor Helium level Receiver coil and accessories check Fixation device check Emergency power off switch	Comprehensive Functional		AAPM TG-284 [23]
Imaging	**MRI**			AAPM TG-284 [23], ACR MRI QA [40, 97]
	Review of imaging sequences			
	High contrast spatial resolution	≤ 1 mm		
	Low contrast detectability	Total number discernible spokes (for four slices) for fields < 3 T: 21		

		(0.3 T) to 36 (1.5 T), 40 for 3 T		
	RF coil testing	Functional		
	Large field of view 3D geometric distortion	Verify ≤ 2mm across 25 cm FOV		
	Percent image uniformity	Head coil: ≥ 87.5% for < 3 T		
	Signal to noise	Scan and B0 dependent		
	Spatial linearity	0.5%		
	Slice thickness accuracy	± 1.0 mm		
	Static field verification - Transverse B0 & B1 maps	ctr freq. < ± <1ppm/day during acceptance, <0.25ppm/day for first 1-2 months operation		
	Central frequency drift	Manufacturer specified		
	MR and MV coincidence/isocentre shifts	Translations: 1 mm to baseline		
	Scaling Transverse and coronal	Within 1 mm		
	Transmitter gain stability	± 5% from baseline		
	Cryostat check (Helium level check)	Against baseline		
	Table check	± 1 mm from isocentre		
	Hardware check	Functional and without damage		
	MV			
	Positioning/repositioning	≤ 1 mm		
	Low contrast visibility – Las Vegas phantom	Baseline		
	Image quality – uniformity, artifact check (MV)	Baseline		
End to End	**End to End** TPS QA, routine patient for Annual QA Second check MU software audit	Baseline		Chen et al. (Unity) [96]

679

9. Future developments and challenges in MRI-Linac Technology

Adaptive radiotherapy strategies in the light of new technologies poses a challenge to the workforce. As detailed by Hogan et. al., training and credentialing requirements underpin the safe and efficient delivery of treatment on the MRI-Linac [99]. As this technology continues to evolve and mature, time to treat will invariably shorten. The use of automation and artificial intelligence in plan preparation presents a viable option towards workflow optimization as detailed by Künzel et al [100] and Spieler et al. [101].

There are several developments underway to the MRI-Linac platforms, including advanced gated delivery [102], improved treatment workflow optimization, and helical delivery [103]. The working group concedes that as clinical platforms develop, pertinent considerations for acceptance and commissioning specific to each commercial offering will evolve.

10. Summary

The MRI-Linac QA working group make the following summarised recommendations:

a. Execute an end-to-end system check whenever a new or updated procedure is introduced.
b. Include patient stabilization and support device transmission as a part of the commissioning process.
c. Adaptive radiotherapy workflows require specifically designed QA protocols to ensure a comprehensive assessment is made.
d. Collaborative commissioning is encouraged, including all relevant craft groups to ensure a complete capture of the clinical workflow is assessed comprehensively.

11. Acknowledgments

The quality assurance working group would like to express their sincere gratitude for the time and effort in reviewing this position paper. All the insightful comments and suggestions were invaluable in helping us refine and improve this resource. We would like to thank external reviewers [ADD EXTERNAL REVIEWERS], Katrina Biggerstaff for their thorough and thoughtful review. We appreciate the dedication and expertise that the MRI-Linac Working Group have brought, and we are grateful for the opportunity to collaborate with such a knowledgeable and committed team.

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