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Original Article

An ESTRO-ACROP guideline on quality assurance and medical physics commissioning of online MRI guided radiotherapy systems based on a consensus expert opinion

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ABSTRACT

Objective: The goal of this consensus expert opinion was to define quality assurance (QA) tests for online magnetic resonance image (MRI) guided radiotherapy (oMRgRT) systems and to define the important medical physics aspects for installation and commissioning of an oMRgRT system.

Materials and Methods: Ten medical physicists and two radiation oncologists experienced in oMRgRT participated in the survey. In the first round of the consensus expert opinion, ideas on QA and commissioning were collected. Only tests and aspects different from commissioning of a CT guided radiotherapy (RT) system were considered. In the following two rounds all twelve participants voted on the importance of the QA tests, their recommended frequency and their suitability for the two oMRgRT systems approved for clinical use as well as on the importance of the aspects to consider during medical physics commissioning.

Results: Twenty-four QA tests were identified which are potentially important during commissioning and routine QA on oMRgRT systems compared to online CT guided RT systems. An additional eleven tasks and aspects related to construction, workflow development and training were collected. Consensus was found for most tests on their importance, their recommended frequency and their suitability for the two approved systems. In addition, eight aspects mostly related to the definition of workflows were also found to be important during commissioning.

Conclusions: A program for QA and commissioning of oMRgRT systems was developed to support medical physicists to prepare for safe handling of such systems.

Online magnetic resonance image (MRI) guided radiotherapy (oMRgRT) is a novel treatment approach that has gained attention in the last years with the availability of two MRI Linear accelerator (MR Linac) systems approved for clinical use. The Unity system (Elekta AB, Stockholm, Sweden) combines a 7 MV flattening filter-free (FFF) linear accelerator with a 1.5 T magnet. The MRIdian system (ViewRay Inc, Mountain View, California USA) uses a 0.35 T magnet and a 6 MV FFF accelerator. For both systems, the magnetic field is oriented along the cranial-caudal patient axis perpendicular to the radiation beam. Researchers have developed two other proof-of-concept MR Linacs, but they are currently not in clinical use.

The main advantages of oMRgRT systems are better soft tissue visualization and assessment of intra-fractional motion. In combination with fast Software solutions this creates the possibility to perform on-table adaptive radiotherapy and advanced motion management such as gating.

There are several guidelines on quality assurance (QA) and commissioning of computed tomography (CT) guided radiotherapy systems [1–3] and of MR scanners used for diagnostics as well as in

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radiotherapy treatment planning [4–8]. However currently there are no cross-platform guidelines on commissioning and quality assurance for oMRgRT systems. Recently Roberts et al published a comprehensive overview on quality assurance on the Unity system [9] and Corradini et al summarized the clinical implementation of MR Linac systems in radiation oncology [10]. The goal of this consensus expert opinion was to define QA tests during commissioning and routine QA for an oMRgRT system and to define the important medical physics aspects for installation and commissioning of an oMRgRT system. This recommendation is meant as an addition to existing guidelines focusing on linear accelerators, stereotactic treatments and MR scanners.

Materials and methods

Ten medical physicists and two radiation oncologists experienced in oMRgRT participated in the consensus expert opinion consisting of three rounds. Participants were chosen based on their experience with one of the two commercial oMRgRT systems, taking into account that the expert opinion is not biased towards one of the two commercial systems. In the first round of the consensus finding process, a broad spectrum of tasks, insights and aspects on quality assurance and commissioning for oMRgRT systems were collected with an online form. The participants could state there in free text 1) which QA procedure they consider to be important during commissioning and for QA and 2) the important medical physics aspects during commissioning and installation. Only tests and aspects different from commissioning of a CT guided radiotherapy (RT) system were collected. There are many aspects of safety and radiation beam functionality that are in principle the same between oMRgRT and conventional Linacs, therefore we refer for these tests to established recommendations on quality assurance, that should be followed alongside with this recommendation [11]. Additionally patient-specific QA and QA of the adaptive process were not included. Everything was summarized by one additional physicist and a feedback was sent to all participants. In the next round all twelve participants voted on the importance of the QA tests, their recommended frequency and their suitability for the two systems approved for clinical use. Additionally, they voted on the importance of collected tasks and aspects during physics commissioning. If more than 66 % of the participants voted for a specific answer, this was considered as an agreement. The results were sent to all participants and discussed and clarified in a joint meeting. Afterwards there was a third round of voting on all questions for which no consensus had been found during the second round. Again, if more than 66 % of the participants voted for a specific answer, this was considered as an agreement. Agreement and disagreement were summarized and no further voting was done. Each participant only voted on the questions she/he was confident to answer.

Results

The first round identified 24 QA tests that are potentially important during commissioning and routine quality assurance on.

oMRgRT systems compared to CT guided RT systems. Additionally, eleven tasks and aspects related to construction, workflow development and training were categorized as potentially important during commissioning. QA tests comprised four tests related to the linear accelerator performance, nine tests for status of the MR scanner, seven tests for checking the interplay between scanner and linear accelerator and four other tests. During the next two rounds, we found consensus for most tests on their importance, their recommended frequency and their suitability for the two approved systems (compare Table 1). Out of the eleven aspects (compare Table 2) which were initially identified as potentially important during commissioning, a consensus was found on the importance of eight of them, most (six) of them were related to the definition of workflows. For only one of them (a workflow step to check the electron densities) there was an agreement that the physicist should be responsible for this task. For other aspects such as safety training and risk analysis there was an agreement that it has to be done.

Building and construction of the vault

Although vault designs and radiation protection calculations are the same as for CT guided RT systems, and recommendations such as NCRP-151 [12] apply for both clinical available oMRgRT systems, the Faraday cage design needs to be considered additionally. The linear accelerator on the Unity system is positioned outside the cage to cope with radiofrequency interference of the linac and MRI acquisition system [13,14]. Conversely, the MRIdian linear accelerator is placed within the cage and high frequency (HF) emitting components are located inside six isolated buckets symmetrically located on the ring gantry [15].

Two aspects regarding construction of the vault were identified during the first round of the consensus finding process: installation of metal detectors, and safe installation of the quench pipe.

A magnetic field can be dangerous to people and harmful to equipment. The magnetic field stemming from the magnet exerts an attractive force on ferromagnetic objects. There was no agreement if a metal detector installed at the vault entrance or in close proximity to screen staff and patients for ferromagnetic objects is needed. These devices should therefore be seen as an additional safety net and complement well established safety procedures adapted from radiology departments. Both oMRgRT systems use Helium for cooling of the superconducting magnets and need a quench pipe for a safe release of Helium in case of a magnet quench. There was an agreement between all members of the committee that the safe installation of the quench pipe must be addressed during vault construction, but there was no agreement on who is responsible for this task.

Linac QA

It is important to note that the radiation beam functionality of oMRgRT systems is in principle the same as of conventional linacs. Even some beam generating and beam shaping components such as jaws are newly designed and might need to be monitored initially more carefully. Hence standard commissioning and QA checks should be performed following international recommendations [1–3]. Since QA for conventional linear accelerators is well established, only MR Linac specific areas are covered here. In dosimetry, these are due to the additional presence of the magnetic field in the bore.

Three QA checks and two aspects regarding Linac QA and dosimetry were identified during the first round of the consensus finding process. Evaluation of dosimetric effects of air gaps and magnetic correction factors were aspects to be considered and suggested QA checks were: water phantom measurements at 0 T, table transmission and transmission through bridge and coils.

An evaluation of the dosimetric effect of air gaps around detectors for phantom measurements (Table 2) was considered as important (44 %) or important for early adopters (33 %). If solid phantoms are used, air gaps around the detector must be avoided, for instance by filling with water or gel. Even for low field strength small air gaps could change measured output by 1–2 % [16,17]. Air bubbles adjacent to detectors should also be avoided when making measurements in water phantoms. There was an agreement that detector specific magnetic correction factors are required for abso-

Table 1
Recommended QA tests during commissioning and routine MR Linac QA including recommended frequencies. Whenever no agreement (agreement was defined as > 66 %) in the consensus expert opinion was achieved, the most frequently stated answers are noted and in () the percentage of participants voting for this specific answer.

Category	QA Test	Important during commissioning?	Important for Routine QA?	Recommended Frequency	Specific to?
Linac	Water phantom measurements at 0 T	Not important (55.6 %), good to look at if time allows (22.2 %)	no	NA	all systems
Linac	Table transmission	must be done	no	NA	all systems
Linac	Bridge and coil transmission	must be done	no	NA	all systems
MR scanner	B0-field homogeneity	must be done	yes	monthly (44.4 %), weekly (44.4 %)	all systems
MR scanner	Cage and RF interference	must be done	yes	annually	all systems
MR scanner	Slice position and slice thickness accuracy	must be done	yes	monthly	all systems
MR scanner	Image contrast (high contrast resolution, low contrast and low contrast detectability)	must be done	yes	monthly	all systems
MR scanner	Uniformity and SNR for the body coil (bore)	must be done	yes	monthly	all systems
MR scanner	Uniformity and SNR for all clinically used coils	must be done	yes	monthly	all systems
MR scanner	MR spatial integrity	must be done	yes	monthly	all systems
MR scanner	MR spatial integrity in 2D fluoroscopy	must be done	yes	quarterly	all systems
MR scanner	MR artefacts, such as ghosting	must be done	yes	quarterly (44.4 %), annually (33.3 %)	all systems
Interaction	Alignment MR isocenter to beam isocenter	must be done	yes	monthly (44.4 %), weekly (44.4 %)	all systems
Interaction	Dependence of the MR isocenter on movable parts in particular as a function of the gantry angle	must be done	yes	annually (44.4 %), quarterly (33.3 %)	all systems
Interaction	MR distortion dependent on gantry angle	must be done	yes	annually	all systems
Interaction	Cryostat attenuation and inhomogeneity	must be done	yes (55.6 %), no (44.4 %)	annually (55.5 %)	ELEKTA system
Interaction	Gantry angle dependent relative dosimetry	must be done	yes	annually	all systems
Interaction	Full end-to-end testing static targets, non-adaptive	must be done	yes	annually (44.4 %), quarterly (22.2 %)	all systems
Interaction	Full end-to-end testing including motion management	must be done	yes	annually	all systems
Interaction	Full end-to-end testing including adaptive re-planning	must be done	yes	(monthly 55.6 %, annually 22.2 %)	all systems
Others	Check of Helium level (if not checked automatically)	must be done	yes	daily (44.4 %), weekly (22.2 %), monthly (22.2 %)	all systems
Others	MRI safety (interlocks, signaling devices, patient monitoring systems)	must be done	yes	daily (55.6 %), monthly (22.2 %)	all systems
Others	Alignment of all isocenters (laser, MV panel, beam, MRI)	must be done	yes	monthly	all systems
Others	Effect of the magnetic field on the symmetry of the linacs in the vault next to the MR Linac (measured during ramp-up of the magnets)	must be done	no	NA	all systems

Table 2
Important aspects during commissioning. Whenever no agreement in the consensus expert opinion was achieved, the most frequently stated answers are noted and in () the percentage of participants voting for this specific answer.

Category	Important aspects during commissioning	Important?	Responsible staff group	Valid for
Building and construction	Installation of metal detectors	Not important (36.4 %), good to look at if time allows (37.3 %), important for early adopters (18.2 %)		all systems
Building and construction	Safe installation of the quench pipe	Very important has to be addressed	Required, but not specifically physics	all systems
Linac	Magnetic correction factors for different detectors	Very important has to be addressed	Physics (55.6 %), Required, but not specifically physics (11.1 %)	all systems
Linac	Evaluation of the dosimetric effect of airgaps around detectors for phantom measurements	Very important has to be addressed (44.4 %), important for early adopters (33.3 %)		all systems
MR Scanner	Acoustic noise level of scanner	Very important has to be addressed (36.4 %), good to look at if time allows (45.5 %)		all systems
Workflow	Adapt workflows to the fact that airborne electrons and electron streaming is present	Very important has to be addressed	Physics (55.6 %), Required, but not specifically physics (22.2 %)	all systems
Workflow	Teaching of emergency procedures	Very important has to be addressed	Required, but not specifically physics	all systems
Workflow	Screening protocols to declare measurement devices and patient positioning devices as MR safe for example using handheld metal detectors	Very important has to be addressed	Required, but not specifically physics	all systems
Workflow	Workflow for checking the electron density during adaptions	Very important has to be addressed	Physics	all systems
Workflow	Plan acceptance criteria during online adaptive workflow	Very important has to be addressed	Physics (45.5 %), Required, but not specifically physics (55.5 %)	all systems
Workflow	Risk analysis	Very important has to be addressed	Physics (27.3 %), Required, but not specifically physics (63.6 %)	all systems

lute dosimetry within magnetic fields (Table 2). The literature should be consulted to find the correction factors for the specific magnetic field strength and chamber combination [18–24]. It must be kept in mind that these factors vary with detector orientation with respect to the incident beam and the magnetic field vector.

At present, the MRIdian system comes with a complete beam model from the company. For the Unity system, the company collects the beam data together with the institution and beam modelling is done by Elekta. Nevertheless, the accuracy of these models should be carefully checked by the user. Three tests were suggested in the consensus finding process to complement recommendations on commissioning and QA of CT guided linear accelerators [25]. There was an agreement that transmission through components such as table, bridges and coils has to be checked during commissioning but that there is no need for regular QA of this (Table 1). Due to their design, MR Linac beams have to pass through (sometimes highly) attenuating components, which therefore have to be modelled carefully within the planning system. There was no consensus on the importance of water phantom measurements at 0 T. One major reason for this might be that this is often not even possible because the magnets are installed before the linear accelerator is installed and an easy and inexpensive switching off the magnetic field is not possible. However if there is a possibility of such measurements it allows for a better characterization of the effect of the magnetic field.

On board MR scanner QA

Some requirements for MR image quality are different in radiology and radiotherapy. The most prominent example is spatial integrity, which is critical in radiotherapy, whereas in radiology higher SNR and resolution is a preferred trade-off. Furthermore, in radiotherapy, QA frequency and tolerance levels for MR simulators may be less demanding compared to on-board MR scanners. This section describes minimum MRI QA and test frequency recommendations, specific for on-board MR scanners. General MRI QA recommendations can be found in other more extensive reports, for example, AAPM report 100 or AAPM report 284 [7,8].

In total nine tests were identified potentially important for QA of the on-board MR scanner during the consensus finding process and one aspect specific to the MR scanner.

During oMRgRT treatments, the MR image is the primary image for patient alignment, plan adaptation and safe delivery. Incorrect spatial information can lead to uncertainties in the estimation of shape and positions of the therapy volumes. The importance of evaluating the geometric fidelity in a large field of view has been highlighted in many studies [26,27] and there was a strong agreement in the consensus finding process that it should be checked during commissioning and at least monthly thereafter. Additionally there was a consensus on that if 2D MR fluoroscopy imaging is used, spatial integrity should be checked at monthly basis.

Main tests to assess spatial integrity include B0-field homogeneity and gradient non-linearity (GNL). Vendor-provided 3D phantoms and analysis software is recommended for this test [7,9]. Third party solutions and in-house developed methods can be alternative options and used as independent tests [28]. Spatial integrity of all MRI sequences should be evaluated before use in the clinical workflow including cinematic imaging during treatment.

Another important MR test, recommended on a monthly basis, is the evaluation of the uniformity and the Signal to Noise ratio (SNR) of the body coil integrated in the bore and the surface coils.

Surface coils are stressed by daily use in the oMRgRT workflow. MR- Radiofrequency (RF) interference (from inside or outside of treatment room) can reduce SNR and image homogeneity, and as a reduction can therefore be noticed while performing those tests. A good starting point for implementing test protocols are the ones from the National Electrical Manufacturers Association (NEMA) standards [29,30]. A monthly frequency of checking the body coil as well as all clinically used coils was recommended.

It is recommended to test general MR image quality such as slice position and thickness accuracy, the high and low contrast resolution and the detectability of objects on low contrast images [5,8] on a monthly basis. Vendor-provided QA methodology is recommended [9]. As an alternative the American College of Radiology (ACR) phantom can be used and analyzed with available open source analysis tools [31].

Image quality can also be influenced by the presence of artefacts, which has to be visually evaluated during commissioning and according to the consensus finding process quarterly or annually.

There was an agreement that during commissioning it needs to be checked that the cage shields the RF frequency of the MR scanner adequately. This should be monitored on a yearly frequency to find changes inside the RF cage.

There was no consensus on if the acoustic noise level of the scanner has to be checked and preventive measures need to be taken to avoid hearing damage of the patient and the personal.

MRI and Linac interaction

The linear accelerator and the magnetic field interact with each other. Therefore, additional tests are needed to evaluate the influence of this interaction.

Eight dedicated tests were identified in the first consensus finding round.

Consensus was reached amongst all experts that relative dosimetry measurements as a function of the gantry angle position should be carried out on a yearly basis because the magnetic field might influence the primary beam characteristics [32,33]. Consensus was also reached for assessing the level of MR distortion as a function of different gantry positions on a yearly basis [26,34]. Changes in gantry position may influence B0-/B1-field homogeneity, which are crucial for the geometric reliability of MR Linac systems. A majority (56 %) of the experts agreed on the fact that cryostat attenuation characteristics should be measured not only during MR Linac commissioning but also on a yearly basis for MR scanners, where the photon beam passes through this hardware component, which currently is only true for the 1.5 T Unity [14]. Agreement was also found on the need to regularly check the alignment between the MR isocenter and the treatment beam [26,32]. However, no consensus was reached about the frequency of carrying out this test. Furthermore, the positional variation of the MR isocenter depending on the movable parts of the MR Linac, especially the gantry, should be checked during commissioning and regularly during machine QA [7,26]. Also here, no consensus was found on the frequency. In order to guarantee high quality for the entire adaptive oMRgRT process in clinical use, meaningful end-to-end tests involving all steps from MRI acquisition until plan delivery are required [35–39]. Here, expert consensus was to carry out end-to-end tests for static targets and non-adaptive MRgRT as well as end-to-end test procedures including motion monitoring on an annually basis. However, for end-to-end testing of fully adaptive MRgRT including online adaptive re-planning, there was no agreement on the frequency of the test.

Other tests

When evaluating a possible location to install an oMRgRT system or a MR scanner in a radiotherapy department, the site planning guide of the manufacturer will set out the requirements with regards to different magnetic field components and vibrations. While those requirements are focusing on the new MR Linac, it is important to evaluate the impact of the fringe field on the surrounding installations. The studies by Kok et al. and by Perik et al. showed that fringe fields can have an impact on the beam steering of the accelerators in adjacent vaults [40,41]. Consensus was further found on the need to analyze the symmetry of conventional linacs located close to the MR Linac (<10 m) before and after ramp-up of the magnetic field. Even for MR Linacs which have a lower nominal magnetic flux density (e.g. the 0.35 T MRIdian), the fringe field is not necessarily smaller than for 1.5 T or 3 T MR scanners. Therefore, this check should be performed for all MR Linac systems currently available.

There was a strong agreement that the alignment of all isocenters (beam, MV imaging, MR imaging, lasers) should be checked during commissioning and at least monthly thereafter.

An important aspect to ensure patient safety is the check of the MRI safety components including the patient monitoring, alarm bell and communication system. There was no agreement if these devices should be checked daily (55.6 %) or monthly (22.2 %). A recent recommendation by Glide-Hurst et al for MR simulators recommends a daily frequency for this check [8].

MR Linac systems are equipped with a zero boil off magnet. The amount of helium within the cryostat will be approximately constant unless an incident occurs such as a quench or a failure of the cooling system. For the Unity system the radiation beam passes through the cryostat and the helium level has a minor gantry angle dependent impact on the transmission and should therefore be checked on a regular basis [9]. On the MRidian system the helium level is checked automatically. There was no agreement on the frequency this check should be done.

Clinical workflow development and training

Online adaptive MR-guided radiotherapy requires development of clinical workflows with a multidisciplinary team of RTTs, radiation oncologists and medical physicists. The workflows may differ between tumor sites, systems and institutes. In the first round of the consensus finding process we identified five important clinical workflows and one teaching aspect, which should be addressed during commissioning. For all of them there was strong consensus that they are important.

The magnetic field of a MR Linac can create dangerous situations that can seriously injure a person, damage the system or cause interference in the measuring equipment [4,5,42–44]. Therefore, screening protocols to ensure that devices are MR safe must be in place for clinical practice. Content information or certification should be requested from the manufacturer. In addition, conventional (handheld) metal detectors, strong static magnets or ferromagnetic detection systems can be used before labeling a device as MR safe [42] as recommended by organizations in the field of MR safety.

In order to minimize risks to patients, staff and equipment, structured procedures should be in place, including authority, responsibilities and contact information for MR safety screening, access, quench and evacuation of patients and staff [44]. All staff members working in the MRI environment (RTTs, radiation oncologists, medical physicists) should receive dedicated MRI safety training on a regular basis (usually annually). This is not limited to department personnel, but may also include other involved staff accessing the MRI environment (e.g. cleaning staff, emergency

response team, etc.). An important part of the MR safety training should be to teach the protocols for MRI emergencies (i.e. emergency preparedness plans including medical emergencies, MRI equipment emergencies, emergency shutdown "quench" procedures) [4]. In case of a medical emergency, the patient should be evacuated from the vault immediately to a designated location where basic life support can be applied while awaiting the arrival of medical emergency personnel. Emergency response training is advised on a regular (annual) basis.

A risk analysis to ensure patient safety before the clinical introduction of a new or modified treatment procedure is valuable. In some countries, a risk analysis prior to the implementation of new techniques is a regulatory requirement. With regard to MR Linac systems, the adaptive oMRgRT workflows bring new challenges and working procedures to the entire multidisciplinary team. Therefore, an institution-specific risk analysis is recommended (according to the expert consus) to define workflows and responsibilities, assess possible risks and elaborate mitigation strategies to enhance the quality and safety of oMRgRT. One possible method used for risk analysis is the process failure mode, effects and criticality analysis (P-FMECA) [45–47]. Recently, Klüter et al. reported their experience with the practical application of a P-FMECA risk analysis prior to the clinical introduction of adaptive oMRgRT [48]. Risk mitigation strategies support the generation of a standardized workflow, clearly defined protocols and the definition of checklists and standard operating procedures (SOPs) for the safe and effective implementation of MR guided adaptive radiotherapy.

Adaptive oMRgRT requires an up-to-date relative electron density (RED) map to be able to perform an accurate dose calculation. Current clinically implemented RED assignment methods rely on deformable image registration (DIR) of a baseline CT or on a combination of DIR and bulk RED assignment [15,49]. The reliance on DIR may lead to inaccuracies in dose calculation when large anatomical differences occur between the baseline CT and the daily MRI. This is particularly important in oMRgRT because the magnetic field can significantly perturb the dose calculation in the presence of tissue inhomogeneities. To avoid this, there was consensus that a workflow is neede for checking the newly generated RED map during the plan adaption process. This is usually done by the physicist or radiation technologist, who visually checks the RED map for errors or mismatch with respect to the MR primary image. In case of discrepancies, typically in rectal or bowel filling, a manual structure densities override can be performed before dose calculation and plan adaptation. There was a strong agreement that it is the task of the physicist to define the protocol for the generation of the RED.

During oMRgRT, interactions of secondary electrons within the magnetic field have to be considered. These interactions include the electron air stream effect (ESE) which can lead to out-of-field dose deposition and the electron return effect (ERE) which may result in increased dose to the skin and at air/tissue interface [50]. Especially for targets close to the skin such as breast, ERE can cause an increase in in-field dose to the skin and air-tissue interfaces, and also, due to the ESE, the out-of-field dose can increase, especially on the chin [51]. Both effects need to be correctly calculated and compensated for. ERE and ESE must be considered in the planning phase (e.g. imaging out-of-field areas such as the chin), during delineation (the skin is an organ at risk), during optimization of the plan and eventually a bolus has to be placed during treatment delivery [50–52].

Due to the time critical nature of oMRgRT, all tasks need to be performed swiftly in a safe and structured manner. For plan acceptance criteria during the online adaptive workflow, it is therefore helpful to implement clear target coverage and OAR dose constraint parameters to define whether a plan is acceptable for dose delivery (e.g., traffic light system) with different action levels for easy online decision making.

Discussion

The goal of this consensus expert opinion was to identify QA tests to be carried out during commissioning and routine QA of oMRgRT systems and to define the important medical physics aspects for installation and commissioning of an oMRgRT system. We focused only on tests complementing tests recommended for CT guided RT system and MR systems in international recommendations[1,8]. Tests for checking the linear accelerator, the MR scanner and the interaction of the two systems were identified. Additionally, we concluded on the aspects, which should be addressed during commissioning. However, for only one of them there was a consensus that this has to be done by the physics team, all others were rated important but not necessarily the task of a physicist. This is probably due to different roles of the physics team in different countries and departments. For example in small departments, the physics team is most likely responsible for the vault construction whereas larger hospitals have dedicated construction teams and engineers.

For most QA tests we found a consensus on the importance of the test, however for many tests we did not find a consensus on their frequency. This might be related to the treatments performed on the system but also to the differences in national guidelines for QA on conventional linear accelerators. Schmitt et al recently performed an extensive review on QA for stereotactic treatments and found significantly different frequencies between recommendations [53]. We evaluated if the different test frequency was related to the type of oMRgRT system but this was not the case. All members of this consensus expert opinion agreed that the stated frequencies of the QA tests are for experienced users of the system. It is highly recommended to start with a higher test frequency to get to know the system behavior and after successful implementation and observation of the stability of the system to reduce the frequency.

oMRgRT is an emerging field. As such there is little document evidence on required QA procedures and frequencies for oMRgRT to guarantee a save operation of the machine. Therefore this recommendation is based on expert opinions rather than a higher level of evidence approach. Each of the participants carefully balanced the expected benefit of the QA procedures against the increase in costs and staffing connected to it [54]. However no systematic review was done to make sure nothing was missed. It is important that the field reports on the long term stability of such kind of devices to generate the evidence for QA procedures and frequencies in the future. However for this data of several institutions over a longer period of time is needed.

The spatial accuracy is probably the most important parameter for radiotherapy, which has to be checked on a regular basis. Roberts et al recommend for the Unity system a daily quick check of the scaling and then a large distortion test on a monthly basis [9]. Here we recommend as minimum a monthly check of the large field of view spatial distortion.

Commissioning of an oMRgRT system is a multi-disciplinary project and all members should be involved in the process. However here we focused on the medical physics aspects. Corradini et al described the clinical part of commissioning addressing training, patient selection and different workflows [10]. To date no dedicated recommendation for radiation therapist aspects covering patient positioning, patient coaching and intrafractional motion monitoring exists. The entire expert panel of this recommendation is using the Unity or the MRIdian system. To the best of our knowledge, we propose tests, which are potentially also applicable for other MR Linac systems.

oMRgRT requires specifically designed QA protocols to verify the online adaptive radiotherapy workflow [48,55]. However, this

is a highly complex topic for a separate recommendation and could not be covered here.

In conclusion a program for QA and commissioning of oMRgRT was put together based on expert consensus to support medical physicists.

Conflict of interest

Davide Cusumano has received speaker honoraria and travel reimbursement from ViewRay Inc.

Stephanie Tanadini-Lang and Lotte Wilke: The Department of Radiation Oncology, University Hospital Zurich has research agreements with Siemens Healthineers and Viewray Inc.

Linda Kerkmeijer: The Radboudumc is member of the Elekta MR-linac Consortium. The MR-linac consortium members receive funding from Elekta.

Daniela Thorwarth: institutional collaborations including financial and/or technical support by Elekta, Philips, PTW Freiburg, Siemens, Kaiku Health, Dr. Sennewald. Research agreements with Therapanacea.

Geoff Budgell: The Christie NHS Foundation Trust is member of the Elekta MR-linac Consortium.

Faisal Mahmood: The Department of Oncology, Odense University Hospital has research contracts with Elekta and Philips.

Simeon Nill: The Institute of Cancer Research and The Royal Marsden NHS Foundation Trust are members of the Elekta MR-Linac Consortium.

Stefanie Corradini and Michael Reiner: The Department of Radiation Oncology, University Hospital, LMU Munich has a research agreement with ViewRay Inc.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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