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Magnetic Resonance Guided Radiotherapy:
MR-simulation and MR-linac



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Methods

CADTH Horizon Scanning bulletins are not systematic reviews and do not involve critical appraisal of all studies or include a detailed summary of study findings. The evidence provided in the summary of the evidence is based on two CADTH Rapid Response Summary with Critical Appraisal reports.^{24,25} The detailed summaries are not presented in this document, but rather in the published reports on the [CADTH website](#). Bulletins present an overview of the technology and available evidence. They are not intended to provide recommendations for or against a particular technology.

Literature Search Strategy

A series of limited literature searches were conducted using the following bibliographic databases: MEDLINE, Embase, and the Cochrane Library. Grey literature was identified by searching relevant sections of the Grey Matters checklist (www.cadth.ca/grey-matters). The searches were completed in April 2019 and were limited to English-language documents published after January 1, 2015. Conference abstracts were excluded from the search results.

Study Selection

Two authors screened the literature search results and reviewed the full text of all potentially relevant studies. Studies were considered for inclusion if the intervention was related to the use of MRI for the treatment of cancer. Studies providing direct cost data, narrative reviews, and expert commentaries were also included. Grey literature was included when it provided additional information not available in the published studies selected.

Peer Review

A draft version of this bulletin was reviewed by two clinical experts.

Stakeholder Review

A draft version of this bulletin was posted publicly for stakeholder review.

Summary

- Magnetic Resonance Simulation (MR-Sim) is a diagnostic magnetic resonance imaging (MRI) platform that has been adapted to optimize radiotherapy treatment planning;¹ Magnetic Resonance linear accelerator (MR-linac) systems are a new type of hybrid technology that allow for online MR-guidance for high-precision radiotherapy.²
- Evidence on the performance of MR-guided radiotherapy (MRgRT) is limited.
- MR-linac has potential in personalized image-guided radiotherapy because it can acquire dynamic, real-time MR images that provide visualization for adaptive radiotherapy.³
- MR-linac systems offer real-time tumour tracking and beam gating.⁴

Background

Radiotherapy (radiation therapy) is a cancer treatment that uses high doses of radiation to kill cancer cells and reduce the size of tumours.⁵ It is an important therapeutic tool used in approximately two-thirds of people with cancer.^{6,7} It can be used on its own, or in combination with chemotherapy and/or surgery.⁸ The success of radiotherapy is dependent on the accurate demarcation of the cancer tumours (the area to be irradiated) and the organs at risk (surrounding healthy tissue), and the precise delivery of radiation with respect to these parameters.⁹

MRI is a non-invasive imaging technology that produces three dimensional detailed anatomical images. It uses superconducting magnets to produce a strong magnetic field, and combined with special radiofrequency coils creates images of the body without the use of ionizing radiation. It is often used for disease detection, diagnosis, and treatment monitoring.¹⁰ Computed tomography (CT) is the current primary imaging modality used for most pre-treatment clinical radiotherapy planning.^{9,11} It is used either as a conventional scanner installed in a radiotherapy suite, or a cone-beam CT scanner mounted on the structure of a linac. It is the standard of care; dose calculation and patient positioning rely on CT, as it provides electron density information and high geometrical accuracy.¹² Radiotherapy systems were originally designed for CT datasets¹³ chiefly because CT provides a direct measurement of electron density that calculates radiation dose requirements.¹³ The popularity of CT as the primary imaging modality used for radiotherapy planning¹⁴ may be influenced by the fact that it is more available than MRI,^{15,16} the cost of conducting CT imaging exams is typically less than MRI,^{15,16} and

CT imaging is faster than MRI.^{13,17} MRI has historically been used in radiotherapy treatment planning, mainly as an adjunct to CT, because it can provide a better definition of tumour volume and organs at risk⁷ due to its superior soft-tissue contrast.¹⁷

More recently, MRI is being used for treatment guidance¹⁸ because it offers functional imaging that is able to depict spatial maps of clinically relevant cancer hallmarks and normal tissue physiology that can reduce toxicity to healthy tissue.¹⁹ MRI also facilitates the use of real-time adaptive radiotherapy,¹⁸ which has the potential to optimally deliver radiation doses to a patient in a way that accommodates anatomical changes due to natural body motion such as breathing and swallowing.²⁰

Both MR-Simulation (MR-Sim) and MR-linac use MR technology for treatment planning. MR-Sim is a diagnostic MRI that has been adapted to optimize radiotherapy treatment planning.¹ MR-linac is a hybrid device that includes a linear accelerator (Linac) to deliver the radiotherapy and an MRI scanner to visualize the cancer targets.²¹ CT-simulation (CT-Sim) is the main comparator to MR-Sim. While there is no direct comparator to MR-linac, because it is the first system to integrate an MRI with a linac,² it shares some broad similarities to a cone-beam CT scanner mounted on the linear accelerator.²² It is anticipated that MRI in radiotherapy has a promising future and will enable dose escalation and margin reduction, leading to higher cure rates and less toxicity for patients.¹ Some experts suggest that MR-Sim is merely a stepping-stone to MR-linac,²³ and that during the next decade, MR-linac will become the standard clinical system in radiotherapy.²¹

The Technology

The main reason diagnostic MRI was introduced into radiation oncology departments for treatment planning relates to its ability to provide superior definition of tumours and organs at risk compared with other imaging modalities.⁶ Since MRI does not use ionizing radiation, repeated scanning can occur without concerns related to escalating the patient radiation burden.²⁶ The increased use of diagnostic MR in radiotherapy has led to the implementation of MR-Sim for radiotherapy treatment planning, and has influenced the development of MR-linac.²⁷ These technologies evolved to compensate for some limitations with conventional diagnostic MRI that may not be important in the diagnostic setting, but are considered essential in a high-precision radiotherapy setting.²⁶ These limitations include geometric inaccuracies that occur with diagnostic MRI, which in the context of MR-guided radiotherapy can cause misplacement of the radiation dose, that can have an impact the effectiveness of the treatment and possibly increase toxicity to organs at risk,⁷ although spatial integrity is of lesser concern at lower field strengths.²⁸⁻²⁹ Additionally, the lack of information in MRI to calculate electron density estimations can lead to a misplacement of radiation dose.⁶

Both MR-Sim and MR-linac provide information on tumour characteristics, such as cell density, tissue oxygenation, and perfusion²⁶ that aid in the accuracy of target and tissue delineation.¹⁷ In some instances, such as with prostate cancer, image quality may be improved with dedicated organ coils.³⁰ MR-Sim and MR-linac can also achieve direct, individual nodal imaging in the radiotherapy position.¹¹

MR-linac uses fast dynamic MR sequences for tumour tracking and real-time motion monitoring.¹¹ Currently, radiotherapy is a static process, where the intensity of radiation beams are calculated before treatment is initiated and is therefore unable to adapt to natural body movement during treatment delivery.²⁰ Real-time adaptive radiotherapy, such as that which is MR-guided, can alleviate poor dose conformity because it accommodates natural body movement which can improve the coverage of the treatment volumes and lowers the radiation dose to organs at risk.²⁰

Immobilization devices play an important role in both the planning and delivery of disease specific and site specific treatment, especially for prostate, lung, breast, and head and neck cancer.⁶ Some conventional immobilization devices are not compatible with MRI from a safety perspective, may not fit inside the MRI bore, and may reduce image quality due to the coils being placed further away from the patient to accommodate immobilization.²⁷ It has been suggested that the impact of these modifications on

image quality, as well as the interaction with the Linac component of the system, need to be monitored² to determine the optimal use of equipment and system specific guidelines need to be developed.¹⁹

Current Practice

As previously stated, CT is currently the primary imaging modality used for most pre-treatment clinical radiotherapy planning.^{9,11} CT enabled radiotherapy has some limitations, including an inability to provide high-quality soft-tissue contrast, which may make it difficult to distinguish cancerous tissue from surrounding healthy tissue.⁹ On-board online cone-beam CT (CBCT) imaging is the current standard for image-guided radiotherapy. CBCT can only be used before or after treatment and not during the procedure³¹ and does not allow for optimal imaging of tumours and organs at risk when surrounded by soft tissue. CBCT guidance can also result in additional exposure to radiation, which presents challenges for radiation-sensitive pediatric patients and those needing continued monitoring with repeated CBCT scans.³¹

For the most part, diagnostic MRI scans supplement CT and are incorporated into the planning process by being co-registered to CT.³² Co-registration is the process of transforming different sets of image data into a single coordinated imaging system.³³ The co-registration of CT and MRI images can complicate the clinical workload;⁷ the co-registration process can introduce additional uncertainties that can misalign local targets (with an estimated target accuracy error of 1 to 2mm¹⁷) and result in harm to organs at risk.⁷

MRI does not have the same level of accuracy as CT in calculating electron density estimates. Attempts have been made to overcome this limitation by providing additional electron density estimations¹⁴ using software that auto-generates electron density values using correctional algorithms.^{27,7} Nonetheless, the calculation of electron density estimations is still considered to be a technical challenge for MRI and as such, limits the accuracy of dose measurement calculations.¹⁴

Other imaging modalities often used for prior planning in radiotherapy include positron emission tomography (PET) and X-ray.³⁴

MR-Sim

MR-Sim has been adapted from diagnostic MR to optimize radiotherapy treatment planning, however, imaging protocols needed for accurate treatment planning differ significantly from those used in diagnostic MRI. Dedicated MR platforms such as MR-Sim for radiation treatment planning accommodate unique

radiotherapy requirements and workflows that differentiate it from diagnostic MRI. These differences include:

- coil bridges to prevent deformation of the patient's body contour⁶
- MRI compatible mobilization devices to minimize patient movement¹³
- rigid flat table top¹³
- laser positioning system⁷
- wider bore⁷
- patient imaged in treatment (as opposed to imaging) position⁷
- dedicated scan protocols.^{35,7}

The expansion of MR in radiation oncology stems from its use in treatment simulation of the head, neck, and prostate tumours using a low magnetic field (0.23 Tesla).¹ While an MR-only treatment approach is an emerging trend implemented by numerous groups,⁶ it has not been widely used for target definition because of challenges with measuring geometric accuracy and electron density estimates which can lead to misplacement of radiation dose.^{7,6}

Consequently, many facilities still use CT in addition to therapeutic MR-Sim.^{13,17}

In most instances, the role of CT with regard to target delineation in treatment planning can be replaced with MRI;¹⁹ evidence suggest that improvements in the accuracy of target delineation in MRI-guided radiotherapy may improve clinical outcomes for some types of cancer due to improved dosimetry and the potential to increase the therapeutic ratio.³⁶

There is a growing trend toward the use of MR-Sim as the sole imaging modality in radiotherapy.⁶ This may be influenced by the fact that a MR-only treatment approach would negate the cost of CT equipment and associated radiation dose.⁶ Additionally, an MR-only workflow removes the need to co-register CT.⁶ From a logistical perspective, an MR-only workflow may be more efficient as not all CT and MR-Sim exams can be performed sequentially on the same day and there can be changes in internal anatomies which can affect the registration of CT and MR images used for treatment planning.³⁷ As well, there is potential for cost saving and time saving with the adoption of an MR-only approach to radiation planning.¹⁹

MR-linac

MR-linac is a hybrid device that integrates two technologies – a linear accelerator used to deliver external beam radiotherapy and an MRI that provides images that guide the delivery of radiation to the tumour.²¹ MR-linac may also function as a MR-Sim during the planning stage of radiotherapy.¹¹ The system enables the delivered radiation dose to be adapted to the current position and shape of the tumour and surrounding healthy tissue, enabling online adaptive radiotherapy. It also facilitates tumour tracking for high-precision targeting.³⁸ Theoretically, more precise targeting means that higher doses of radiation can be delivered to the cancerous tissue while minimizing damage to the surrounding tissue, which may improve clinical outcomes (i.e., increased local control, survival, decreased toxicity, improved quality of life) and reduce hospital stay compared with existing alternatives.^{31,38}

There is a growing trend toward the use of MR-Sim as the sole imaging modality in radiotherapy.

There are two different magnetic field configurations of MR-linac, the perpendicular beam field and the parallel beam field.³⁹ Most MR-linacs have either a fixed perpendicular or a parallel beam field, but at least one has both types of beam fields.³¹ There are numerous types of systems, some of which are commercially built and others that are developed within hospitals by research teams.¹¹ MR-linac systems differ in some aspects of their performance.² The various types of MR-linac systems and their different configurations are presented in Table 1.

It has been predicted that, during the next ten years, MR-linac will become the standard clinical system in radiotherapy.³⁹ It has also been suggested that it may enable the acquisition of non-invasive imaging biomarkers capable of determining response before or during the early phases of treatment which may have significant clinical utility,⁴¹ with regard to facilitating the adaption of treatment plans or changing the treatment objective based on real-time data.³⁵

Table 1: Different Types of MR-linac Configurations^{3,27,40}

MR-linac System	Radiation	Magnetic Field Configuration	Magnetic Field Orientation	Tesla Strength	Bore Size (cm)	Rotating Couch/ Gantry
ViewRay MRIdian	Cobalt-60	split superconducting	Perpendicular	0.35 T	70 Closed	Rotating gantry
ViewRay MRIdian Linac	6 MV	split superconducting Perpendicular 0.35 T	Perpendicular	0.35 T	70 Closed	Rotating gantry
MagnetTx Aurora RT	6 MV	superconducting rotating	Parallel	0.5 T	110 Open	Rotating gantry
Australian MRI Linac	6 MV	superconducting open bore	Parallel/ Perpendicular	1.0 T	82 Open	Rotating couch
Elekta Unity	7 MV	superconducting close bore	Perpendicular	1.5 T	70 Closed	Rotating gantry
MRgRT Suite	6 MV, Ir-92	MR on rails	NA	1.5 T	70 Open	Rotating gantry

MR = magnetic resonance; MRgRT = magnetic resonance guided radiotherapy; MV = megaelectronvolt; NA = not applicable; RT = radiotherapy; T= tesla.

Regulatory Availability

The first MR-Sim was approved by Health Canada in 2010,⁴² and the first MR-linac system was approved by Health Canada in 2017.⁴³

Emergence of MR-guided Radiotherapy (MRgRT) in Canada

Both MR-Sim^{17,27,44} and MR-linac³⁵ are used in Canada for radiotherapy treatment planning. There are at least three MR-Sims in Canada (in Toronto⁴⁵ and Montreal¹⁷) and there are three facilities in Canada conducting research with MR-linac – two in Toronto,³⁵ and one in Edmonton.⁴⁶

Radiotherapy departments across Canada not investing in the installation of dedicated MR-Sims are negotiating protected access to diagnostic MRI scanners in other departments for the purpose of radiotherapy treatment planning.²⁶

Cost

MR-Sim

The estimated Canadian cost of a MR-Sim is unknown and is dependent on specific facility level needs.

MR-linac

The estimated Canadian cost of an Elekta MR-linac is anticipated to be between \$8.5 and \$10 million depending on configurations [Justin Turpin, Director, Adaptive Radiotherapy Solutions, Elekta, Atlanta, GA: personal communication, 2019 July 5].

The estimated cost of the ViewRay MRIdian MR-linac is anticipated to be between \$8 and \$10 million USD. This cost includes the assembly of the system in a renovated vault. According to the manufacturer, vault renovation and design costs of the MRIdian system are less than other MR-linacs because of its split magnet design, which allows MRIdian to be installed in a smaller vault. [Joseph Authement, Vice-President Global Key Accounts, ViewRay, Oakwood Village, Ohio: personal communication, 2019 Nov 15].

In the UK, the machine cost of an MR-linac at one site was £5.3 million.⁴⁷ At a site in the US, the machine cost amounted to US\$10 million.⁴⁸ It is estimated that they may be approximately double the cost of conventional systems.²³ The cost may be offset by other considerations, such as the potential provision of improved outcomes or reduced costs associated with toxicity compared with other image-guided radiotherapy options.²³

Initially, there may be additional staff related costs associated with MRI-guided radiotherapy systems which, are operated by a team consisting of a radiation oncologist, radiation therapists,

medical radiation technologist, and medical physicist.⁴⁹ In contrast, CT-guided radiotherapy requires radiation therapists to perform the procedure.⁴⁹

Overall, MR-guided radiotherapy systems are considered to be expensive and pose challenges to value-based health care.⁴⁹

Who Might Benefit?

Based on the anticipated clinical benefit, potential patient numbers anticipated at the participating sites, and the tumour-site expertise in the collaborating hospitals, the international MR-linac Consortium has selected brain, breast, cervix, esophagus, lung, oropharynx, pancreas, prostate, and rectum as tumour sites for which MRgRT will initially be used.³¹ However, because it can be used for virtually any type of cancer,²³ its use may expand.

If MRI was only used for cancers in which the medical literature already suggests that it is superior to the standard of care, such as cancers of the brain, prostate, and cervix,³² and cancers where it shows signs of promise, such as lung, breast, and head and neck,³² there would be approximately 75,355 new incidences in Canada every year for which MR-guided radiotherapy could be used.

MR for radiotherapy planning may be of particular benefit for pediatric populations in which radiation dose is rigorously regulated, in cases where repeat scans during treatment are required to change the treatment plan to accommodate tissue changes caused by radiation, and to monitor early response.¹³

Summary of Evidence

MR-Sim

CADTH recently published a review on MR-Sim²⁴ regarding the clinical and cost-effectiveness, as well as guidelines for the use of MR-Sim for treatment planning for patients requiring radiotherapy. Clinical evidence of limited quality from one retrospective cohort study of patients with prostate cancer suggested that the use of MR-Sim in conjunction with CT-simulation for treatment planning may reduce acute genitourinary toxicity compared with CT-simulation only and that MRI use had no identified benefit for reduced acute gastrointestinal (rectal) toxicity.

No relevant cost-effectiveness studies or guidelines were identified on the use of MR-Sim for simulation and treatment planning for patients requiring radiotherapy.

Given the limited availability and low quality of evidence, the effectiveness and use of MR-Sim for treatment planning for patients requiring radiotherapy remains uncertain. However, since MRI is already an integral part of treatment planning for central nervous system,²⁶ head and neck,²⁶ gynecological,²⁶ urological,²⁶ gastrointestinal cancers,²⁶ chest,⁶ brain,⁶ liver,⁶ pancreas,⁶ and prostate cancers,⁵⁰ researchers may feel that additional studies on the effectiveness of MR for treatment planning are not required.

MR-linac

CADTH recently published a review of the clinical effectiveness, cost-effectiveness and guidelines for the use of MRgRT delivery systems treatment of patients with cancer requiring radiotherapy.²⁵ One relevant non-randomized, retrospective cohort study was identified comparing the clinical effectiveness of MR-linac for the treatment of lung cancer requiring radiotherapy. This study examined mean lung density changes after treatment as an approach to examine early radiological lung damage.²⁵ Evidence of limited quality from this study found no significant differences in mean lung density changes for patients who had lung stereotactic ablative radiotherapy using a MR-linac versus a linear accelerator delivery system.

To reduce uncertainty of the clinical effectiveness of MR-linac, outcomes to consider for future research may include: overall survival, progression-free survival, mortality, quality of life, and harms. No evidence regarding the cost-effectiveness of MR-linac for the treatment of patients with cancer requiring radiotherapy were identified. No relevant evidence-based guidelines were identified for the use of MR-linac for the treatment of patients with cancer requiring radiotherapy.²⁵

Published after the CADTH review, a multicenter retrospective cohort involving patients with pancreatic cancer were treated with and without dose escalation with MR-linac was identified. This study examined overall survival freedom from local failure and freedom from distant failure. Evidence from the study found that patients treated with dose-escalated MR-linac demonstrated improved overall survival and freedom from local failure.⁵¹

An additional single centre study that evaluated the treatment of MR-linac as a method to deliver stereotactic body radiotherapy for the treatment of localized prostate cancer was identified. Patient experience with MR-linac was assessed using a patient-reported outcome questionnaire. Evidence from the study found that treatment with MR-linac was feasible and well-tolerated.⁵²

Ongoing Research

In 2012, the MR-linac Consortium was established for the collaborative clinical implementation of MR-linac.³¹ The main role of the consortium is to design studies and a data registry system for the gathering of evidence to demonstrate the clinical benefit of MR-linac.³¹ One of the founding members of the international consortium, Sunnybrook Health Sciences Centre,⁵³ is one of the first hospitals to use MR-linac in Canada.

Other consortium members include: the University Medical Center Utrecht, and the Antoni van Leeuwenhoek Hospital – both from Netherlands; the Royal Marsden Hospital and the Manchester Cancer Research Centre in the UK; and the University of Texas MD Anderson Cancer Center and the Froedtert & Medical College of Wisconsin in the US.³¹ Industry partners working with the consortium include Elekta and Philips.⁵³

In 2019, the MR-linac Consortium launched the Multiple Outcome Evaluation of Radiotherapy Using the MR-linac (MOMENTUM) study.⁵⁴ The purpose of the study is to collect real world evidence on clinical and technical data to optimize the technology and evaluate treatment outcomes.⁵⁴

ViewRay has developed an Investigator-Initiated Research program and partners with multiple institutions to share clinical data and best practices on MRgRT.⁵⁵ The main priority of this program is to obtain clinical evidence to establish the value of MRgRT across various tumour sites. ViewRay has established several tumour-site specific research consortiums which bring together leading scientists to research and publish the clinical outcomes and patient benefits of adaptive planning, tissue tracking, and automated beam gating. [Dr. Martin Fuss, MD, Chief Medical Officer, ViewRay, Oakwood Village, Ohio: personal communication 2019 Nov 15]

In addition, four clinical trials are currently underway, including a single arm, open-label, study to measure differences between target volumes and organs at risk contoured on PET, CT, and MRI images in lung cancer,⁵⁶ a single arm, open-label, study to assess the technical feasibility of delivering radical radiotherapy for prostate cancer using MR-linac,⁵⁷ and two observational studies, one investigating the optimal pulse sequence parameters for MR-linac suitable for patients undergoing radiotherapy⁵⁸ and the other to develop MR-linac image sequences suitable for tumour and normal tissue at the time of radiotherapy and to determine variations in image registration and tissue contouring.⁵⁹ Most of these studies focus on dosimetry and technical performance and/or the feasibility of MR-linac rather than patient outcomes.

In January 2019, the Stereotactic MRI-guided On-table Adaptive Radiation Therapy (SMART) study for locally advanced pancreatic cancer was launched. Radiation therapy is delivered using MR-linac. The purpose of the study is to evaluate toxicity, overall survival, distant progression-free survival and patient-reported quality of life over five years.⁶⁰

Safety

There are some unique safety issues associated with MRI⁶¹ that, due to limited experience with the technology, oncology departments may be less familiar with.⁴⁸ MRI safety issues relate to the projectile capabilities of metallic objects in the strong magnetic field of a MRI unit, as well as the necessity to screen patients for contraindications such as aneurysm clips, cardiac bypass surgery, some heart valves, embedded wires, stimulators, batteries, implanted electrodes, shunts, pumps, pacemakers, and some penile implants.¹⁷ In addition to the projectile concerns of these objects, implanted metal devices, even if they are not magnetic, may cause artefacts in the MR images, such as signal loss, intense areas of signal accumulation, and distortion in areas near the implant.³⁵

The strong magnetic field and pulsed gradient field of MRI machines can create loud knocking noises which can harm hearing if ear protection is not used and cause peripheral nerve stimulation. As well, the thermal effects of radiofrequency energy used during an MRI scan can lead to heating of the body.⁶²

Implementation Issues

The assimilation of MRI into radiotherapy has been found to be associated with challenges.²⁶ There is general agreement that more refinement is required, particularly with regard to image quality, protocols, safety, and quality assurance²⁷ to ensure that both MR-Sim and MR-linac can be successfully integrated into the routine clinical workflow of radiation oncology departments.¹ MR-linac workflows are different from current CT workflows⁶³ and the transition of radiation therapists' use of this technology may be made easier with their prior knowledge of MR-Sim.²⁷ Some of the current barriers to the implementation of MRgRT are outlined in this section.

Education and Training

The introduction of MR-Sim and MR-linac has created new practice challenges that have been exemplified by gaps in knowledge and skills related to MR in the radiation oncology environment.⁵⁰

Areas of MRgRT-related focused training include:^{40,63}

- New treatment planning systems
- MR safety, patient screening
- MR-based anatomy – image assessment on MRI versus cone beam CT versus CT
- MR image quality, formation, scan optimization and interpretation
- Multimodality image registration
- Contour/modify organs at risk for adaptive radiotherapy
- Adaptive radiotherapy strategies and methodologies
- Novel radiotherapy delivery techniques
- Daily/weekly quality assurance and quality control requirements.

It has been noted that scope of practice changes will emerge from the implementation of the MR-linac that may require a reassessment and expansion of traditionally held professional roles.^{26,63}

In February 2019, a National Magnetic Resonance in Radiation Therapy Taskforce, initiated by the Canadian Association of Medical Radiation Technologists, met to discuss the knowledge and skills required to safely and effectively integrate MR into radiotherapy practice. The taskforce's role is to identify and validate competency requirements for MR in radiotherapy and recommend a national approach to education and training for MRI in the radiotherapy environment. During the meeting preliminary competency domains were identified via a consensus building process. The domains and specific knowledge and skills that fall under the domains will be further developed and validated through an international Delphi process. A number of the skills and knowledge areas identified during the meeting were felt to be new or integrated competencies that extend beyond the current education and practice expectations for radiation therapists and MR technologists at entry-to-practice in Canada. This suggests that there will likely be a need to develop new educational programming to fill this gap. [Carrie Bru, Canadian National Magnetic Resonance Taskforce, Canadian Association of Medical Radiation Technologists, Ottawa, ON: personal communication, 2019 July 8]

Safety

While the unique safety issues associated with MRI have been outlined previously, it is important to highlight that the dangers of MRI for patients and hospital staff may not commonly understood in oncology departments.⁷ An incident with a newly installed MR-Sim in the radiotherapy department at Sunnybrook Health Sciences Centre, involving a commercial floor buffer that

was accidentally placed in an MRI suite and subsequently smashed into the MR scanner, underscores the need for formalized MRI safety programs that target a wide audience with diverse skill sets.⁶⁴

Quality Assurance

Currently, quality assurance guidelines, processes, and recommendations specific to tumour sites, and optimized by vendor and imaging platform, are not in place.¹⁹ Rigorous quality assurance is required to maintain consistent and accurate images to avoid errors that can result in unfavourable patient outcomes.²⁶

As well, the quality assurance requirements for the therapeutic use of MRI differ from those for diagnostic MRI,^{2,27} and the quality assurance control methods established for MR-Sim need to be tailored for MR-linac.⁶⁵

Technical Challenges

Numerous technical challenges are currently present at all levels of the patient workflow process.⁷ Image quality, implantable devices, artifacts in proximity to images of interest, and receiver coils differ from those used in diagnostic MRI and need to be customized to the new environment. To further complicate matters, image sequences (collections of images related by time) vary by vendor.⁵⁰ As well, there are some technical hurdles associated with electron density estimations, the delineation of targets and organs at risk, treatment planning, treatment verification, daily treatment planning adaption, and early assessment of treatment response that require attention.⁶⁶

Multidisciplinary Communication and Collaboration

To address the technical challenges in the clinical environment it will be necessary to have open communication and close collaboration between radiation oncologists, radiologists, radiation therapists, pathologists, medical physicists, and surgeons.^{50,67} It is suggested that the fostering and development of collaborations across disciplines will require support from national and international scientific and professional societies.¹ These collaborative endeavours may also accelerate advances in the development of MRgRT.¹

Access

From a practical perspective, the current limited integration of MRI into radiotherapy workflows may be linked to access to the technology (there are 366 MRI units in Canada compared with 561 CT units⁶⁸), with the more limited access to diagnostic MRI dictating its availability for radiotherapy purposes.^{19,50}

Workflow

An MRI-based workflow is more complex than the well-established CT workflow, and has been found to be associated with higher costs and requires both new technology and new software tools.⁶⁹ While methods for performing MR as the primary imaging modality have been developed, the actual clinical implementation and workflow still require refinement.⁷⁰

At this time, most MRI workstations do not support radiotherapy digital imaging structures which can make it more challenging to transfer information between radiotherapy systems and MR workstations.¹³ The more widespread use of MRI in radiotherapy treatment planning is anticipated to bring about software developments that are better-able to integrate MRI into workflow processes.¹³ In comparison, CT is well integrated with radiotherapy departments and the fundamentals of CT are better understood by radiation oncologists compared with MRI.⁶⁹

Staffing

There is a lack of clarity around the optimal staffing model for MR-linac. The most commonly implemented staffing model in Canada for MRgRT is to employ people certified in both radiotherapy and MRI. However, there are few employees with the dual certification. Additionally, most MRI post certification programs have a diagnostic focus and are limited in their address of oncologic or therapeutic practice and theory.²⁶

Another staffing approach may be to assimilate MRI technologists into radiotherapy departments and provide focused training on radiotherapy workflow.²⁶ This approach may also be limited by the fact that therapeutic MRI is a new area for MRI technologists.²⁶

A third approach that has been successfully adopted in one Canadian facility is to focus on upgrading the MRI qualifications of radiation therapists.²⁶ Early MR-linac users have established advanced training programs for radiation therapists to take on expanded roles in the use of MR-linac.^{52,4}

Manufacturers

MR-Sim

There are at least two manufactures of MR-Sim. They include Philips (Ingenia MR-RT)⁷¹ and the Siemens Magnetom MRI scanner with the dedicated RT Pro edition.⁷²

MR-linac

There are several MR-linac systems available: the Elekta Unity that incorporates a Philips 1.5 Tesla MRI and a 7.5 megavolt (MV) (acceleration rate) linear accelerator,⁷³ the MRIdian by ViewRay that integrates a 0.35 Tesla magnet with a 6 MV Linac,⁷⁴ and the rail-mounted MRgRT Suite.⁴⁰ Another MR-linac, the Aurora RT radiotherapy system from MagnetTx, combines a 6 MV linear accelerator and a 0.5 Tesla MRI magnet, and has a non-clinical working prototype.⁷⁵

Concurrent Developments

The advancement and clinical implementation of MR-linac has led to developments in MRI-proton units.¹ The clinical potential of merging MRI with proton therapy may provide an opportunity to explore further improvements in patient care. A number of groups have conducted studies of the feasibility of different aspects of combined MR proton therapy and it is predicted that MR-guided proton beam therapy may be the next major advance in proton beam radiotherapy practice.⁷⁶

Final Remarks

MRI is increasingly utilized in radiotherapy treatment planning due to its improved soft-tissue visualization compared with conventional CT even though evidence of effectiveness has not been established. Maximizing the safety, efficiency and effective use of MRI would require new processes, techniques, workflows, and guidelines. Close collaboration and multidisciplinary communication between diagnostic radiology, imaging physicists, and radiation oncology teams will be required to manage technical challenges. To overcome implementation barriers, issues related to education and training, safety, quality assurance, staffing, cost, and access need to be appropriately addressed.

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