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Abstract. Image guidance plays a critical role in radiotherapy. Currently, cone-beam computed tomography (CBCT) is routinely used in clinics for this purpose. While this modality can provide an attenuation image for therapeutic planning, low soft-tissue contrast affects the delineation of anatomical and pathological features. Efforts have recently been devoted to several MRI linear accelerator (LINAC) projects that lead to the successful combination of a full diagnostic MRI scanner with a radiotherapy machine. We present a new concept for the development of the MRI-LINAC system. Instead of combining a full MRI scanner with the LINAC platform, we propose using an interior MRI (iMRI) approach to image a specific region of interest (RoI) containing the radiation treatment target. While the conventional CBCT component still delivers a global image of the patient's anatomy, the iMRI offers local imaging of high soft-tissue contrast for tumor delineation. We describe a top-level system design for the integration of an iMRI component into an existing LINAC platform. We performed numerical analyses of the magnetic field for the iMRI to show potentially acceptable field properties in a spherical RoI with a diameter of 15 cm. This field could be shielded to a sufficiently low level around the LINAC region to avoid electromagnetic interference. Furthermore, we investigate the dosimetric impacts of this integration on the radiotherapy beam. © 2017 Society of Photo-Optical Instrumentation Engineers (SPIE) [DOI: [10.1117/1.JMI.4.1.015004](https://doi.org/10.1117/1.JMI.4.1.015004)]

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1 Introduction

The success of radiotherapy relies on the precise delivery of a potent radiation dose to the cancerous target, while sparing nearby normal organs. Image guidance plays a critical role. Before each treatment delivery, the patient's anatomy is observed through an imaging method. The patient is accurately positioned with respect to the radiotherapy beam as designed in the treatment plan. Over the years, advancements in modern radiotherapy have made image guidance increasingly important. From a technology viewpoint, the use of novel therapeutic delivery methods, e.g., intensity modulated radiation therapy,^{1,2} and treatment modalities, e.g., proton therapy,³ have led to the achievement of dose distributions conformal to the target. From a clinical standpoint, novel therapeutic approaches, e.g., stereotactic body radiation therapy (SBRT),⁴ require a reduction of margin size in treatment planning to spare normal tissue and achieve target dose escalation. These advancements have led to dose distributions that are more sensitive to positioning errors because a small spatial misalignment between the target and the beam could potentially cause a large drop in tumor coverage. The vulnerability of radiotherapy dose to setup errors highlights the importance of image guidance.

On-board kV cone-beam computed tomography (CBCT) is the most widely used image-guidance tool in radiotherapy.⁵ While its benefits in patient setup accuracy have been consistently demonstrated for many tumor sites in a variety of clinical scenarios, two drawbacks still exist. A fundamental physics

limitation is that soft tissues have low image contrast under x-rays. This hinders soft-tissue visualization, such as in liver and cervical cancer radiotherapy, impeding patient setup accuracy. In addition, patient exposure to ionizing radiation during a long treatment course may cause harm. High imaging doses limit routine application of CBCT, especially in radiation-sensitive populations, e.g., pediatric patients.

Studies have been conducted to overcome the limitations of CBCT and develop novel image guidance strategies for radiotherapy. Magnetic resonance imaging (MRI) is a promising candidate because of the superior image contrast resolution, the absence of ionizing radiation, and the option of functional imaging. The integration of an MRI device into a radiotherapy machine is challenging because of the sharp conflicts between the two devices in terms of physics and geometry. From a physics perspective, a strong magnetic field is required to achieve a high MRI signal-to-noise ratio. Shielding this strong field from a medical linear accelerator (LINAC) is challenging because many electronic components are susceptible to electromagnetic interference. In terms of geometry, a conventional MRI system employs a bulky design to realize a sufficiently large field-of-view (FoV), hindering integration into a space-limited LINAC system. This is particularly challenging if one would like to maintain noncoplanar delivery capability in radiotherapy, which has been shown to have great clinical benefits.⁶

Over the years, several groups have made tremendous progress in the integration of MRI with a radiotherapy machine. The MRIdian system (ViewRay Inc., Oakwood Village, Ohio)

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Fig. 1 (a) Design of the iMRI device. (b–d) Illustration of how the iMRI device is mounted on a radiotherapy LINAC gantry, while allowing the gantry and couch to be placed at different angles for radiotherapy delivery. Vertical blue line and horizontal red line indicate couch and gantry rotational axes.

was the first commercially available system that combined a 0.35-T MRI and a cobalt-60 therapy machine.⁷ Efforts to integrate MRI with a LINAC have also led to rapid advancements in several groups. A prototype system combining a 1.5 T Philips MRI scanner with a compact accelerator was available at Utrecht University and is expected to be clinically available soon.^{8–10} The Cross Cancer Institute developed a prototype system comprising a 0.6-T MRI and a 6-MV accelerator.^{11,12} The Australian MRI-LINAC Program is also in the process of developing a system combining a 1 T open-bore MRI and a 6 MV LINAC.^{13,14} These pioneering efforts have clearly demonstrated the feasibility of MRI-LINAC and their advantages for radiotherapy image guidance.

Existing efforts have exclusively focused on combining a full diagnostic MRI system with a radiotherapy machine. Recently, advancements in the interior tomography field have enabled theoretically exact and numerically stable reconstruction of an image in an interior region-of-interest (RoI).¹⁵ This motivates us to propose a new concept for the development of an MRI-LINAC system. Specifically, instead of combining a full MRI scanner with the LINAC platform, we propose using an interior MRI (iMRI) approach to obtain local imaging in a specific RoI of radiotherapeutic relevance. MV CBCT realized via the therapeutic beam could be employed to acquire additional and complementary global image information. In this approach, the small RoI will only require a magnetic field with desired properties for MRI imaging just large enough to cover it. This fact may relax technical requirements on the hardware and achieve a compact MRI design that is geometrically and electromagnetically compatible with the current LINAC systems. It may be potentially feasible to retrofit the iMRI device onto an existing LINAC to enable MRI-based image guidance radiotherapy.

In this paper, we will present a potential design for this concept. A few aspects within this proposed scheme will be shown, including system geometry, integration to a LINAC platform, imaging capability, impacts on radiotherapy treatment, etc. Presenting the results is only for the purpose of illustrating our idea. It does not mean that such a system has been built

or that the design is final, comprehensive, or optimal. At the end of the manuscript, we will also present comparisons between this new conceptual design and existing systems, limitations of our study, future directions, and potential clinical applications. We hope our manuscript will point out a direction to solve the MRI-LINAC problem that has not been explored by the field. Our study will potentially stimulate discussions from the community and inspire new developments toward MRI-guided radiation therapy.

2 Methods

2.1 Interior Magnetic Resonance Imaging System Design

The main hardware component for the proposed iMRI system is illustrated in Fig. 1(a). To facilitate our discussion, a coordinate system fixed to the device is defined as in the figure. Two permanent magnets, with a side length of ~50 cm and a thickness of 30 cm, will be used to provide a main magnetic field B_0 for MRI in spherical RoI located in the middle of the two magnets. The separation between the two magnets will be ~60 cm, which should provide enough space to accommodate a typical patient. With magnetic material such as NdFeB, the field strength can be ~0.3 T in the RoI. The two magnets will be placed within a U-shaped yoke made of ferromagnetic material, e.g., steel. This structure confines the magnetic flux and shields the magnetic field from the outer region. Other components for iMRI, such as gradient coils, RF coils, and circuits, are also needed, as illustrated by the circular objects attached to the front surfaces of the magnets. A hole on the top side of the U-shaped yoke allows the radiotherapy beam to pass through.

2.2 Interior Magnetic Resonance Imaging Integration to a Linear Accelerator

The iMRI device will be mounted on robotic arms attached to the two sides of the LINAC gantry, as illustrated in Fig. 1(c).

The hole on top of the U structure will be in front of the LINAC head to allow the radiotherapy beam to pass through. On the LINAC, the kV CBCT is realized using an x-ray tube and detector mounted on the left and right side of the gantry. Since the iMRI device takes the position of the conventional kV CBCT, it is not possible to use kV CBCT for image guidance. Instead, MV CBCT may be an alternative for obtaining a global view of the patient's anatomy complementing the interior MR image. This employs the treatment beam as an x-ray source and an electronic portal imaging device (EPID) as a detector. The EPID is mounted on the gantry and faces the therapeutic beam. Due to the compact design, the iMRI system does not prevent LINAC gantry rotation around the patient, which enables the rotational scan of the MV CBCT. Moreover, this design also allows different combinations of the gantry and the couch angles, preserving noncoplanar radiotherapy treatment delivery. Three examples of imaging positions at different gantry and couch angle combinations are illustrated in Figs. 1(b)–1(d). The iMRI device can be split into two halves through its mid plane, as needed. With the arms and the device retracted, 4π treatment delivery will not be affected under the current LINAC.⁶

2.3 Image Acquisition and Reconstruction

It might be challenging to achieve a magnetic field that meets the homogeneity requirement for the conventional MRI image acquisition. Recently, the desire to develop portable MRI scanners has led to a number of novel approaches for performing MRI imaging under a nonuniform magnetic field. At the stage of proposing a new direction to combine MRI with a LINAC, we only present one potential spatial encoding method borrowed from a novel system developed by Massachusetts Institute of Technology.¹⁶ In this approach, the magnet mechanically rotated around the object. A rotating spatial encoding magnetic field (rSEM) method was employed to create generalized projections of the unknown MRI image.^{17,18} This rotational data acquisition method naturally fits to our proposed iMRI-LINAC system as the CBCT data acquisition requires gantry rotation as well. This rSEM method has also been recently proposed in a study on simultaneous CT and MRI data acquisition.¹⁹ After data acquisition, the discretized signal is related to the unknown magnetization image $f(x)$ as $s_\theta(n) = \sum_x e^{-i2\pi k(\theta, x, n)} f(x)$, where x is the spatial coordinate, θ is the rotation angle, n is the index for the data acquired at the rotation angle, and $k(\theta, x, n)$ is the evolved phase. This sets up a linear equation system $Mf = s$, where M stands for the system matrix. The interior tomography techniques¹⁵ can be used to perform reconstruction of the RoI image by solving an optimization problem $f = \arg\min_f \left\{ \frac{1}{2} \|Mf - s\|^2 + \lambda J[f] \right\}$. Here, the first least square term ensures the fidelity of the reconstructed image to the measurement, whereas $J[f]$ stands for a regularization term to impose constraints on f based on prior knowledge about it. λ is a parameter tuning the relative weights between the two terms.

2.4 Simulation Studies

To investigate the proposed iMRI-LINAC concept in more detail, we first calculated the magnetic flux density distribution around the iMRI device using the FARADAY software (V9.3), a numerical solver for Maxwell equations using the 3-D boundary element method. In particular, we examined the field

Fig. 2 An MRI image of a liver cancer patient used in the simulation study. The red circle indicates an FoV with a diameter of 15 cm.

homogeneity within the FoV. We also investigated the field distribution around the device to examine potential interference with electronic components in a LINAC.

Second, we examined imaging performance in a liver cancer to illustrate the application of the proposed iMRI system in a clinical scenario. The liver cancer case was selected in our study as it is one clinical scenario in which MRI-based image guidance is expected to be critical due to low contrast of tumor and potential tumor deformation. The use of a human subject was approved by the Institutional Review Board of the University of Texas Southwestern Medical Center. Patient consent was not required since this was a retrospective study using anonymized patient data previously collected following a standard radiotherapy treatment protocol. The patient was scanned using a GE Signa HDxt scanner under a liver scan protocol (TE/TR = 2.056/4.268 ms). The T1-weighted diagnostic MRI image in Fig. 2(a) was used in our study as the ground truth image. Since the purpose of this paper is to demonstrate the idea of using iMRI for radiotherapy image guidance, we did not perform a detailed simulation of the MRI imaging process. Instead, the ground truth image was transformed to the k-space and sampling in the k-space was simulated. We reconstructed the iMRI image inside the FoV using the interior tomography framework with a dictionary learning regularization.^{20,21} Specifically, the optimization-based reconstruction problem was as follows:

$$f = \arg \min_{f,D} \left\{ \frac{1}{2} \|Mf - s\|^2 + \lambda \sum_{(i,j) \in \text{RoI}} \|R_{i,j}f - D\alpha_{i,j}\|^2 \right\},$$

$$\text{s.t. } |\alpha_{i,j}|_0 \leq T_0. \quad (1)$$

The matrix $R_{i,j}$ is an operator extracting the image patch centered at the pixel (i,j) from the image f , and $\alpha_{i,j}$ is the coefficient vector that represents this patch using a dictionary D . The constraint enforced the sparsity level of the dictionary representation. While solving this optimization problem in an iterative process, the dictionary was adaptively trained by intermediate solution images and only applied in the RoI. We also examined the performance of the reconstruction algorithm under different levels of noise due to the concern of high noise at a

Fig. 3 (a) B field around the iMRI device. The sphere in the middle indicates the FoV with a 15-cm diameter. Part of the device was not drawn to improve visibility. (b) Distribution of the magnetic field in three orthogonal planes through the center of the FoV. (c) Variation of magnetic flux density along three major axes around the center of the FoV.

relatively low magnetic field. The image was normalized to a maximum magnitude of 1. To evaluate the reconstruction performance with noise, zero-mean complex Gaussian noise signals of standard deviations of $\sigma = 0, 10, 20$, and 40 were added in k -space. Image reconstructions were conducted using the noisy data. We used this simple noise model for the purpose of illustrating robustness of the reconstruction to noise. However, the noise introduced did not represent the actual noise in the system.

Third, we studied the impact of the magnetic field on radiotherapy dose distribution. We performed dose calculation using an in-house GPU-based Monte Carlo (MC) dose calculation package gDPM.^{22,23} Charged particle transport simulation in a magnetic field was enabled. We first performed the dose calculation for a 10×10 cm² open field normally impinging to a homogeneous water phantom along the x direction. The phantom was subjected to a homogeneous magnetic field of 0.3 T along the z direction. Dose distributions were compared with and without the magnetic field. We also calculated dose distribution in the liver cancer patient undergoing SBRT treatment. The planning target volume (PTV) was located in the central region of the liver with an approximate ellipsoid shape. The prescription dose was 10 Gy per fraction for five fractions, which is a typical prescription dose for liver SBRT at our institution. The patient was treated using volumetric modulated arc therapy in which a 6-MV beam delivered radiation to the tumor from a 360-deg angular range in a full gantry rotation. The field size was 5×5 cm², but the radiation was further modulated by the multileaf collimator (MLC). The dose distribution was computed using the MC method with the magnetic field, which was then quantitatively compared with the dose distribution without the field.

3 Results

3.1 Magnetic Field Distribution

The magnetic flux around the iMRI device is drawn in 3-D in Fig. 3(a). The sphere of a 15-cm diameter in the middle region indicates the image FoV. The magnetic flux density in color wash is illustrated in Fig. 3(b). We observed that the strongest magnetic field appeared inside the permanent magnets. The field became weaker as it moved away from the surfaces of the permanent magnets. Using a magnetic material of NdFeB N45, the flux density inside the FoV was ~ 0.3 T and could be further amplified by constructing the magnets with higher grade magnetic materials. With this design, the field variation with respect to the strength at the center of the FoV was $[-4.8\%, 8.27\%]$. The variation of the field strength along three major axes is shown in Fig. 3(c). The field was symmetric along the y and z axes due to the symmetry in the device.

With this relatively simple design, the magnetic field was mainly confined within the permanent magnets and the stainless steel U-shaped yoke. This shielded the field from the outer region and reduced the electromagnetic interferences with the LINAC. The field strength on the outer surface of this yoke was ~ 0.01 T. The LINAC head was on top of the hole on the yoke. The head contains several components that are sensitive to a magnetic field, such as a MLC controller. The field strength in this region was ~ 0.02 T, which was expected to be acceptable.²⁴

3.2 Imaging Capability

Many disease sites have relatively low image contrasts under CBCT and are expected to benefit from MRI-based image guidance. Examples include liver and cervical cancers in the

Fig. 4 (a) Display of one axial slice of planning CT image with PTV and GTV contours. (b) CBCT of the same slice acquired before a typical treatment delivery. (c) Blending of CBCT and reconstructed iMRI image in the FoV.

Fig. 5 (a)–(d) Reconstructed iMRI images with noise standard deviations of 0, 10, 20, and 40, respectively.

abdominal and pelvic areas. Here, we used a liver cancer patient case to demonstrate the potential advantages of the iMRI system for radiotherapy. The treatment planning CT image with the gross tumor volume (GTV) and PTV is shown in Fig. 4(a). The GTV was derived from a contrast-enhanced CT acquired at the treatment simulation stage. For radiotherapy planning, however, noncontrast-enhanced CT images were used to acquire an accurate CT number in the tumor area to derive electron density for dose calculation purposes. In these images, the tumor was not distinguishable from the rest of the normal liver.

On the day of the treatment, a CBCT image was acquired before radiotherapy delivery for patient setup purposes. The real CBCT image in this patient case is shown in Fig. 4(b). The CBCT image presented many artifacts, which were the combined consequence of many image degradation factors, such as x-ray scatter. The current standard clinical practice has to rely on this image for patient positioning. Because of the challenge of distinguishing the target from the rest of the normal liver, positioning was typically based on the entire liver organ and other visible nearby structures, e.g., bony structures. This, however, inevitably introduces setup uncertainties.²⁵

We have reconstructed the MRI image in the FoV using the method presented in Sec. 2.4. The resulting image was blended with the CBCT image to illustrate our idea of using iMRI for local imaging and CBCT for global imaging. Although we expected the global-view CBCT to be obtained through the MV beam, we used a kV CBCT image for simplicity. Highly improved structural information was visible within the liver and in nearby organs as compared with CBCT. We expect that the information will substantially improve patient positioning accuracy as compared with the current CBCT-alone approach. The reconstructed images with different noise levels are presented in Fig. 5. Even at a relatively high noise level of 40, the fine structures of the liver can still be clearly visualized.

3.3 Dosimetric Impacts of the Magnetic Field

Another important issue is the impact of the magnetic field on the radiotherapy beam for dose delivery. Figure 6 shows the comparison of dose distribution in the xy and xz planes with and without the magnetic field with an open $10 \times 10 \text{ cm}^2$, 6-MV radiotherapy beam normally impinged to a homogeneous water phantom along the x direction. The phantom was placed in a homogeneous field of 0.3 T along the z direction. It was observed that the dose distribution was only slightly distorted by the magnetic field. The isodose lines were moved only in the xy plane toward the positive y direction by $\sim 1 \text{ mm}$ because the electron trajectories were curved to this direction. This calculation did not consider inhomogeneity of the magnetic field in the proposed iMRI system. Nonetheless, the beam path will follow the x direction [Fig. 3(c)], where the field was strongest within the FoV. Hence, the perturbation seen in Fig. 6 is expected to occur in the worst case scenario. Similar behaviors have also been observed in research from other groups.^{26,27}

We also calculated the dose distribution in the liver cancer patient, and the results are presented in Fig. 7. The difference between the doses with and without the magnetic field was small within the tumor and its surrounding area. However, a difference in dose was observed in the lower lung area. This can be ascribed to the long electron range in the low-density lung medium, which made the dose more susceptible to the magnetic field. Dose volume histograms (DVHs) are also compared in Fig. 7(c). Apart from the lung, the DVHs with the magnetic field were almost indistinguishable from those without. This study indicated that the presence of a 0.3-T magnetic field introduced non-negligible dose perturbations, particularly to those regions with a low tissue density. Hence, treatment planning with the magnetic field considered is necessary, which has also been suggested previously by other studies.^{28–33}

Fig. 6 (a) and (b) Comparison of isodose lines on two planes for a 6-MV photon beam in a water phantom with (solid colors) and without (solid lines) a 0.3-T magnetic field in two views. Inserts are zoomed-in views of the rectangular regions.

Fig. 7 (a) Color wash plot of dose distribution for a liver SBRT case in a 0.3 T magnetic field. (b) Difference distribution between cases with and without the magnetic field. (c) Comparison of DVH curves for different organs between cases with (dashed lines) and without (solid lines) the magnetic field.

4 Discussions

4.1 Comparison with Existing Systems/Technologies

4.1.1 Field of view

The most distinct feature differentiating our conceptual system from the existing MRI-LINAC systems is its smaller FoV. As opposed to integrating a full body MRI scanner with a LINAC, we propose using a new MRI design that has a small (~15 cm diameter) FoV. Since the most critical information

needed in radiotherapy is at the target region, using an iMRI system to specifically image an RoI is acceptable for radiotherapy image guidance purposes. However, for those applications requiring anatomy outside the FoV, e.g., dose calculation for adaptive therapy, our system has to be supplemented by another global imaging method, e.g., the proposed MV CBCT, although this leads to the drawbacks of low image quality and additional x-ray dose. On the other hand, dose calculation requires x-ray attenuation information. This can be derived from the CBCT images directly. In the existing MRI-LINAC designs, due to the absence of CT capability, MRI-based treatment

planning or deriving pseudo-CT images from the MRI have to be employed. Great success in these approaches has been demonstrated in a number of studies.^{34–38}

4.1.2 Compact size

The smaller FoV may allow a more compact scanner design as compared with the existing MRI-LINAC systems. This should, in principle, help mitigate the electromagnetic and geometric interference problems between the imaging and therapy subsystems. Another benefit associated with the compact size is the potential to retrofit the iMRI device on an existing LINAC without significant modification of the current LINAC system. This is an attractive feature from a practical point of view as it may enable MRI-based image guidance on existing LINACs, as opposed to purchasing a new MRI-LINAC system. In addition, the reduced system size may also maintain the use of noncoplanar beam angles in radiotherapy, a feature that has been recently explored extensively and shown to be effective for achieving high quality plans.⁶ While many studies have investigated noncoplanar treatment issue in MRI-LINAC systems,¹⁴ to our knowledge, existing MRI-LINAC systems are constructed with only coplanar delivery capability.

4.1.3 Low field strength

The concept design utilized a low magnetic field of ~ 0.3 T for the purpose of proof-of-principle. However, under this design, it may be challenging to substantially increase the field strength to ~ 1.5 T, the highest level reported in existing MRI-LINAC systems.^{8–10} The low field strength in our system will result in a lower signal-to-noise ratio and reduced image quality. The MRI images may be clinically acceptable for radiotherapy image guidance applications, as is shown in the MRIdian system with a 0.35-T field. However, advanced applications in other clinical scenarios, e.g., MRI-based functional and physiological imaging, are expected to be limited.

4.1.4 Rotational scan

If the system will employ an rSEM method, a rotational scan is need for MRI data acquisition. This will actually prevent the system from imaging at a fixed gantry angle and therefore real-time imaging during treatment delivery. Compared with other MRI-LINAC systems, the lack of real-time imaging capability is a downside of the proposed system. When treating tumors with motion, (e.g., lung or liver cancers), a certain form of motion management method has to be used.³⁹

4.1.5 System cost

Cost can be generally categorized into system development, production, and clinical deployment. Similar to other MRI-LINAC systems, our system will require substantial developments from this initial concept to a final project. In terms of system production, since other MRI-LINAC systems employ mature MRI techniques and products for diagnostic imaging field, they are expected to be cost effective, especially considering that all the novel developments, e.g., MRI sequences, can be adopted. On the other hand, our system may hold the advantage of cost-effectiveness at the clinical deployment stage. If the proposed concept can be realized to retrofit the iMRI component on an existing LINAC platform, the cost to upgrade an LINAC with the iMRI part may be lower than purchasing a new

MRI-LINAC system. Other costs such as treatment vault design and renovation are also expected to be lower.

4.2 Study Limitations and Future Directions

This paper serves as a proposal to introduce a new concept of an integrated MRI-LINAC system. It is only for the purpose of illustrating this principle and is by no means comprehensive. One notable limitation is the simplified calculation without considering many realistic factors. For instance, the magnetization of the LINAC components and their impacts on the MRI device were ignored. The design of the RF coil was not included.⁴⁰ The performance and shielding of the RF field were not considered. In addition, in the imaging study, the Gaussian noise added to the simulation was overly simplified. With these limitations, the proposed design should be only accepted as a concept, whereas its feasibility should be studied in the future with more in-depth investigations. It is also noted that a number of research groups have made valuable contributions in this MRI-LINAC field and have addressed the aforementioned issues that were not considered in our studies. Pioneering work on these issues will be of tremendous importance for us to further improve the system design in the future. Here, we will briefly present a few directions.

4.2.1 Field homogeneity

Field homogeneity is the first concern. We have used a simple permanent-magnet design to illustrate our idea, whereas the achieved homogeneity level cannot meet the requirement for a conventional MRI imaging method. There are many directions to further improve the system. With an optimized surface shape of the magnets, the field variation within the FoV can be reduced.⁴¹ Together with shimming techniques,⁴² it may be possible to achieve a sufficiently homogeneous field in the RoI for imaging purposes. Another direction is using superconducting magnetic coils in lieu of the permanent magnets. Many novel magnet optimization approaches can be employed to develop a design to meet system requirements.⁴³ Using superconducting magnets is also beneficial in terms of increasing the field strength and, hence, improving the MRI signal-to-noise ratio. However, the associated cooling and electronic systems would increase system complexity. In addition, it is also noted that the impact of MLC motion on field distortions cannot be ignored for MRI-LINAC systems.⁴⁴ Further studies must be performed to resolve this issue.

On the other hand, novel spatial encoding, data acquisition, and reconstruction methods that have emerged recently have allowed the use of a nonhomogeneous field for MRI imaging.^{16–18,45} With carefully designed magnets, it is possible to achieve a constant gradient and, hence, permit projection-based reconstruction.⁴⁶ In either way, mechanically rotational data acquisition, which naturally fits to the iMRI-LINAC system due to the required CBCT data acquisition, is used. We will also explore research along this direction as relaxing field homogeneity requirements would lead to tremendous benefits in terms of making a compact and low-cost system.

4.2.2 System size

One of the motivations of the proposed concept is to achieve a compact-size system to allow integration on an existing LINAC platform. While the proposed system can achieve several treatment configurations, as illustrated in Figs. 1(b)–1(d),

Fig. 8 (a) Another design of the iMRI device installed on the LINAC gantry. (b) Comparison of field strength along the x direction with and without the U structure.

it requires thorough investigations that consider all possible scenarios in radiotherapy treatments. In addition, the currently shown design weighs about 2.2×10^3 kg, posing a challenge to maintaining mobility and geometry accuracy. Hence, it is necessary to seek a more compact and light-weighted design. For instance, using a simple bar connecting the two arms holding the permanent magnets may return the magnetic flux [as indicated by the arrow in Fig. 8(a)] rather than a full U-shaped yoke. In this case, the arms holding the iMRI device should be made of ferromagnetic material. In addition, using superconducting magnets is another option to reduce system size.

4.2.3 Computed tomography image quality

Due to limited FoV, x-ray CBCT is necessary in the proposed concept to provide global imaging. The current design relies on MV CBCT to achieve this goal. However, this modality is rarely used in current clinics due to the concerns of low image quality compared with kV CBCT⁴⁷ and high imaging dose.⁴⁸ To mitigate these concerns, future developments, such as using a low-Z MV x-ray target for imaging⁴⁹ and advanced reconstruction algorithms, are needed.⁵⁰

4.2.4 Other considerations

One of the most important considerations in the design of the iMRI device is the placement of a ferromagnetic material component wrapped around the two permanent magnets. This component guides the flow of the magnetic flux in the 3-D space, confines them, and hence shields the field from other electromagnetic pieces in the LINAC system. It is desirable to seek materials with high magnetic permeability to improve the effectiveness of guiding the magnetic flux and shielding.^{41,51} At the same time, this can also increase the field strength at the iMRI FoV. The comparison of the magnitude of the magnetic flux density along the x axis with and without the U-shaped yoke is shown in Fig. 8(b). When moving away from the FoV toward the LINAC gantry (at the negative x direction), the field reduced to zero and then slightly increased in magnitude but with its direction reversed.

4.3 Clinical Applications

Our simulation study on a liver patient case demonstrated the potential application of the iMRI system for pretreatment patient

positioning. This is beneficial for disease sites that have relatively low image contrast under current CBCT image guidance and are, at the same time, subject to nonrigid anatomy motion from day to day, as have been demonstrated by many other studies.⁵² Examples include liver, cervical, and head-and-neck cancers. While brain tumors can be better visualized with MRIs as compared with CTs, the benefit of using an MRI is probably not significant. The position of the brain tumor is relatively rigid to bony structures that can be used as a clear surrogate in CBCT-based patient positioning, although directly imaging the target is desired for robustness considerations.

Many tumors rapidly regress during the treatment course in response to radiotherapy. The ability to image the corresponding tumor shape variation and its position change relative to normal organs is critical for the success of adaptive therapy. The adaptively adjusted treatment plan will improve treatment optimality at every fraction.⁵³ At present, the software workflow in the existing MRIdian system has enabled the performance of online treatment replanning while the patient stays on the treatment couch.⁵⁴ Clinical advantages have been initially demonstrated with many other ongoing investigations. Our group has also performed developments to overcome the computational burden in the treatment replanning problem.⁵⁵ Study about treatment replanning is beyond the scope of this manuscript. Our future work will adapt our in-house replanning tools to the context of MRI-based treatment adaptation.

Disclosures

Authors declare that no conflicts of interest exist.

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