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Initial clinical experience building a dual CT- and MR-guided adaptive radiotherapy program

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ABSTRACT

Introduction: Our institution was the first in the world to clinically implement MR-guided adaptive radiotherapy (MRgART) in 2014. In 2021, we installed a CT-guided adaptive radiotherapy (CTgART) unit, becoming one of the first clinics in the world to build a dual-modality ART clinic. Herein we review factors that lead to the development of a high-volume dual-modality ART program and treatment census over an initial, one-year period.
Materials and Methods: The clinical adaptive service at our institution is enabled with both MRgART (MRIdian, ViewRay, Inc, Mountain View, CA) and CTgART (ETHOS, Varian Medical Systems, Palo Alto, CA) platforms. We analyzed patient and treatment information including disease sites treated, radiation dose and fractionation, and treatment times for patients on these two platforms. Additionally, we reviewed our institutional workflow for creating, verifying, and implementing a new adaptive workflow on either platform.
Results: From October 2021 to September 2022, 256 patients were treated with adaptive intent at our institution, 186 with MRgART and 70 with CTgART. The majority (106/186) of patients treated with MRgART had pancreatic cancer, and the most common sites treated with CTgART were pelvis (23/70) and abdomen (20/70). 93.0% of treatments on the MRgART platform were stereotactic body radiotherapy (SBRT), whereas only 72.9% of treatments on the CTgART platform were SBRT. Abdominal gated cases were allotted a longer time on the CTgART platform compared to the MRgART platform, whereas pelvic cases were allotted a shorter time on the CTgART platform when compared to the MRgART platform. Our adaptive implementation technique has led to six open clinical trials using MRgART and seven using CTgART.
Conclusions: We demonstrate the successful development of a dual platform ART program in our clinic. Ongoing efforts are needed to continue the development and integration of ART across platforms and disease sites to maximize access and evidence for this technique worldwide.

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Introduction

Advances in image-guidance and treatment planning techniques have widened the therapeutic index of radiotherapy. In prostate cancer, image guided radiotherapy (IGRT) has improved progression-free and overall survival while limiting toxicity compared to conventional radiotherapy [1]. In lung cancer, volumetric-modulated arc therapy (VMAT) produces improved dosimetry compared to intensity modulated radiotherapy (IMRT) with reduced delivery time [2]. These techniques have allowed for the delivery of dose-escalated and stereotactic body radiotherapy (SBRT) to disease sites that have previously been limited by radiosensitive organs at risk (OARs), such as the luminal gastrointestinal tract in pancreas cancer and the bronchial tree in ultra-central lung cancer [3,4].

Online adaptive radiotherapy (ART) is an advanced image guidance and treatment planning technique that involves re-contouring and re-optimizing a patient's radiation treatment plan based on the patient's anatomy-of-the-day, all while the patient is on the treatment table. A robust ART delivery system requires high quality on-board imaging for daily target and OAR visualization, a fast and efficient integrated treatment planning system capable of re-optimization while the patient is on the treatment table, and patient-specific quality assurance (QA). Magnetic resonance-guided adaptive radiotherapy (MRgART) has been demonstrated to improve outcomes while reducing toxicity in a variety of disease sites whose treatment was previously limited by poor inter- and intra-fraction motion management [5–8]. Most notably, the phase II SMART trial (NCT03621644) evaluating stereotactic MR-guided adaptive radiotherapy (SMART) for locally advanced pancreatic cancer demonstrated promising outcomes in this challenging patient population [9], and a phase III trial is underway (NCT0558554).

Our institution was one of the first to clinically implement an MRgART platform in 2014 and have since demonstrated the dosimetric and early clinical benefits of MRgART for a variety of disease sites [6,10–12]. We have previously described our clinical experience at two-and-a-half [13] and four-and-a-half [14] years into the installation of this ART modality. More recently, in 2021 we installed a cone beam computed tomography-guided adaptive radiotherapy (CTgART) platform for clinical use, being one of the first clinics in the world to have a dual modality adaptive radiotherapy clinic. Herein we discuss our one-year experience building a dual CT- and MR-guided adaptive radiotherapy program at a high-volume academic center by analyzing our treatment numbers and use of adaptation. Additionally, we describe our approach to implementing new ART treatment techniques to assist clinics around the world that are interested in installing a similar dual-modality ART program.

Materials and methods

Department and adaptive radiotherapy service overview

ART is the process of modifying a treatment plan based on clinical indications to adapt the treatment plan or recover back to the initial physician intent [15]. ART can be performed with (online) or without (offline) the patient on the treatment table. Online ART presently is most often used to account for inter-fractional changes such as luminal bowel motion or bladder filling. At our institution, we have both MRgART (MRIdian, ViewRay, Inc, Mountain View, CA) and CTgART (ETHOS, Varian Medical Systems, Palo Alto, CA) ART platforms. For added context for others to understand our clinical environment, we analyzed clinical information from a departmental prescription ordering software (Oncologic Computing Facility, Washington University School of Medicine, St. Louis, MO) for a brief overview of all patients treated within our department as well as an in-depth analysis of all patients treated with adaptive intent on these platforms to obtain information such as treatment census volume, disease site, and dose and fractionation patterns between October 2021 to September 2022. Treatment times were evaluated by accessing time slot information from the ARIA (Varian Medical Systems, Palo Alto, CA) scheduling software.

MR-guided adaptive radiotherapy overview

The MRgRT system utilized at our institutions has been described previously [16–18]. As for the default adaptive workflow, the system uses a cascade or iterative ART workflow, meaning the most recent plan delivered is used as the initial plan for adaptation in the next fraction, which helps minimize redundant adaptation to account for gross changes occurring from time of simulation to first treatment [19]. The primary dataset is typically a T1/T2 weighted TrueFISP MR-image. The MRgRT system rigidly or deformably registers the primary dataset and contours onto the daily anatomy. MR images are the primary image for planning, and thus electron density information is assigned using bulk density override and/or deformation of a CT to the primary dataset. Density information must be verified before treatment. Upon contour completion, a plan of the user's choice (typically the plan most recently used for treatment) is predicted on the anatomy-of-the-day. If clinical intent is not met on the predicted plan, the plan is then re-optimized and re-generated based on the anatomy-of-the-day. During re-optimization, the planning objectives and normalization can be adjusted to further account for nuanced changes within the patient's anatomy or change in clinical intent. Upon plan approval, a full volumetric 3D dose calculation is performed along with auxiliary QA for plan integrity [20,21]. As for treatment delivery, motion monitoring is conducted using cine-MRI imaging. An automatic deformable registration algorithm is utilized to monitor the target on cine-MRI, and gate the beam on and off when the target moves from the treatment position [22,23]. In addition to this overarching MRgART workflow, disease-site-specific workflows for adaptation have been developed and previously described [5–7]. For the MRgART patients, we collected the number of intended adaptive patients, breakdown of disease sites by pancreas, abdomen, hepato-biliary, pelvis, and head & neck. Additionally, we evaluated the intended dose and fractionation prescription for each adaptive patient.

CT-guided adaptive radiotherapy overview

The components of the CTgART linac utilized at our institution have been described previously [24,25]. By default, the adaptive workflow uses a serial ART workflow where the treatment plan created at time of simulation is used as the initial plan for all adaptive fractions, which minimizes risk of propagation of systematic errors made during the adaptive process [19]. During the adaptive workflow, the underlying planning CT is deformed to the CBCT image for electron density information and must be verified. However, all contouring and plan visualization is displayed on the daily CBCT. Depending on the disease site, either artificial intelligence (AI) or contour deformation is used for target and OAR segmentation. One has the option to rigidly propagate the target if desired. Upon contour completion, the initial plan developed on the simulation CT is then calculated on the anatomy-of-the-day along with the re-optimized adaptive plan. No further planning adjustments can be made unless contours are manipulated, which requires plan re-optimization and re-calculation. Upon plan approval, a full volumetric 3D dose calculation is performed along with auxiliary QA for plan integrity. Motion management is done using repeat CBCT imaging or surface monitoring (if beam gating is needed). In addition to this overarching CTgART workflow, disease-site-specific workflows have been developed and previously described [26–30]. For the CTgART patients, we collected the number of intended adaptive patients, with breakdown of disease sites by pancreas, abdomen, hepato-biliary, pelvis, and head & neck. Additionally, we evaluated the intended dose and fractionation prescription for each adaptive patient.

Adaptive radiotherapy workflow development

With the adaptive platforms described above, we will now discuss how our institution develops ART workflows for various disease sites (Fig. 1). The selection of a new adaptive treatment site is driven by the perceived clinical need for adaptation, which is generally determined by target proximity/dose to OAR position/dose limit as well as inter-fractional changes in tumor and adjacent OAR geometry [31]. For example, our team has demonstrated that proximity within 1 cm of mobile OARs predicts for need to adapt when treating primary liver cancers with MRgART (Chin et al 2022, accepted by *Clinical and Translational Radiation Oncology*). Once a new potential disease site/scenario is identified, a prospective clinical imaging study is typically used to determine if image quality is adequate for online ART for that specific disease site.

If visualization is deemed appropriate (adequate visibility of the target and/or OAR changes that the clinician intends to respond to through ART), the adaptive physicians then communicate to the ART team, such as physics, to develop treatment planning protocols that match physician intent. Importantly, these adaptive treatment plans must be robust to daily changes unique to each disease site (i.e., bladder or rectal filling in the pelvis, vs. bowel displacement in the abdomen) and match clinical intent throughout the treatment. To test this, *in silico* evaluations are then performed to evaluate the robustness of the adaptive treatment plan template in responding to inter-fraction changes and to ensure that adapted plans can be created online, *in silico,* to match clinical intent. The *in-silico* portion of the workflow uses daily patient treatment images, typically from the imaging study, that are injected into an ART emulator system to simulate the adaptive workflow for this disease site. ART emulators are used for the evaluation of both MRgART and CTgART. Once the ART treatment process intent is rigorously developed and tested, ideally a prospective clinical trial is developed if there are no existing studies that match the adaptive treatment intent to evaluate the paradigm in the clinic. Presently current accruing studies and studies that have been in development during the year this manuscript evaluated treatment data are described, many of which were developed via this process.

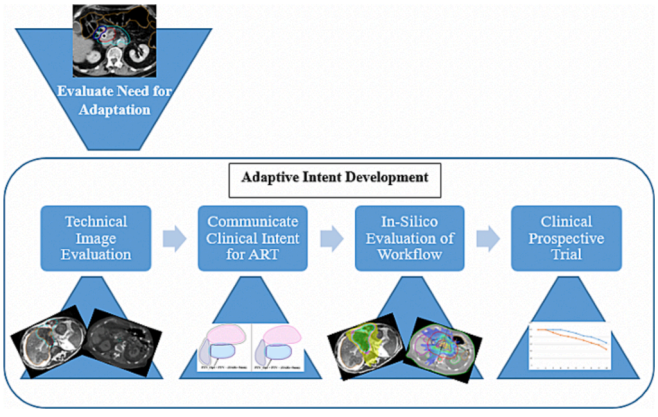

Fig. 1. Implementation of a new adaptive workflow. The implementation of a new adaptive workflow for a novel disease site is a rigorous multi-step process. The necessity for adaptation for a disease site is generally driven by the proximity of that site to adjacent OARs as well as by inter-fractional tumor and/or OAR change. Once a disease site is identified to be evaluated for an ART workflow, image evaluation is performed to confirm that the ART platform can adequately and consistently image the target and adjacent OARs. Clinical intent for ART is then communicated and a robust site-specific treatment planning template is created. This template is evaluated in-silico, and if ART appears to be dosimetrically feasible, clinical prospective trials are initiated to evaluate the paradigm in the clinic.

Results

Department and adaptive radiotherapy service overview

Our dual-modality adaptive program is deployed within an academic clinical site that treats approximately 130 to 150 patients per day. In addition to the MRgART and CTgART platforms, this departmental site has a single, cobalt-based stereotactic radiosurgery device, five conventional C-arm linacs, one SBRT-focused c-arm linac, two high-dose-rate brachytherapy after-loaders, two proton units (one active, one under construction), two CT simulators, and one MRI simulator. From October 2021 to September 2022, the total number of distinct adaptive treatment courses treated on both adaptive platforms was 256.

Comparison of MR-guided and CT-guided adaptive radiotherapy programs

The MRgART platform treated 186 courses of planned adaptive treatments compared to 70 courses of planned adaptive treatments on the CTgART platform. The MRgART platform mostly treated pancreas at 106 courses, followed by abdomen at 34, and hepato-biliary at 27. On the CTgART platform, the highest volume of adaptive courses was pelvis at 23, followed by abdomen at 20, and both pancreas and head & neck equal at 13. The disease site breakdown is illustrated in Fig. 2. The fractionation patterns for our adaptive program are illustrated in Fig. 3. On the MRgART platform, 93.0% of adaptive courses had an SBRT intent whereas in the CTgART setting, 72.9% of adaptive courses had an SBRT intent. Relating to fractionation patterns, treatment time slots for select treatment sites are presented in Table 1. Abdominal gated cases were in shorter time slots on the MRgART platform compared to the CTgART platform. Conversely, pelvic treatments had shorter time slots on the CTgART platform when compared to the MRgART platform. Within the CTgART workflow, pelvic cases are aided by AI-driven auto-segmented pelvic OARs during the re-contouring part of the adaptive process, which greatly decreases the adaptive treatment time for pelvis.

To demonstrate our observation that either ART platform could be suitable for a given case in similar disease sites, cases of separate patients with similar left-sided and right-sided adrenal lesions treated with MRgART and CTgART, respectively, are illustrated in Fig. 4. The left-sided lesion, treated on the MRgART platform, was near the stomach and small bowel which necessitated adaptation. The right-sided lesion, treated on the CTgART platform, was abutting the duodenum, again necessitating adaptation. Both patients were treated to 50 Gy in 5 fractions. Both targets had a 5 mm margin from gross tumor volume (GTV) to planning target volume (PTV). Both treatment plans limited the luminal gastrointestinal OARs to V36Gy $\leq$ 0.5 cc. The MRgART plan used 18 static step and shoot beams and the CTgART plan used two partial VMAT arcs. The motion management techniques used were real-time MRI cine gating on the MRgART and optical surface monitoring on the CTgART platforms, respectively. Both modalities were able to rectify failing constraints and achieve clinically acceptable plans with adaptation in a similar manner with near-equivalent treatment approaches.

Products of adaptive radiotherapy workflow development

All trials accruing during the reviewed period and/or treated as per protocol are presented in Table 2. Of the trials listed, five were feasibility studies designed to prospectively verify that our adaptive developmental process, as described above, culminated in successful workflows (NCT05096286, NCT05030454, NCT04379505, NCT03878485, NCT03824366). All other trials had endpoints designed to evaluate clinical gains with adaptive radiotherapy, thus acknowledging that adaptive radiotherapy is feasible in various disease settings.

Discussion

We have successfully integrated a dual-platform adaptive

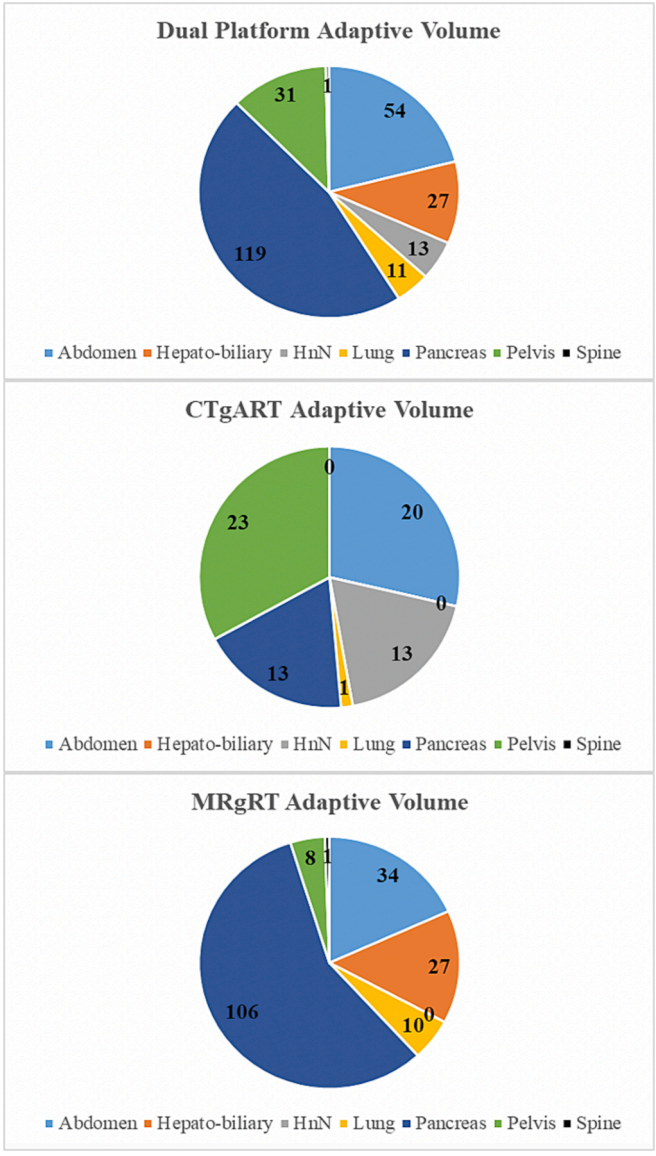

Fig. 2. Adaptive radiotherapy volume. Pie charts of our total, CT-guided, and MR-guided ART patient volume over the 2021–2022 time period. The vast majority of the MR-guided ART volume was dedicated to pancreatic cancer, whereas the top two sites treated with CT-guided ART were the pelvis and the abdomen. The numbers indicate the number of patients treated with adaptive intent within each disease site. HnN = head and neck.

radiotherapy program into our clinic. We have demonstrated that adaptation can be utilized across a diverse patient census, ranging from cancers of the head & neck to the pelvis. Additionally, we have also shown that both CT- and MR-guided ART platforms can achieve similar adaptive treatment intents, including for complex sites like the upper abdomen. Through meticulous development and deployment of an ART implementation technique across multiple platforms, the flexibility and accessibility of ART for use in diverse practice settings and patient scenarios is improved and continues to grow.

Both CTgART and MRgART can improve the dosimetric therapeutic index across diverse disease sites and clinical scenarios, with growing clinical evidence for safety and early efficacy supporting ART's continued use [26,32–34]. In particular, several *in silico* studies have shown that the use of ART has the ability to resolve OAR constraints, improve target coverage, or do both simultaneously [10,26,27]. For example, an *in silico* study of CTgART for locally advanced pancreatic cancer demonstrated that the use of adaptation significantly improved target coverage while resolving 94 OAR constraint violations, which occurred across 40/40 fractions performed [27]. Similarly, it has been shown that large dose gradients between intended target dose and adjacent OAR constraint doses predict increased need for adaptation to preserve the therapeutic index [31]. These improvements in the dosimetric therapeutic index through ART have translated to an improvement in the clinical therapeutic index. For example, the phase II SMART trial (NCT03621644) evaluating five fraction SMART for locally advanced pancreatic cancer demonstrated a 1-year local control and overall survival of 82.9% and 93.9%, respectively, which compare extremely favorably with historical controls [9]. This efficacy was achieved with a clinically and statistically significant reduction in radiation-related acute grade 3 or greater toxicity from a historic rate of 15% to 0% observed in the trial. Adaptation was used in 93.1% of fractions. This trial is one of multiple prospective and retrospective studies now demonstrating that the dosimetric benefits of ART can translate to clinical benefits for patients.

Although fundamental differences exist between CT and MR guidance, as well as their current, respective commercial platforms, we have shown that in certain clinical scenarios, CT-guided and MR-guided ART can be used relatively interchangeably. In our experience, an example of this was SBRT to the pancreas or other abdominal lesions, which was performed on both platforms (89.9% of total patients treated using MRgART and 47.1% of total patients using CTgART in this one-year experience). Our observation is supported by the recent completion of a phase II trial of adaptative pancreas SBRT with MR-guidance as described above, as well as the active accrual to a parallel, phase II trial of adaptive pancreas SBRT with CT-guidance (NCT05764720). Given the established complexity of abdominal SBRT compared to many other disease sites (historically challenging target visualization, close proximity of OARs to the target, substantial inter- and intra-fractional motion), the ability to implement ART using both CT and MR-guided platforms in the upper abdomen indicates the capacity to treat a variety of disease sites on either platform. Indeed, prospective clinical and dosimetric evidence supports the feasibility and safety of treating abdominal and thoracic primary and oligometastatic tumors using adaptive SBRT on both platforms [5,7,26,35]. Adaptive thoracic radiotherapy for ultra-central non-small-cell lung cancers is currently under investigation in similar phase I/II and phase I clinical trials on both CT- and MR-guided platforms (NCT40925583; NCT04917224; NCT05785845). Similarly, adaptive prostate radiotherapy has been implemented across both CT-guided and MR-guided platforms [36,37].

Nonetheless, some of the present differences between CT- and MR-guided ART platforms have shaped our current, institutional, clinical use. The current CT-guided commercial platform integrates AI-driven auto-contouring that performs particularly well in pelvic disease settings. It also enables VMAT and sliding window dynamic multi-leaf collimator IMRT delivery, which are known to be faster than step-and-shoot IMRT delivery. Thus, despite that pelvic adaptive radiotherapy has been implemented on both platforms with success at other institutions in our clinic, pelvic and hypo-fractionated ART regimens are preferentially delivered on our CT-guided ART platform, where the reduced time from imaging to treatment on our CT-guided platform is critically advantageous to avoid time for bladder or rectal filling. Similarly, inherent imaging properties of MRI enable improved soft tissue contrast over CT that is well-established and impactful in several disease scenarios, such as for treating liver tumors [38–40]. Current commercial MRgRT platforms also enable real-time cine gating, which can allow for unique continuous visualization and tracking of particularly mobile tumors [41]. This is consistent with our observation of a larger proportion of abdominal cases being treated with MRgART at our institution. However, as the technology for both CT- and MR-guided ART platforms swiftly evolve, such as with efforts to reduce MR treatment times [42] and improve the quality of on-board CT imaging [43], these differences will also evolve, and in many cases, the interchangeability of CT- and MR-guided ART is likely to increase as commercial

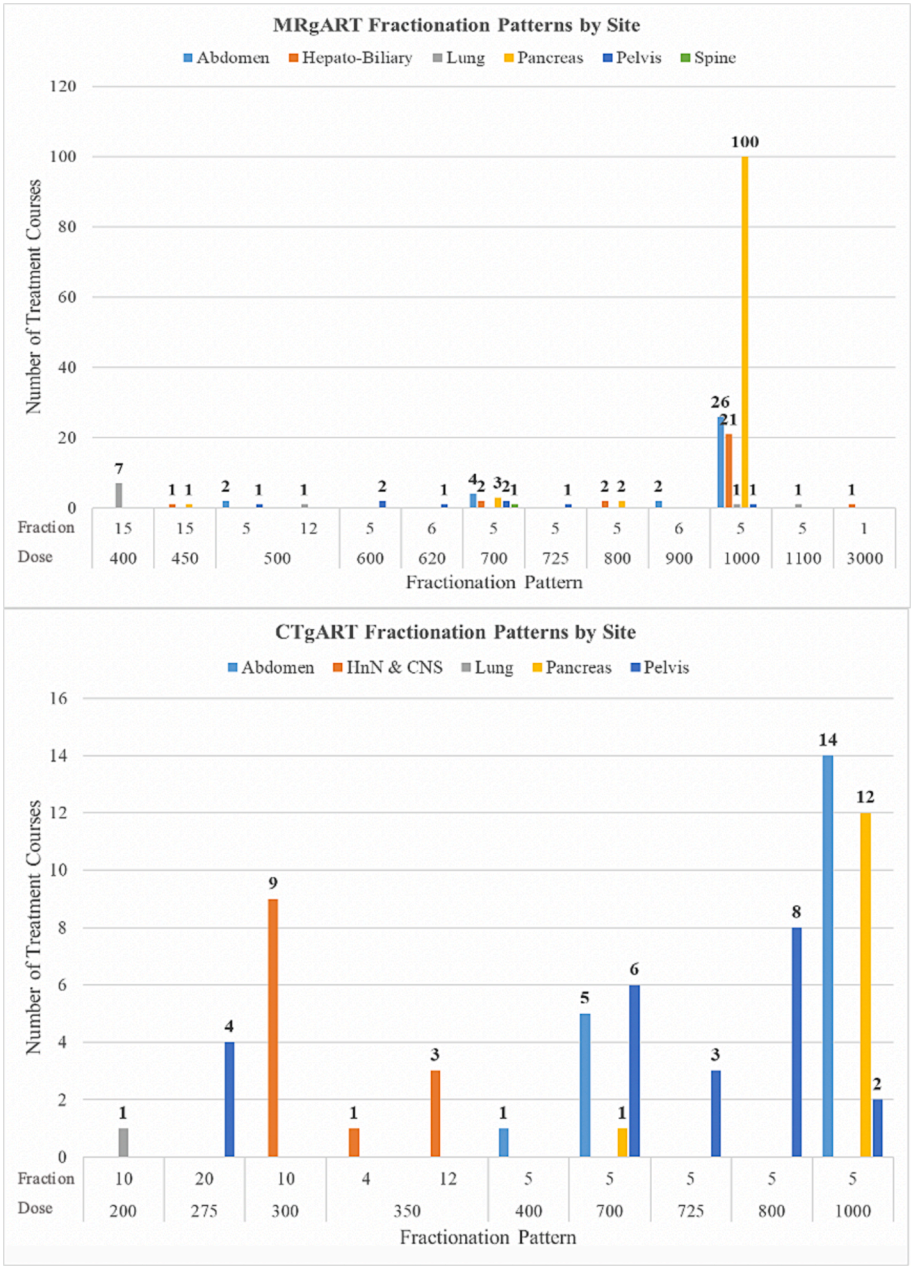

Fig. 3. Dose and fractionation patterns for MR-guided and CT-guided ART. Dose and fractionation patterns are demonstrated for our MR-guided and CT-guided ART platforms over the 2021–2022 time period. The vast majority of patients treated with MR-guided ART were 5000 cGy in 5 fraction pancreatic cancer patients, whereas the CT-guided ART distribution was more varied in terms of disease site as well as dose and fractionation. The x-axis indicated the number of treatment courses for each specific dose/fractionation pattern. The fractionation units are in the top row of the y-axis and the dose units are in the bottom row of the y-axis, with the dividers in the y-axis separating different dose levels. Y-axis dose units are in cGy and fractionation units are in number of fractions per treatment course. HnN = head and neck, CNS = central nervous system.

Table 1
Treatment time per patient. A comparison of average treatment time slot per patient for adaptive bladder IMRT, prostate SBRT, and gated pancreas SBRT treatments.

Treatment Type	MRgART Treatment Time Slot (min)	CTgART Treatment Time Slot (min)
Adaptive Bladder IMRT	60	30
Adaptive Prostate SBRT	70	45
Adaptive Gated Pancreas SBRT	80	100

entities attempt to compete for market share and clinical teams strive to implement dosimetrically useful adaptive techniques across disease sites, using whichever system is locally available. Nonetheless, we highlight and evidence here that small differences between systems can be capitalized upon to carefully tailor use by disease site/indication and that a single clinic can potentially support both CT- and MR-guided adaptive technologies at the same time, with nuanced use for each.

Significant factors for building a multi-platform CT- and MR-guided ART clinic are the time and staffing resources involved. Considering that in many ART applications, a new daily plan is created while the patient is on the treatment table, which is similar to patients receiving brachytherapy or Gamma Knife radiosurgery who are waiting with implant or frame in place. Therefore, parallels can be drawn from brachytherapy and Gamma Knife radiosurgery in terms of staffing models, time required, and time pressure to rapidly produce daily plans. Time required for ART varies by disease site (Table 1) but at present, is typically longer than a standard IGRT timeslot in our clinic [6,44]. We anticipate that further integration of AI and use of parallelized workflows will drive down the time and required resources necessary for ART and improve accessibility [45]. It stands to reason that just as brachytherapy, Gamma Knife, and even IMRT were once significantly more time-consuming, so will ART delivery times further improve. In addition to AI, integration of specialized team members, such as advanced practice radiation therapists to assist with contouring and plan review

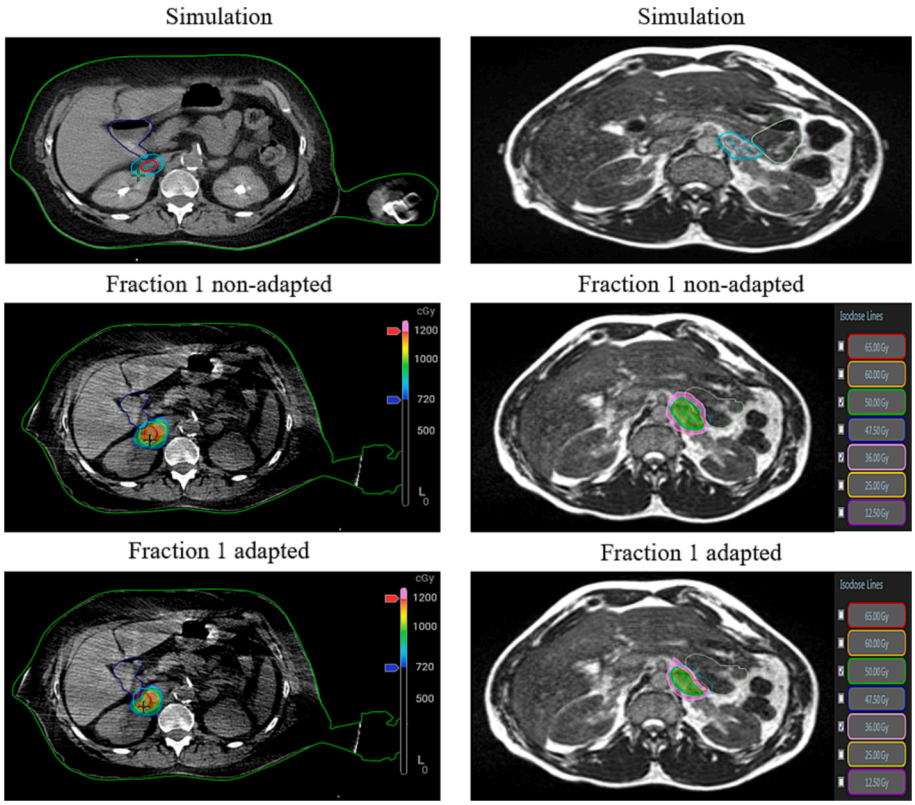

Fig. 4. CT-guided and MR-guided ART for adrenal metastases. Simulation, first fraction non-adapted, and first fraction-adapted CT- (left) and MR-guided (right) SBRT treatments for right- and left-sided adrenal metastases. Each set of images demonstrates how use of the non-adapted plan on the anatomy-of-the-day would have violated the relevant luminal gastrointestinal OAR constraint, which was resolved with ART.

Table 2
Adaptive prospective clinical trials. An exhaustive review of all clinical trials open at our institution over the past year in which patients were treated with either CT-guided or MR-guided ART.

National Clinical Trial Number	Modality	Disease Site	Brief Trial Description	Single vs. Multi-institutional	Primary Endpoint	Status
05764720	CTgART	Abdomen	CT-STAR for locally advanced pancreatic cancer	Multi	Toxicity	Accruing
05096286	CTgART	Central nervous system	Simulation-free hippocampal avoidance whole-brain radiotherapy	Single	Feasibility	Accrued
05628363	CTgART	Genitourinary	SBRT to prostate and pelvic nodes for unfavorable intermediate and high-risk prostate cancer	Single	Toxicity	Accruing
05700227	CTgART	Genitourinary	Short-course radiotherapy and concurrent chemotherapy for muscle-invasive bladder cancer	Multi	Toxicity	Accruing
04379505	CTgART	Head and neck	Adaptive quad shot palliative radiotherapy	Single	Feasibility	Accruing
05785845	CTgART	Thorax	CT-STAR for ultra-central early-stage NSCLC	Single	Toxicity	Open
05030454	CTgART	Thorax and abdomen	Optical surface guidance system for gated CTgART delivery	Single	Feasibility	Accrued
03621644	MRgART	Abdomen	SMART for locally advanced pancreatic cancer	Multi	Toxicity	Accrued
04331041	MRgART	Abdomen	SBRT and focal adhesion kinase inhibitor for advanced pancreatic cancer	Multi	Progression-free survival	Accruing
04162665	MRgART	Abdomen	Pre-operative radiotherapy for gastric cancer	Single	Pathologic complete response	Accruing
03878485	MRgART	Spine	Same-session simulation and treatment for spinal oligometastases	Single	Feasibility	Accruing
03916419	MRgART	Thorax	Hypofractionated radiotherapy with concurrent chemotherapy for locally advanced inoperable lung cancer	Single	Local and regional control	Accruing
03824366	MRgART	Thorax, abdomen, pelvis	Same-session simulation and treatment with palliative radiotherapy	Single	Feasibility	Accrued

steps, can further reduce present costs considerations like duration and frequency of physician and physicist presence for ART delivery [46].

Swift evolution of technology as well as broadening clinical uses for ART also require that the clinical adaptive team constantly re-evaluate and shape new workflows, train (and re-train) members, and reassess machine use and practice models. In our initial implementation of CTgART, we have developed novel workflows for the treatment of intact bladder cancer, prostate SBRT with nodal chains and Simultaneous integrated boost (SIB)-style boosts, among others, that differ from other established adaptive workflows [47]. Team member turnover is a clinical reality in most clinics, and so on-boarding of new members (as well as re-training of old members for new techniques) using a typical

shadowing, buddy-system, and then independent practice ("see one, do-one, teach one") approach is essential. At present, our institution holds a monthly adaptive working group meeting where involved members present and refine novel workflow and trial concepts, enabling streamlined team teaching and group involvement in the development of new disease site applications. When "doctor-of-the-day" style coverage is utilized for daily ART procedural coverage, communication of clinical intent between team members is also essential; we utilize a well-described adaptive guideline approach, in which a detailed written hand-off guides the covering physician to meet the prescribing physician's clinical goals for individual ART patients [48]. Reassessment of clinical use following major technologic upgrades is also critical for evolution of ART use. In our clinic, widespread use of CTgART for abdominal SBRT did not occur until feasibility and safety of the paired intrafraction motion management system for breath-hold gating was demonstrated (Kiser et al, presented at ASTRO 2022). ART represents a rapidly evolving research and clinical space, and team flexibility, communication, and training continue to be necessary.

Evolution of ART is also likely to broaden its application across radiotherapy platforms. Just as CT- and MR-guided commercial platforms rely on imaging, integrated treatment planning systems, and pre-treatment QA to enable ART, so might other platforms integrate these components for ART. Proton gantries and C-arm linacs likely represent the immediate next frontiers for ART integration and open-ended machine-agnostic commercial solutions are being developed [49] to improve ART accessibility on existing machines. Functional imaging will also continue to be incorporated into ART [50] as well novel applications of ART, such as for simulation-free, treatment expediting workflows.

Overall, through multi-platform ART integration, we have increased the accessibility and clinical applications of ART in our clinic. Just as IMRT and VMAT have become standard tools in the radiation oncology clinic, so might ART become a standard component of radiotherapy treatment considerations. Ultimately, the goal of multi-platform ART development is to make it so that our clinic is no longer unique; we strive to make ART a commonplace, ubiquitous tool used to the dosimetric and clinical gain of diverse patients across the global radiation oncology clinic.

Conclusion

Herein, we demonstrate the successful development and integration of a dual platform ART program within our clinic. ART can widen the dosimetric and clinical therapeutic index and applications of radiotherapy. Further thoughtful and clinical-evidence-generating efforts are needed to continue the development and integration of ART across platforms and disease sites to maximize access and evidence for this technique, worldwide.

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Data availability

Research data are stored in an institutional repository and will be shared upon request to the corresponding author.

Declaration of Competing Interest

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