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Scientific Article

Online Adaptive Radiation Therapy and Opportunity Cost

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Abstract

Purpose: Changes in patient anatomy and tumor geometry pose a challenge to ensuring consistent target coverage and organ-at-risk sparing; online adaptive radiation therapy (ART) accounts for these interfractional changes by facilitating replanning before each treatment. This project explored the opportunity cost of computed tomography (CT)−based online ART by evaluating time and human resource requirements. Time-driven activity-based costing (TDABC) was employed to determine the cost of this time to assess if the dosimetric benefit is worthwhile.

Methods and Materials: CT-based online ART was recently employed at our institution and has been used to treat pelvic disease sites (prostate, prostate bed, prostate with nodal coverage, bladder, rectum); data points from all adaptively treated patients (415 fractions) were used. Time taken for each adaptive fraction before treatment, which at our facility is best represented by the duration between 2 cone beam CT scans, was used as a broadly applicable and transferable metric, representing the additional time required for ART on top of standard image guided radiation therapy. Dosimetric effect was also considered by taking the difference of planning target volume V100% for the scheduled and adapted plans. Using recently validated TDABC at this facility, the per fraction cost of ART was determined, reflecting the added cost of ART on top of image guided radiation therapy.

Results: A median time of 15.97 (interquartile range, 13.23-18.83) additional minutes was required for each adaptive fraction. TDABC demonstrated an average minimum cost per adapted fraction of $103.58. Dosimetric differences between V100% of the scheduled versus adapted plan showed a mean dosimetric difference of 15.8%.

Conclusions: Although online ART decreases the uncertainty of anatomic shifts, each adaptive fraction requires more staff time, delaying completion of other tasks and increasing resource utilization. Although toxicity benefits require further studies, the implementation of progressively complex radiation therapy technologies, like ART, requires consideration of the time and human resource requirements and subsequent opportunity cost.

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

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Introduction

Changes in patient anatomy and tumor geometry pose a challenge to maintaining desired target coverage and organ-at-risk (OAR) sparing. Large margins are typically used to ensure adequate tumor coverage in spite of daily anatomic variation, but at the cost of normal tissue irradiation.[1] Adaptive radiation therapy (ART) has sought to account for these changes by using near real-time replanning to account for anatomic changes and maintain consistency in dose delivery.[2]

When done in an online fashion where treatment planning is repeated immediately before daily treatment delivery,[3] ART affords the possibility of accounting for organ movement, including filling changes, respiration, and peristalsis. Greater ability to spare OAR and optimize target volumes has been seen in head and neck,[4] gastrointestinal[5-8] (including liver stereotactic body radiation therapy [SBRT[9]), pelvic,[10-15] and even ultracentral[16] and locally advanced lung cancers.[17]

Improvements in artificial intelligence and iterative cone beam computed tomography (CBCT) for anatomic review have decreased the amount of human time expenditure in ART,[18,19] allowing for broader implementation. However, despite auto-contouring, physician knowledge and time are still required to delineate target structures as well as to confirm accuracy of auto-contoured OARs.

To date, there is no direct literature evaluating the time, human resource, or opportunity cost of CT-based online ART and how this compares to conventional image guided radiation therapy (IGRT). The frequency of plan adaptation has not always been shown to improve clinical goals and can have diminishing returns depending on the clinical context.[20] This is true especially when OAR anatomy is stable and tumor response is gradual over several weeks; in this case, ART may be an impractical use of resources and lack clinical benefit. Frequent plan adaptation seems to have an incremental benefit when OAR and tumor anatomies vary daily.[21] Nevertheless, performing a full treatment planning workflow for every fraction of RT continues to be challenging, as it is a complicated process and mandates additional time and human intervention.

Time-driven activity-based costing (TDABC) is a system that accurately assigns costs to each step of a workflow.[22] This is an improved version of activity-based costing that seeks to map asset and expense categories to patient processes and further categorize this based on specific conditions. It considers the cost of each resource used and the time that a patient spends with each resource. Thus, TDABC has been posited to eliminate unnecessary and useless process variations,[23] improve resource capacity utilization, coordinate correct processes with correct locations, match clinical skills appropriately to each process, speed up treatment time, and optimize the full care cycle.[24]

Through a holistic evaluation of the CT-based online ART workflow at our institution, this project explored the opportunity cost by looking at the time and human resource requirements for adaptive versus conventional IGRT. Using TDABC analysis, it evaluated the cost and time effectiveness of ART with respect to cost per fraction and daily staffing.

Methods and Materials

This study evaluated the opportunity cost required for CT-based online ART across a variety of genitourinary disease sites, including prostate (8), prostate bed (2), prostate with nodal coverage (3), seminal vesicle alone (1), rectum (1), and bladder (6). Online ART was first implemented at our institution in January 2021, initially with hypofractionated prostate treatments, after which additional sites were implemented with increasing institutional experience. All adapted treatments from this first treatment through January 2022 were included. We generated a process map to delineate the workflow of online ART and the staff required for each step (Fig. 1) and collected data from 21 patients who collectively underwent 417 fractions, 415 of which were adapted. As such, these 2 fractions based on scheduled (original CT simulation-based) treatment plans were excluded from analysis. Time, which at our facility is best represented by the duration between 2 CBCT scans taken for each adaptive fraction, was selected as a broadly applicable and transferable metric that can create a robust foundation for the implications of online ART. The first CBCT captures the anatomy to which the adapted plan is being optimized, while the second CBCT is a pretreatment, post-ART verification scan of anatomy (that may have changed during the ART process) for translational IGRT. Rarely, a third or even fourth CBCT is done due to patient movement; in these cases, the time stamps collected were maintained as the first and final CBCT.

Previous studies have found that essentially all parties (dosimetrist, 2 therapists, physicist, physician) need to be present for the duration of treatment planning given the rapid response time required.[14] This is true at our institution as well. Thus, we presume the time burden on these parties to be the same, being measured from the time stamp on CBCT 1 to CBCT 2, which is the additional time required for adaptive treatment (on top of standard IGRT). As such, we do not include timepoints outside of the 2 CBCT images, as these are already part of standard IGRT workflows. These data were then plotted for comparison (Fig. 2) and a median value was obtained.

Statistical analysis was performed using Mann-Whitney U tests to evaluate the median times and

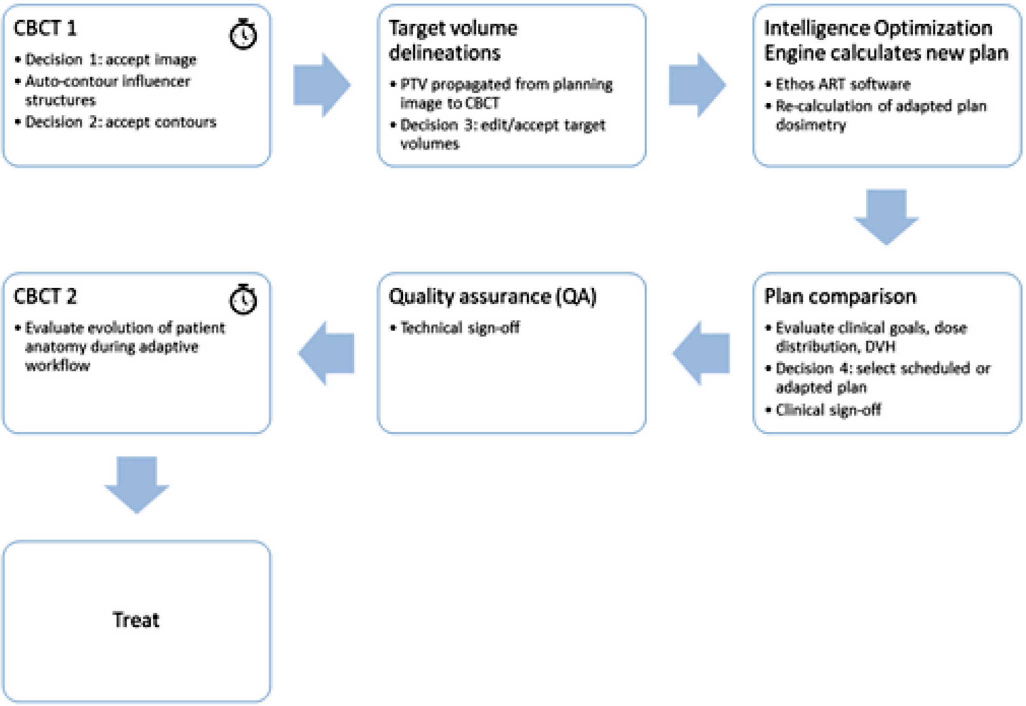

Fig. 1 Process map demonstrating the workflow for 1 online ART fraction using CT-based planning technology. Does not include setup time, treatment time, or other aspects of standard IGRT workflow. Personnel involved included radiation oncologist, physicist, dosimetrist, and 2 radiation therapists. *Abbreviations:* ART = adaptive radiation therapy; CT = computed tomography; DVH = dose-volume histogram; IGRT = image guided radiation therapy.

distributions of time between CBCTs. We define hypofractionated prostate treatment as the baseline group and report the results for hypofractionated prostate versus prostate with nodal coverage, hypofractionated prostate versus SBRT prostate, hypofractionated prostate versus conventionally fractionated prostate bed, and hypofractionated prostate versus bladder (Table 1). Rectum and seminal vesicle only patients were not included given low sample size limiting basis for comparison (each category only had 1 patient).

We then used recently validated TDABC data and strategy at our facility[22] to account for each employee's cost per minute, using the weighted average attending salary per Bingham et al[22] and proprietary dosimetrist, therapist, and physicist salaries. Internal work-hour estimates were proprietary. Salaries were then deconstructed to determine each employee's cost per minute (Table 2), which were then multiplied by the median time difference between CBCT 1 and CBCT 2 and summed to generate an average per fraction cost, which is additional to standard IGRT costs.

Dosimetric effect was also considered. The planning target volumes (PTVs) receiving 100% of the dose (V100%) for both the scheduled and adapted plan were recorded per fraction. We then took the difference between these values to evaluate the dosimetric difference between the 2 plans (Fig. 3). An average value was obtained.

Results

Time intervals from CBCT 1 to CBCT 2 for 415 online adapted fractions demonstrated a median time of 15.97 minutes (interquartile range [IQR], 13.23-18.83). The maximum time was 46.60 minutes and the minimum time was 6.05 minutes. This is the additional time required for adaptation of the plan, not including actual treatment time. Thus, this time represents the per-fraction time added to standard IGRT treatments. There was variability in the median time between disease sites, with more complex treatments taking a greater amount of time, such as SBRT and prostate treatments, which included lymph node coverage (Table 1).

As shown in Table 1, median times of ART fractions for prostate with nodal coverage (18.22 minutes; IQR, 14.95-26.77) were significantly higher than hypofractionated prostate treatments without nodal coverage (14.93 minutes; IQR, 13.04-17.73; U = 3619; Z = −5.17; $P < .00001$). Similarly, median times of ART fractions for SBRT prostate (17.34 minutes; IQR, 17.10-18.13) were significantly higher than hypofractionated prostate treatments (14.93 minutes; IQR, 13.04-17.73; U = 413.5; Z = −2.49; $P = .01314$). Median times of ART fractions for conventionally fractionated prostate bed (11.68 minutes; IQR, 9.05-14.40) were significantly lower than hypofractionated prostate treatments (14.93 minutes; IQR, 13.04-17.73; U = 873.5; Z = −3.72; $P < .0002$). No significant

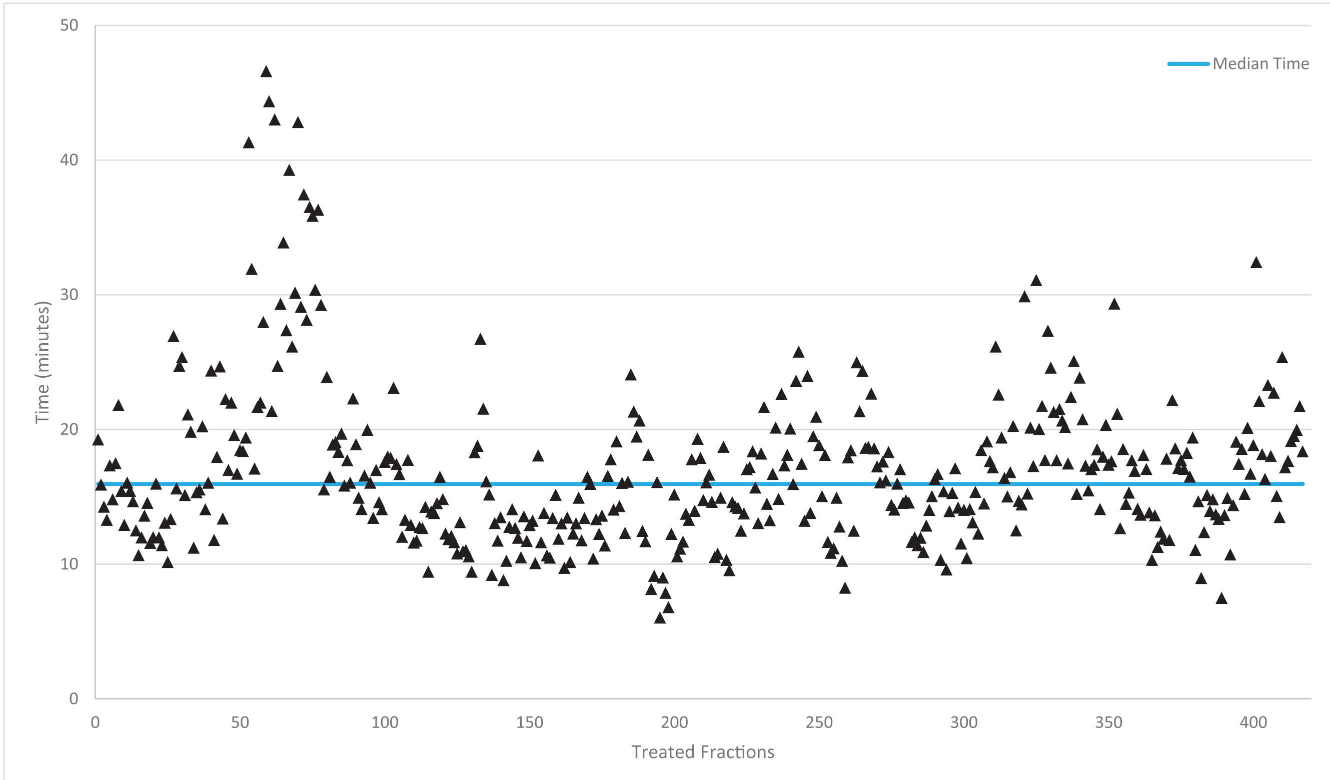

Fig. 2 Time interval from cone beam computed tomography (CBCT) 1 to CBCT 2 for 415 online adapted fractions. Treated fractions are plotted chronologically, with fraction 1 being the first fraction treated adaptively at this institution. Disease sites included prostate, prostate bed, prostate with nodal coverage, bladder, rectum, and seminal vesicle only. Median time of 15.97 minutes demonstrated by blue line.

Table 1 Demographic information for adapted fractions analyzed

Treatment site	Technique	Number of patients	Dose (Gy)	Fractionation	Median time between scans (h:m:s)	*P* value
Prostate	Hypofractionated	6	70.2	26	0:14:56	Ref
Prostate with pelvic nodes	Hypofractionated (2)	3	70.2 (2)	26 (2)	0:18:13	<.00001
	Conventionally fractionated (1)		79.2 (1)	44 (1)		
Prostate	SBRT	2	40	5	0:17:20	.01314
Prostate bed	Conventionally fractionated	2	19.8	11	0:11:41	.0002
Prostate total		13			0:15:55	
Bladder	Hypofractionated	4	55	20	0:17:35	
Bladder	Conventionally fractionated*	2	64.8	36	0:13:14	
Bladder total		6			0:16:08	.61006

Abbreviation: SBRT = stereotactic body radiation therapy.
We define hypofractionated prostate treatment as the baseline group (ref) and report the results for hypofractionated prostate versus prostate with nodal coverage, hypofractionated prostate versus SBRT prostate, hypofractionated prostate versus conventionally fractionated prostate bed, and hypofractionated prostate versus bladder.
* One patient stopped after 17 fractions due to poor tolerance of treatment.

difference was observed when comparing median times of ART fractions for bladder treatments (conventionally and hypofractionated) to hypofractionated prostate treatments (15.15 [IQR, 12.90-18.57] vs 14.93 [IQR, 13.04-17.73] minutes; U = 10009.5; Z = −0.51; *P* = .61006).

Table 2 Employee cost per minute per validated TDABC analysis

	Attending radiation oncologist	Physicist	Dosimetrist	Therapist
Total annual compensation (USD)	$423,527	$177,000	$115,637.60	$56,597.25
				$32.81/h
Annual days	365	365	365	365
Weekend days	104	104	104	104
Holidays	6	6	6	6
Vacation days	20	20	20	20
Sick days	2.5	7	9	5
Available days per year	232.5	228	226	230
Total work day (h)	12	8	8	8
Scheduled breaks (h)	0	0.5	0.5	0.5
Clinically available time per day (h)	12	7.5	7.5	7.5
Clinically available time per day (min)	720	450	450	450
Total available time per year (min)	167,400	102,600	101,700	103,500
Cost per minute of available time (USD)	$2.53	$1.73	$1.14	$0.55
Median adaptive planning time (min)	15.97	15.97	15.97	15.97
Average cost of adaptive planning per fraction (USD)	$40.40	$27.55	$18.16	$8.73
Total average minimum cost of adaptive planning per fraction (USD)	$103.58			

Abbreviations: ART = adaptive radiation therapy; TDABC = time-driven activity-based costing; USD = United States dollar.
Attending radiation oncologist salary is averaged from institution-specific TDABC. Physicist salary represents the national average starting salary. Dosimetrist salary is the midpoint annual salary (graded annually) at this institution. Therapist annual compensation is based on hourly wage, not salary. Average cost per fraction of ART accounts for 2 therapists. In general, salaries and vacation/sick days are for starting level positions and therefore represent the *minimum* values.

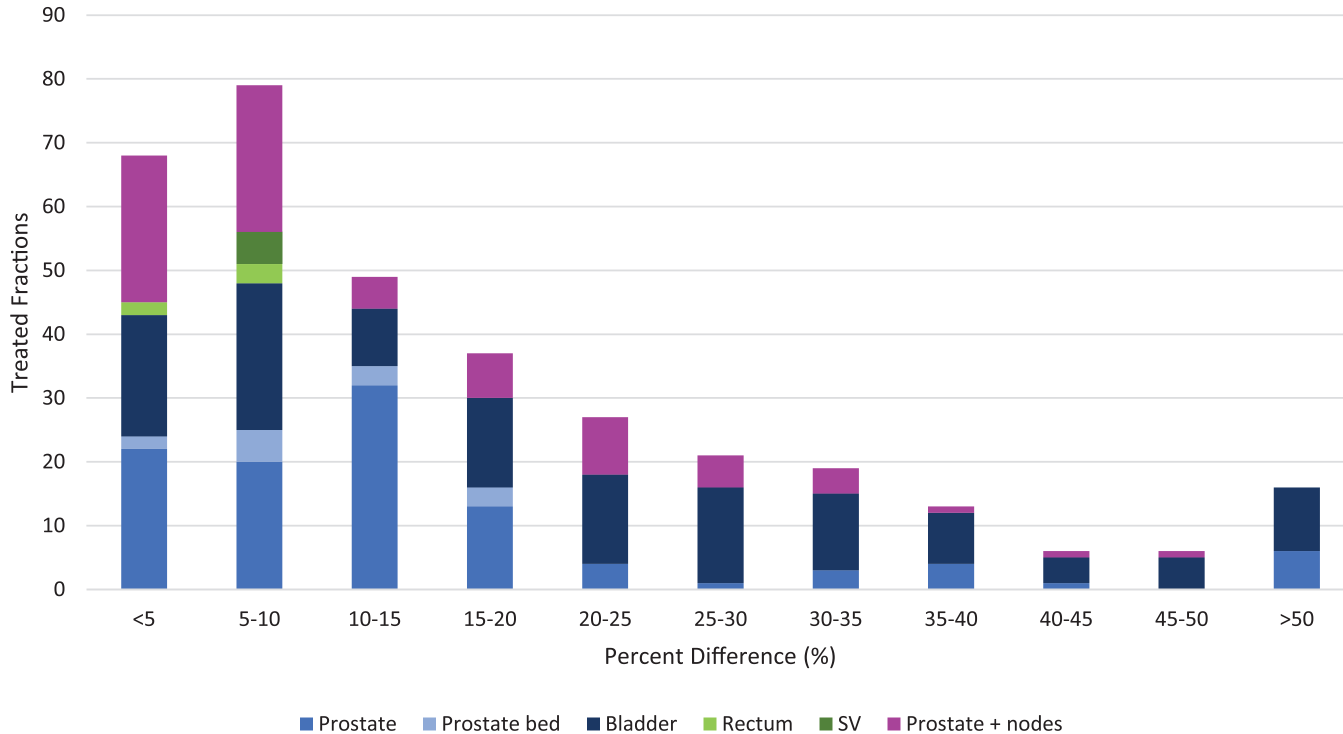

Fig. 3 Dosimetric difference between V100% of scheduled versus adapted plan for 415 online adapted fractions. Disease sites included prostate, prostate bed, prostate with nodal coverage, bladder, rectum, and seminal vesicle only (SV). Average difference 15.8%.

Applying TDABC analysis to the median time resulted in an average minimum cost per adapted fraction of $103.58. This was based on our institution's use of 1 physician, 1 dosimetrist, 1 physicist, and 2 therapists for the duration of online ART. Table 2 demonstrates the breakdown of each employee's cost per minute of work, based on institution-specific and national average starting salaries, and then multiplies that by the median adaptive planning time to determine a minimum cost per adaptive fraction just for staffing at this institution.

Evaluation of dosimetric differences between V100% of the scheduled versus adapted plan showed a mean dosimetric difference of 15.8%, with a maximum difference of 74.7% and a minimum difference of −6.2% (the adapted plan had a smaller V100% than the scheduled plan in this case). In the vast majority of cases (78%), the adapted plan was superior to the scheduled plan, as expected given the daily changes in patient anatomy and corresponding adjustment to treatment volumes.

Discussion

Our data demonstrate an *additional* time requirement of approximately 16 minutes for online CT-based ART on top of standard IGRT treatment times. This is consistent with prior emulator data that demonstrated an average planning time of 16.81 minutes for patients with cervical and rectal cancer.[14] Historically, average daily IGRT treatments at our institution take approximately 7 minutes (not including time getting the patient into the room or positioning the patient). The additional time required for online ART is reflective of the added cost of ART on top of IGRT. Adding this to the 16 minutes of online ART time results in an average ART treatment time of 23 minutes (again, not including patient positioning). In other words, approximately 3 patients can be treated with IGRT for every 1 ART treatment, and each fraction requires more staffing for the duration of time. Ultimately, this is time taken away from other clinical tasks for all parties. Moreover, due to this daily time demand, the original planning physician may not always perform the adaptive fraction contouring and plan approval for each day. The lack of a consistent provider in conjunction with the specificity of each patient's plan necessitates complex, time-intensive physician sign-outs to ensure standardized delivery of adaptive treatments,[25] furthering the resource burden and feasible implementation of online ART.

In addition to this opportunity cost, there is also a financial cost to assess. Our study shows a minimum increase in daily fraction cost of $103.58 (similar to prior data of $99.86 per fraction[14]) allocated for human resources (physician, physicist, dosimetrist, and 2 therapists).

There do appear to be opportunities to improve efficiencies and reduce costs in the clinical implementation of ART. Figure 2 demonstrates a general trend of reduced ART times, with a median time of 17.97 minutes for the first 100 fractions, which improved to 15.75 minutes for the remaining fractions evaluated. This likely reflects staff becoming more comfortable and efficient with the ART workflow, suggesting a "learning phase" with initial integration into daily treatments. Furthermore, although we have found that at our institution we require full staffing for the duration of replanning, there is potential to reduce costs by decreasing staffing as team members become more comfortable and better trained. Streamlining the process such that only therapists are required for the first half of ART planning (influencer structure processing, review and approval, and target contour processing) can reduce costs. In this model, the role of the physician, physicist, and dosimetrist is limited to review and approval of target contours and creating and approving the treatment plan. Based on Yock et al,[14] this would reduce the time demands on higher paid staff to 14.21 minutes per ART treatment, reducing the daily cost per fraction from $99.86 (based on a fully staffed 16.81-minute replanning time) to $85.81.

However, it is important to note that these cost estimates are based on minimum wages and salaries and is therefore representative of *minimum* additional cost. Further, this TDABC analysis is likely the *least* expensive estimate, such that implementing online ART may increase daily fraction costs by much more, especially for more complicated disease sites that take more time (such as head and neck, lung, and pancreas). We saw this trend in the present study where more complex treatments requiring more structures to be reviewed or closer scrutiny of structures increased adaptive times significantly, such as with pelvic nodal radiation or SBRT. Additionally, given the need for a physician, physicist, and dosimetrist to be at the machine for every treatment, the very small blocks of time between patients are likely not useful for other tasks. Hence, if the intent is to treat all patients with adapted fractions, a dedicated team comprised of a physician, physicist, and dosimetrist may be needed for each machine performing ART. This financial burden may not be feasible for all radiation centers to manage and requires careful deliberation and planning.

Dosimetric benefit has been found in previous studies for patients with cervical and rectal cancer, although the clinical significance of this has yet to be elucidated.[14] Deformable image registration, dose accuracy, and dose mapping are all considerations for dosimetric effect, and the question remains as to whether it should be based per fraction or on dose accumulation. In reality, the scheduled plan is optimized for a different CT (different criteria/anatomy) so it will (almost) always be dosimetrically inferior to the adapted plan, which is optimized for the new CBCT, just as we saw at our institution with an average dosimetric difference of 15.7% for the PTV receiving 100% of the dose (V100%). Additionally, with the time and effort already invested in creating the adapted plan, clinicians are likely inclined to use it.

Interestingly, the scheduled plan PTVs are not within preferred ranges. For example, we often seek to achieve 100% of the PTV getting 95% of the dose, when online ART shows it would be closer to 80% of PTV if the scheduled plan is used. One caveat of our CT-based adaptive couch is that it cannot account for pitch and roll, which may explain some of the dosimetric discrepancy. Additionally, there is less inclination to adjust anatomic volumes when a patient is being treated adaptively (eg, have a patient use the bathroom or drink more water if bladder volume is significantly different), which might have influenced the scheduled target dose. Yet, we still have good outcomes with standard IGRT, so it is likely that our ideals are extremes that are beyond what is actually necessary for effective treatment; the signal-to-noise ratio is insufficient.

All this raises the question: What treatment types and disease sites will benefit most from online ART? Institutions should assess how much time they are willing to allow to determine the feasibility of ART within their programs. The time spent should be balanced with toxicity and dosimetry implications.

Toxicity data are forthcoming, so determining which disease site benefits the most in weighing the opportunity cost is unclear. However, treatments that have high toxicity rates may be worth the opportunity cost of online ART to improve patient outcomes. For example, radiation for bladder cancer has been shown to have grade 3 toxicity rates as high as 40%.[26] In the setting of hypofractionation, higher dose-per-fraction therapy raises the concern of acute and late toxicities (gastrointestinal in particular). This posits a role for ART in ensuring target coverage and avoiding the chance of a marginal miss while minimizing dose to OARs in treatment sites where there are large geometric variations or high doses of radiation are used.

Conclusion

Although online ART decreases the uncertainty of anatomic shifts, the added human resources required per fraction not only complicate the workflow of daily treatment but also increase expense (based on previously validated TDABC analyses). Online ART removes physicians from clinical time, which is already burdened by high patient volumes aggravated by system-wide pressures. This opportunity cost is likely to be similar across different disease sites, unlike toxicity benefits, which may vary more depending on anatomic location and require further longitudinal studies. However, as artificial intelligence and automation-based technologies (eg, auto-contouring, knowledge-based treatment planning, and verification automation) improve with more advanced and accurate application, human resource requirements may be reduced and ultimately lessen the opportunity cost of online ART. Regardless, the implementation of progressively complex RT technologies, like ART, requires consideration of the time and human resource requirements and subsequent opportunity cost.

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