Original Article

Customizing Treatment Scheduling Windows with a Time Margin Recipe: A Single-institutional Study

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Abstract

Purpose: Rising cancer incidences, complex treatment techniques, and workflows have all impacted the radiotherapy scheduling process. Intelligent appointment scheduling is needed to help radiotherapy users adapt to new practices. **Materials and Methods:** We utilized van Herk's safety margin formula to determine the radiotherapy department's treatment scheduling window (TSW). In addition, we examined the influence of in-room imaging on linac occupancy time (LOT). Varian Aria™ software version 15.1 was used to collect retrospective data on LOT, treatment site, intent, techniques, special protocol, and in-room imaging. **Results:** Treatment scheduling windows varied across treatment sites. The mean TSW using van Herk's formalism was 31.5 min, significantly longer than the current TSW of 15 min ($P = 0.036$), with the pelvic site having the longest (43.8 min) and the brain site having the shortest (12 min). 28% of patients exceeded the in-practice TSW of 15 min. 46.2% of patients had multiple images per fraction, with the proportion being highest in pelvic patients (33%). Patients treated with palliative intent, intensity-modulated radiotherapy, special protocols (bladder protocol and gating), and multiple in-room images per fraction had significantly higher LOT. High treatment time uncertainty was observed in the pelvic and thorax sites, indicating the impact of in-room imaging frequency and on-couch treatment decisions on overall treatment time and indicating that current treatment practices should be reviewed and modified if necessary. **Conclusions:** The time margin recipe can customize the treatment scheduling window and improve treatment practices. This formalism can help manage the radiotherapy department's workload and reduce patient wait times.

Keywords: Intensity modulated, radiation oncology, radiotherapy, respiratory-gated imaging techniques, time management

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Introduction

According to GLOBOCAN 2020, cancer incidence is rising and is expected to increase by 47% by 2040.[1] This will put pressure on radiotherapy facilities worldwide and have a significant impact on low-and middle-income countries.[2,3] The demand for faster treatment with acceptable precision is increasing.[4,5] Approaches toward this aim include measures such as hypofractionation, higher dose rates, and efficient throughput image guidance.[6] Another measure towards this goal could be to devise a time management strategy that can help in managing the department's workload and keep the radiotherapy professionals motivated for an efficient patient workflow.

Conventionally, a radiotherapy's workload was measured by the number of patients treated per linear accelerator (linac) per unit of time, the number of fields treated per unit of time, and so on. These methodologies lag behind treatment technique-related complexities such as the introduction of multileaf collimators, wedges, compensators, and in-room imaging. A few years ago, the basic treatment equivalent model was proposed to account for the impact of complex treatment methods.[7] Various new models and enhancements to existing models have been proposed over time.[8] The introduction of complex treatments such as intensity-modulated radiotherapy (IMRT) and image-guided radiotherapy (IGRT) has increased overall treatment time. This has resulted in fewer patients being treated per unit time.[9-11] Several strategies were conceptualized to

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minimize patient wait time and maximize the number of new patients booked for radiation.[12,13] The DEGRO-QUIRO trial reported radiation working times for several tumor types and different modalities.[14] To address the challenge of a complex radiation scheduling procedure, optimization and logical models were used based on numerous categorizations.[15]

A significant limitation of these models is that they do not account for the effect of in-room imaging and special protocols on linac workload in an IGRT setup, which is the current standard of care. Additionally, no mathematical models for determining treatment scheduling window (TSW) are available.

While analyzing data from the Aria™ reporting database in our radiotherapy department, we noticed that the total treatment time for patients at different sites varied. This study's primary objective is to develop a customized TSW for radiotherapy patients based on different treatment sites and time margins calculated using van Herk's margin formalism. van Herk's margin formula is a commonly used formula in the field of radiotherapy for calculating the appropriate margin to add around the target volume to account for patient movement and other uncertainties.[16] The secondary objective is to determine the dependence of linac occupancy time (LOT) on in-room imaging frequency.

In our study, "TSW" refers to the period of time during which a particular treatment is scheduled to occur. "LOT" denotes the amount of time that a linac is occupied or in use. "Time margin" refers to the amount of additional time allotted or set aside to ensure a task can be completed within the TSW or to account for unforeseen circumstances. If this were possible, we hypothesized that overall time waste would be minimal and patient wait times could be significantly reduced.

Materials and Methods

For this study, LOT is defined as the total time a patient takes to enter and exit the linac bunker. Based on our personal experience, we developed the hypothesis that the current TSW of 15 min understates the time allotted for treatment at each site, i.e., TSW >15 min.

At our center, we have one TrueBeam version 2.7 linac with four-photon energies (6 MV, 6 MV with flattening-free filter (6FFF), 10 MV, and 15 MV) and five electron energies (6 MeV, 9 MeV, 12 MeV, 15 MeV, and 18 MeV), a Varian GammaMed Plus HDR brachytherapy machine, and one Eclipse treatment planning system version 15.6. Our linac can perform specialized procedures like 4D treatments, stereotactic radiotherapy, and stereotactic radiosurgery (SRS). For patients who are a good fit for the procedures based on the radiation oncologist's (RO) assessment and evaluation, specific protocols such as the bladder protocol and respiratory gating management are used.

The staffing in our department meets the minimum requirements set by the national regulatory authority. The operating hours of the department are from 8:30 am to 5:30 pm. Each patient is assigned a 15-min TSW. Under the supervision of a RO or medical physicist (MP), we conduct an online image review for each patient before delivering a radiotherapy fraction using the no-action level protocol.[17] MP performed daily and periodic quality assurances before and after patient treatment started and after treatment completion.

From April 2018 to July 2022, data was collected and prepared using Microsoft Excel software. Following the inclusion criteria, as shown in Table 1, an in-house database sampling frame was created, for which demographic details are shown in Figure 1. The sampling frame was sampled using a disproportional stratified sampling technique as it ensures adequate representation of each stratum in the sample. The sampling frame was divided into seven treatment site-based strata. For each treatment site, total fractions, prescribed dose, treatment intent, treatment techniques, special protocols, type of in-room imaging, total in-room imaging, and mean LOT were collected, as shown in Table 2. The above data was manually collected by a MP from Varian's Aria software version 15.1 using the Eclipse planning system version 15.6.

Methodology

We utilized van Herk's safety margin recipe to calculate the treatment scheduling window for each treatment site. van Herk's margin strategy is well accepted for providing a safety margin in radiotherapy to account for geometrical errors during treatment delivery. The same van Herk's margin was redefined for our study as the required margin of time for 90% of patients to be treated within 95% of the prescribed time, as shown in the equation, based on the known PTV margin recipes. This methodology predicts the treatment scheduling time and informs radiotherapy professionals of current practice gaps. The greater the margin, the greater the uncertainties associated with the current practice, and the longer the predicted treatment scheduling time. The safety margin (M) can be calculated as;

$$M = 2.5\Sigma + 0.7\sigma \quad (1)$$

where, Σ is the systematic error component and σ is the random error component.

Components of systematic error (Σ) emerge as a result of the treatment process's inherent temporal delay. It incorporates the operator's quickness, expertise, and decision-making abilities when analyzing in-room images prior to beam ON. Random error (σ) originates from everyday patient setup errors and different operators treating the same patient.

Treatment scheduling window was calculated as:

$$\text{TSW} = (\text{LOT} + M) \quad (2)$$

Statistical analysis

A one-way ANOVA test was performed to test the statistical significance between the mean LOT of different treatment sites. The LOT was expressed as a mean (standard deviation) for each category. The LOT distribution's mean, median, and interquartile range (IQR) were calculated. A two-sample t-test was used to test the dependence of in-room imaging frequency

Table 1: Inclusion and exclusion criteria for sampling frame construction

	Inclusion criteria	Exclusion criteria
Patients	Age 13 years and above Treatment completed before July 2022	Pediatric patients, patients with incomplete treatment
Treatment intent	Both palliative and curative	Re-irradiation
Treatment site	Brain, Head & Neck, thorax, breast/chest wall, vertebra, abdomen, and pelvis	Extremities and no multiple-site treatments
Treatment technique	IMRT and VMAT	3D-CRT and manual technique
Treatment energy	6 MV	All electron energies and high energy photons above 10 MV and no FFF beam
Isocenter	Single isocenter plan per patient with the exception of breast/chest wall patients with SCF treatment	Multiple isocenter per plan in a single optimization
Special techniques	Respiratory gating DIBH for breast/chest wall patients	4D-CT, SRS, SRT, SBRT, and CSI treatments
Special protocols	BP	None
Treatment fractions	All uninterrupted fractions with in-room imaging (u-kV, p-kV, and CBCT)[a]	No first-day treatment fraction Fractions with no in-room imaging Fractions with machine interlocks

[a]u-kV images were counted as 0.5 images, while p-kV or CBCT images were counted as one image. IMRT: Intensity-modulated radiation therapy, VMAT: Volumetric-modulated arc therapy, DIBH: Deep inhale breath hold, SCF: Supraclavicular fossa therapy, BP: Bladder protocol, CT: Computed tomography, CBCT: Cone-beam CT, CSI: Craniospinal irradiation, SBRT: Stereotactic body radiation therapy, SRT: Stereotactic radiotherapy, SRS: Stereotactic radiosurgery, 4D-CT: Four-dimensional CT, FFF: Flattening filter-free, 3D-CRT: Three-dimensional conformal radiation therapy, u-kV: Unpaired kV, p-kV: Paired kV

Table 2: Clinical details for the sample population collected through disproportionate stratified sampling technique

Treatment sites	Patients (%)	Fractions	Dose range (Gy)	Treatment intent (%)	Special protocol and technique (%)	Treatment technique (%)	In-room imaging (%)	LOT, mean±SD, min
Brain	19 (16)	301 (16.55)	20–59.4	Cur-10 (52.6) Pall-9 (47.4)	-	VMAT-19 (100) IMRT-0 (0)	p-kV: 147 (47.7) CBCT: 161 (52.3)	9.8±0.7
Head & Neck	18 (15.1)	306 (16.82)	20–69.96	Cur-9 (50) Pall-9 (50)	-	VMAT-17 (94.4) IMRT-1 (5.6)	kV-kV: 145 (43.3) CBCT: 190 (56.7)	12.9±2
Thorax	16 (13.4)	210 (11.54)	15–60	Cur-7 (43.8) Pall-9 (56.2)	-	VMAT-8 (50) IMRT-8 (50)	p-kV: 62 (27.3) CBCT: 165 (72.7)	13.2±4.6
Breast/chest wall	20 (16.8)	324 (17.81)	40–50	Cur-20 (100) Pall-0 (0)	DIBH-11 (55)	VMAT-0 (0) IMRT-20 (100)	p-kV: 225 (43.5) CBCT: 292 (56.5)	20.5±2.6
Vertebra	12 (10.1)	167 (9.18)	20–50.4	Cur-6 (50) Pall-6 (50)	-	VMAT-6 (50) IMRT-6 (50)	p-kV: 67 (35.1) CBCT: 124 (64.9)	11.3±1.3
Abdomen	12 (10.1)	164 (9.02)	20–50	Cur-6 (50) Pall-6 (50)	-	VMAT-10 (83.3) IMRT-2 (16.7)	p-kV: 59.5 (34.7) CBCT: 112 (65.3)	12.2±2.3
Pelvis	22 (18.5)	347 (19.08)	16–66.25	Cur-14 (63.6) Pall-8 (36.4)	BP-22 (100)	VMAT-19 (86.4) IMRT-3 (13.6)	p-kV: 86 (18.3) CBCT: 385 (81.7)	17±8.1
Total	119 (100)	1819 (100)	15–69.96	Cur-73 (60.8) Pall-47 (39.2)	DIBH-11 (9.2) BP-22 (18.3) No protocol: 87 (72.5)	VMAT-80 (66.7) IMRT-40 (33.3)	p-kV: 791.5 (35.6) CBCT: 1429 (64.4)	14.2±5.4

Cur: Curative, Pall: Palliative, DIBH: Deep inhale breath hold, BP: Bladder protocol, VMAT: Volumetric-modulated arc therapy, IMRT: Intensity-modulated radiation therapy, p-kV: Paired kV image, CT: Computed tomography, CBCT: Cone-beam CT, LOT: Linac occupancy time, SD: Standard deviation, Head & Neck: Head and neck

on mean LOT. A two-sample *t*-test was used to compare means for each category (treatment intent, technique, gating, and bladder protocol). One sample *t*-test was used to show the statistical significance of calculated TSWs from the current TSW. The statistical significance was kept at $P < 0.05$.

Results

From April 2018 to June 2022, retrospective sample data were analyzed for 119 patients at seven different treatment sites receiving 1949 fractions. First treatment fractions (119 sessions), sessions with machine interlocks (6), and no-imaging sessions (5) were excluded from the analysis, leaving 1819 fractions.

A one-way ANOVA was used to determine whether there were any significant differences in the mean LOT of the seven treatment sites. The difference between the mean treatment time for seven treatment sites was statistically significant: $F(6, 112) = 14.15$, $P < 001$.The average LOT for the entire sample was 14.2 min (± 5.4), with a maximum of 20.5 min (± 2.6) for the breast site and a minimum of 9.8 min (± 0.7) for the brain site. The average LOT of 27.7% of patients was 16.8 min (± 5.5) longer than the prescribed TSW of 15 min. Figure 2 shows the variation in mean LOT with extra-imaging per fraction for different treatment sites.

The total in-room imaging performed was 2228.5, with each cone-beam computed tomography (CBCT) and p-kV image counted as one, whereas a single kV image is counted as 0.5 images. The in-room images were composed of 64.1% cone-beam computed tomography (CBCT) and 35.9% planar kV (p-kV) images. Overall, 46.2% of patients had extra imaging per fraction. These patients had a mean LOT of 16.8 min (± 5.5), which was significantly higher than patients who did not receive any additional imaging, who had a mean LOT of 12.1 min (± 5.4) ($P < 0.001$). Most extra imaging was performed for patients treated at the pelvic sites (16), followed by the breast/chest wall sites (13) due to the bladder and gating protocols, respectively.

39.4% of patients were treated with palliative intent, with a mean LOT of 12 min (± 3.45), which is significantly less than patients treated with curative intent with a mean LOT of 14.69 min (± 4.78) ($P = 0.001$). 33.7% of patients received IMRT treatment, with a mean LOT of 16.7 min (± 5.1). This was significantly higher than the mean LOT of patients treated with the volumetric modulated arc therapy technique, which was 12.95 min (± 5.2) ($P < 0.001$).

33 patients were treated with unique protocols (11 patients with deep inhale breath hold [DIBH] and 22 patients with the

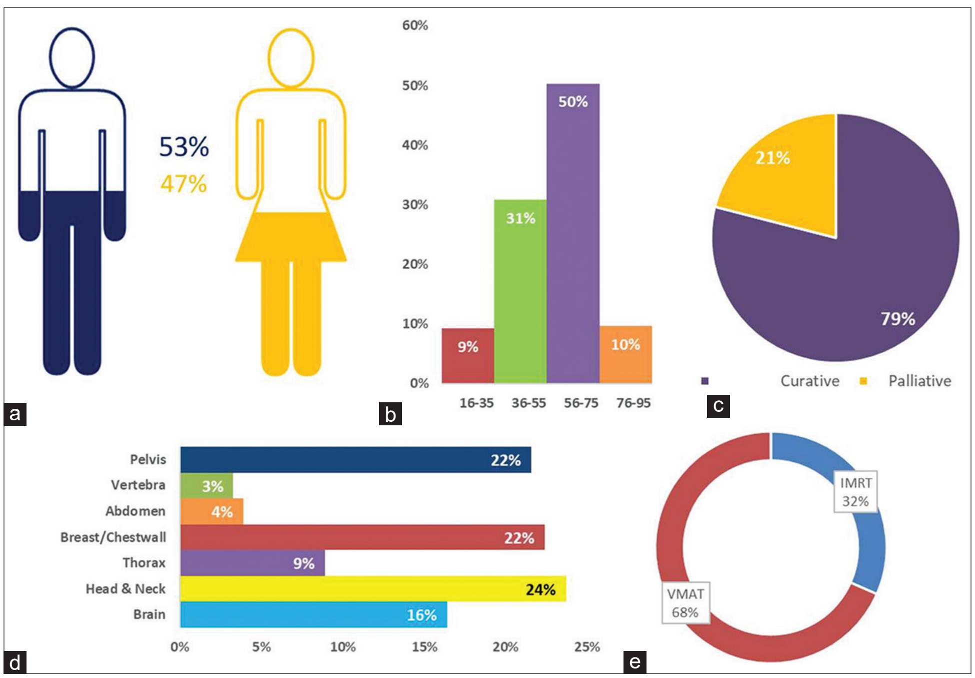

Figure 1: The demographic details of the study population, including (a) gender distribution, (b) age group distribution, (c) treatment intent, (d) patient's treatment site-wise distribution, and (e) treatment technique used

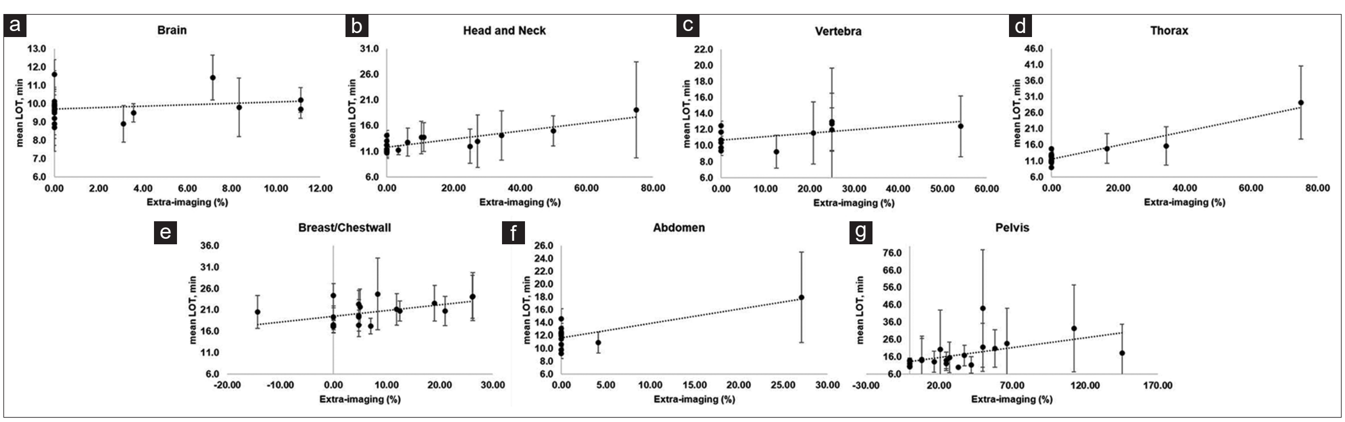

Figure 2: The effect of extra in-room imaging on mean Linac Occupancy Time (LOT) in different treatment sites i.e., (a) Brain, (b) Head and Neck; (c) Vertebra; (d) Thorax; (e) Breast/Chestwall; (f) Abdomen; (g) Pelvis.

bladder filling protocol). The DIBH protocol was used to treat 55% of breast/chest wall patients. DIBH patients had a mean LOT of 22.2 min (± 5.7), which was significantly higher than patients who did not receive DIBH, who had a mean LOT of 18.8 min (± 2.3) (P = 0.004). Patients who received the bladder protocol had a mean LOT of 17 min (± 8.11), which was significantly higher than the overall mean LOT of 13.7 min (± 4.53) (P = 0.041).

Table 3 shows the calculated TSW for different categories. The mean TSW calculated using van Herk's margin recipe was 31.5 min. TSW accounts for LOT with additional margins accounting for random and systematic components derived from van Herk's formula. Figure 3 gives the pictorial representation of TSW incorporating time margins over LOT across various treatment sites. This signifies that we can treat 90% of patients within 95% of the calculated TSW, i.e., within 30 min. This was significantly greater than the current TSW of 15 min (P = 0.036). The maximum TSW was for the pelvic site (43.8 min), and the minimum TSW was for the brain site (12 min). Six out of seven treatment sites had TSWs longer than the existing TSW of 15 min.

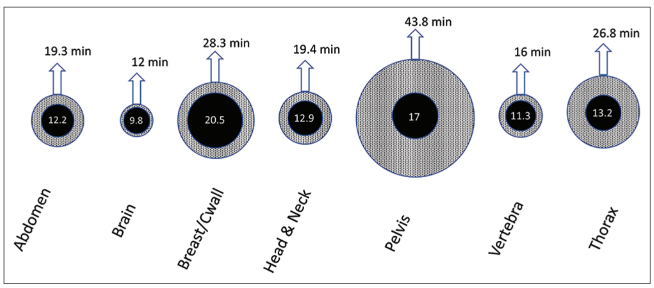

Figure 3: The pictorial representation of TSW incorporating time margins over LOT across various treatment sites. TSW: Treatment slot window, LOT: Linac occupancy time

The proportion of systematic and random error was also most significant in the pelvic site (8.1 min, 9.4 min), followed by the thorax site (4.6 min, 2.9 min), and the lowest in the brain site (0.7 min, 0.5 min). Figure 4 shows the whisker plot distribution of the LOT for all treatment sites. The LOT distribution was most skewed for the pelvic site with (mean, median, and IQR) values of 17, 14, and 7.8 and least skewed for the brain site with values of 9.8, 9.7, and 0.6.

Discussion

The present study illustrates the use of van Herk's margin formula for determining the treatment slot window (TSW) in a radiotherapy center while accounting for various uncertainties related to different treatment protocols and regimes. Our findings reveal significant variation in TSW across treatment sites, which is consistent with previous studies published in the scientific literature.[18,19] Variations in both the systematic and random components of error have been linked to the substantial variation in treatment time. Patients who received special protocols and gating exhibited both systematic and random errors of a significant magnitude. Large systematic errors indicated difficulty on the part of the operator in making on-couch decisions and executing treatments quickly, while large random errors indicated difficulty in achieving set-up accuracy and variations in operator expertise. Thus, due to the variability of treatment sites, it is preferable to tailor TSW based on the

Table 3: Treatment slot window for various categories

Categories	LOT, min	P	Systematic error (∑), min	Random error (σ), min	Margin, min	TSW, min
Treatment sites						
Abdomen	12.2	<0.001	2.3	1.7	7	19.3
Brain	9.8		0.7	0.5	2.2	12
Breast/chest wall	20.5		2.6	1.7	7.8	28.3
Head & Neck	12.9		2.0	2.3	6.6	19.4
Pelvis	17.0		8.1	9.4	26.9	43.8
Vertebra	11.3		1.3	2.0	4.8	16
Thorax	13.2		4.6	2.9	13.6	26.8
Treatment intent						
Curative	15.2	0.001	5.1	5.2	16.4	31.6
Palliative	12.8		5.7	5.2	17.9	30.7
Technique						
IMRT	16.8	<0.001	5.1	2.3	14.3	31.1
VMAT	13.0		5.2	6.2	17.3	30.3
Gating?						
No	13.5	<0.001	5.1	5.5	16.6	30.1
Yes	21.3		3.2	1.9	9.3	30.7
Bladder protocol?						
No	13.6	0.041	4.5	2.1	12.6	26.3
Yes	17.0		8.1	9.4	26.9	43.8

LOT: Linac occupancy time, IMRT: Intensity-modulated radiotherapy, VMAT: Volumetric-modulated arc therapy, TSW: Treatment scheduling window, Head & Neck: Head and neck

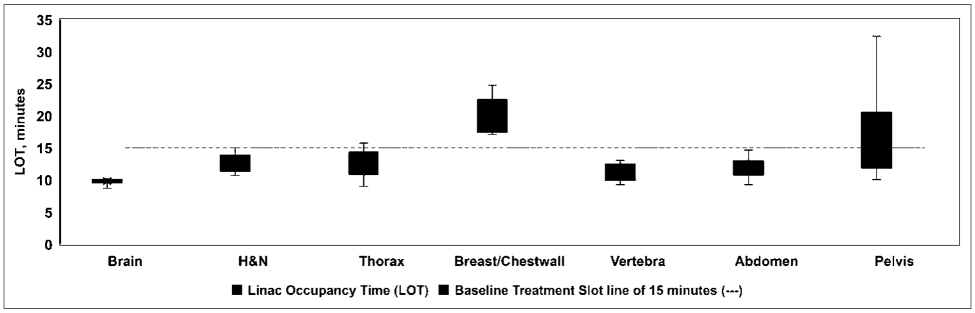

Figure 4: The box and whisker plot representation of the variation of LOT with treatment sites. Dashed line indicates the current treatment scheduling window i.e., 15 min. LOT: Linac occupancy time

treatment sites as opposed to the treatment intent, technique, and special treatment protocols.[20]

Due to the high level of uncertainty associated with internal organ motion, patients treated for pelvic sites were found to have a greater TSW, which necessitates more time-consuming online reviews. Contrary to published literature, we observed a significant difference in LOT and TSW between patients treated with and without a bladder protocol.[21,22] All patients with breast/chest wall cancer also received supraclavicular fossa therapy, resulting in the highest overall LOT among all treatment sites and a higher TSW.[23] Patients treated at the brain exhibit the lowest systematic and random uncertainties, followed by those treated at the vertebra, resulting in the smallest TSW.[24]

Our results also validated the secondary objective of our study, i.e., the relationship between LOT and imaging frequency per session in the room. There is a linear increase of LOT observed with the increasing imaging per session. The results revealed that the average calculated TSW (31.5 min) for all sites is significantly longer than the currently scheduled 15-min allocation. Consistent with the literature, 28% of patient treatments lasted longer than the scheduled 15 min, and 46% of patients had over-imaging per session.[25] In addition, the incidence of additional in-room images was 33.1% among patients with pelvic treatment sites.[26]

The TSW calculated for patients treated with palliative intent did not differ significantly from those treated with curative intent, confirming previous findings.[27] IMRT technique-based treatments had a significantly higher LOT than rapid arc technique-based treatments, in agreement with the published literature.[28]

Various methods such as appointment scheduling algorithms, optimization techniques, machine learning models, and interruption management tools, are discussed in the literature. For example, one paper proposed two approaches to optimize radiation schedules considering inter-patient variability, using a robust formulation and a probabilistic approach.[29] Another study aimed to develop a constraint-based scheduler for optimal treatment planning to improve outpatient scheduling efficiency.[30] Mixed-integer linear programming models have been proposed for scheduling and sequencing radiotherapy sessions, using time window preferences given by patients. This approach has been shown to be effective in real-world scenarios.[31,32] Another paper proposed a two-phase approach to optimize radiotherapy treatment sessions for cancer patients, using integer linear programming for the first phase and mixed integer linear programming and constraint programming for the second phase.[33] One study assessed the impact of using pull and push strategies and explore alternative interventions for improving timeliness in radiotherapy.[34] In another paper, the authors proposed a prediction-based approach for online dynamic radiotherapy scheduling that dynamically adapts the present scheduling decision based on each incoming patient and the current allocation of resources.[35] Another paper presented a new integer linear programming model for real-world radiotherapy treatment scheduling and analyzed the effectiveness of using this model on a daily basis in a hospital.[36] Another paper proposed an algorithm to minimize the maximum completion time of radiotherapy treatments while scheduling patients on different devices at different times, and when to have maintenance activities, by using an improved dynamic programming algorithm and a hybrid algorithm called Gaussian Crow Search Algorithm, which outperforms other algorithms in a feasible time.[37] These share the same aim, albeit with differences in methodology.

The novelty of our study lies in its focus on developing a customized time slot window for radiotherapy patients based on treatment sites and margin formalism. While previous studies have explored various optimization techniques and scheduling models for radiotherapy, this study's approach offers a personalized approach to scheduling appointments, tailored to the specific needs of each patient's treatment. Additionally, this study seeks to investigate the relationship between in-room imaging frequency and LOT, which has not been extensively explored in previous literature.

We recommend that radiation oncology departments realign their strategy for patient treatment slots by establishing a "fast mover" group in the morning and a "slow mover" group in the afternoon, or by establishing site-specific time slots based on van Herk's margin formalism. The calculated time safety margin must be center-specific, as treatment techniques and protocols may vary from center to center. This approach is advantageous for both patients and treatment centers, as it increases efficiency and decreases patient hospital stays, which is extremely relevant during the current pandemic.[38]

This study has limitations, such as not incorporating data on stereotactic techniques (stereotactic body radiotherapy and SRS), special technique treatments, and patients treated at multiple sites. We have not considered the impact of the delay caused by plan implementation on the 1st day of treatment or optimized the distribution of available treatment slots for patients. Further research should focus on validating and clinically implementing this scheduling model and evaluating its impact on wait times in larger multicenter studies. Additional parameters that can affect TSW should also be considered to generate a more refined model.

Conclusions

This study demonstrates the use of van Herk's margin formula to determine treatment scheduling windows for different treatment sites, with the aim of improving radiotherapy efficiency. The findings show that customizing TSW based on treatment sites, rather than treatment intent or protocol, is more effective. The study also highlights the impact of in-room imaging on LOT and the need for workload management. The authors recommend using site-specific time slots to increase efficiency and decrease patient hospital stays.

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Nil.

Conflicts of interest

There are no conflicts of interest.

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