Deriving Performance Measures of Workflow in Radiation Therapy from Real-Time Data

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Abstract. Radiation treatment planning is a complex process with multiple, dependent steps involving an interdisciplinary patient care team. We have previously implemented an interactive, web-based dashboard, which requires a standardised radiation treatment planning workflow and provides real-time monitoring and visualization of the workflow. We present this framework and the results of performance measures characterising the standardised workflow in an effort to optimize clinical efficiency and patient safety. Quantitative representations of longitudinal progression of carepath activities were computed from staff-reported timestamps queried from the EMR. Performance measures evaluated included staff compliance in completing assigned tasks, timeliness in task completion, and the time to complete different tasks. The framework developed allows for informed, data-driven decisions regarding clinical workflow management and the impact of changes on existing workflow as we seek to optimize clinical efficiency and safety, and incorporate new interventions into clinical practice.

Keywords: workflow tracking, performance evaluation, cancer

1 Introduction

Approximately 50% of patients diagnosed with cancer receive radiation therapy. Radiation therapy is a complex process involving multiple, dependent stages whereby an interdisciplinary care team collaborates to create and deliver a personalised radiation treatment plan. Patient safety and clinical efficiency are important during this process [2].

The radiation therapy workflow, illustrated in Fig. 1, consists of acquiring a CT scan of the patient from which a highly conformal, three-dimensional, radiation treatment plan is created to deliver a physician-prescribed dose to the tumour while also sparing surrounding healthy tissue. After creation and quality assurance of the radiation plan and prior to treatment, a simulation of the treatment is performed to verify safe delivery of the plan to the patient. Treatment delivery is usually performed under image guidance. Following treatment, the images acquired and delivered dose are reviewed in the electronic medical record (EMR) system to verify that the prescription was fulfilled.

The focus of this study is on the radiation treatment planning (RTP) stage, which is perhaps the most complex process, in the radiation therapy workflow. It is also the stage

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where radiation treatment errors are most likely to originate [4]. Effective communication among staff [1], adequate staffing levels and the ability to optimise the distribution of work among resources along with process automation [6] are key to ensuring patient safety, clinical efficiency and timely treatment starts. However, a lack of standardisation in clinical practice, inherent limitations in the EMR to display consolidated information that effectively communicates progress in the creation of patients' treatment plans to the care team [7], the need for specialised skills to extract information from the EMR, and a consequent lack of quantitative performance measures of workflow in radiation oncology are all challenges towards achieving these goals.

Electronic whiteboards [10] and carepath management systems [5] have been shown to improve communication and task management in radiation oncology. In an effort to improve communication and the tracking of resource utilisation, we have previously implemented an interactive, web-based dashboard to track clinical workflow [9]. The dashboard integrates with the departmental EMR, and provides real-time monitoring and visualization of the RTP workflow. It consists of several tabs unified by date, physician name, treatment type and treatment location, and monitors utilisation of the linear accelerators, patient appointment status as well as the status of tasks associated with the creation of a patient's treatment plan for several patients simultaneously. As well as providing a consolidated overview of progress in the creation of a patient's radiation treatment plan, the dashboard implements a standardized, integrated framework to analyze data acquired in real-time for quantitative clinical workflow evaluation.

In this study, we derive important quantitative performance measures, which describe the RTP workflow, from these data in an effort to understand how different activities unfold over time. We also estimate the efficiency of clinical practices and processes. The performance measures are calculated from data automatically queried from the EMR, and which provide the status, start and completion times of various tasks completed by the patient's care team during treatment planning. The measures obtained will contribute towards the implementation of informed, data-driven decisions on clinical workflow management and the development of process models for resource allocation with the long-term aim of improving radiation treatment safety and efficacy.

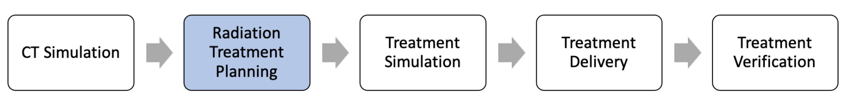

Fig. 1: **Radiation therapy clinical workflow.** The five stages in the radiation therapy clinical workflow. In this article, we focus on the radiation treatment planning stage

2 Methods

In this section, we describe a standardised model of the radiation treatment planning workflow, the implementation of a process to acquire data that tracks workflow in real-time, and the performance measures computed from these real-time data.

2.1 Standardised Model of the RTP Workflow

Process maps and flowcharts were created to model the RTP workflow. These described:

- Tasks representing standardised carepath activities associated with creation of a patient's radiation treatment plan from the time of CT simulation to treatment
- Task timeline and sequence
- Task ownership
- Staff interaction.

We considered patients treated with either of two treatment modalities, namely, three-dimensional (3D) conformal radiation therapy and intensity modulated radiation therapy (IMRT).

A simplified process map of the RTP workflow is shown in Fig. 2.

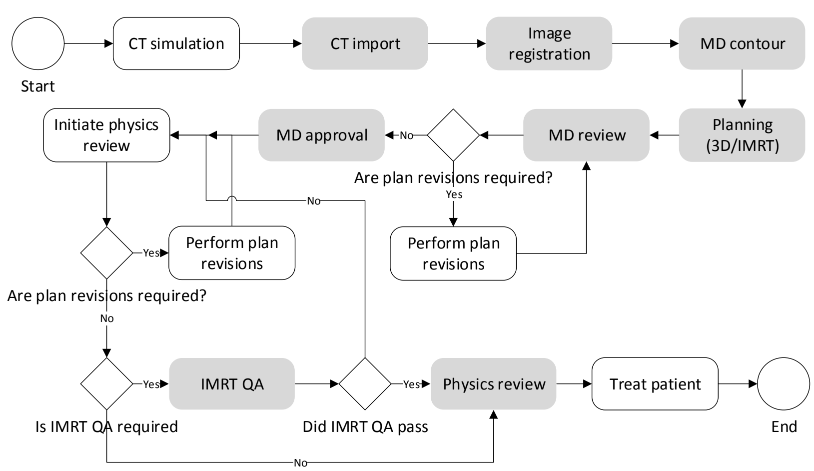

Fig. 2: **RTP workflow.** Standardised carepath activities associated with the creation of a patient-specific radiation treatment plan are shown. Tracked activities are in grey.

Radiation treatment planning starts with the acquisition of a CT scan of the patient during a process known as CT simulation. After CT simulation, the CT is imported into the treatment planning system (TPS) by a dosimetrist who then registers the CT to other images of the patient, if present. Afterwards, a physician contours the tumour and organs at risk and positions the radiation beams on the CT. The dosimetrist subsequently calculates a personalised radiation treatment plan using the CT, contoured anatomical structures and radiation beams. The plan is designed to deliver a physician-prescribed dose to the tumor while minimising irradiation of the organs at risk. After the plan has been calculated, it undergoes quality assurance in the form peer review by physicians and medical physicists. Peer review consists of a physician review, physician approval, IMRT QA, if applicable, and finally, a physics chart review by a medical physicist before the calculated radiation treatment plan is finally being approved for treatment. The planned treatment is then delivered to the patient. Tracked carepath activities during the RTP workflow are shaded in grey.

A description of the tasks created in the EMR to track the carepath activities, the staff responsible for completing the tasks, that is, the owners of the tasks, and the ideal timeline, τ, associated with completion of the tasks are listed in Table 1. An ideal timeline of 6 days from CT simulation to completion of the physics chart review was formulated. The number of days is counted post CT-acquisition, with zero being at the end of the day on which the CT was acquired. The tasks in Table 1 are listed in the sequence of completion during the RTP process. The granularity of the ideal timeline is limited at one day by the EMR. This led to sequential tasks having parallel timelines in the EMR.

Table 1: **RTP tasks.** The table lists, in sequential order, carepath activity tasks, task owner and ideal timeline, τ, for completing the task in terms of number of days following the CT simulation.

i Task	Owner	τ (days)	Description
1. CT Import	Dosimetrist	0	CT import into TPS
2. Image Reg.	Dosimetrist	0	Registration of CT to other images
3. MD Contour	Physician	1	Contouring of anatomy on CT and radiation beam placement
4. Planning	Dosimetrist	3	Calculation of 3D or IMRT treatment plan
5. MD Review	Physician	5	Review of calculated plan
6. MD Approval	Physician	5	Approval of calculated plan
7. IMRT QA	Medical physicist	5	Patient specific quality assurance
8. Physics Review	Medical physicist	6	Final review and approval of radiation plan for treatment

2.2 Real-Time Tracking and Display of RTP Workflow

The status of tasks comprised in a patient's treatment plan was recorded in the EMR by the task owner, and displayed in real-time on a web-based dashboard.

2.3 Performance Measures of RTP Workflow

The standardised RTP workflow was designed to provide measures to characterise and evaluate clinical practice. Task status information and timestamps were automatically queried from the EMR using SQL and used to compute a number of measures describing workflow performance. Of note to us, were: 1) Staff compliance in recording task completion, 2) Time to completion of various tasks, 3) On-time performance relative to the ideal timeline, 4) Elapsed time between different tasks.

A description of relevant variables, constants and performance parameters is provided below.

Variables	
T_i	Task i
M_j	Treatment modality j
$t^j_{i,k}$	Time to complete T_i since date of CT for patient k and M_j
$\mathbb{1}(t^j_{i,k}) = \begin{cases} 1 \text{ if } t^j_{i,k} \neq 0 \\ 0 \text{ otherwise} \end{cases}$	Indicator function on $t^j_{i,k}$
$\mathbb{1}(\delta^j_{i,k}) = \begin{cases} 1 \text{ if } \delta^j_{i,k} \leq 0 \\ 0 \text{ otherwise} \end{cases}$	Indicator function on delay for T_i, M_j and patient k
Constants	
N	Total number of patients studied
N^j_i	Number of patients for whom T_i was completed for M_j
τ_i	Ideal time to completion in days for T_i
Performance measures	
$\beta^j_i = \frac{100}{N^j_i} \sum_k \mathbb{1}(t^j_{i,k})$	Percentage number of patients with T_i completed for M_j
$\mu^j_i = \frac{1}{N^j_i} \sum_k t^j_{i,k}$	Mean completion time for T_i and M_j
$\sigma^j_i = \sqrt{\frac{1}{N^j_i - 1} \sum_k (t^j_{i,k} - \mu^j_i)^2}$	Standard deviation of completion time for T_i and M_j
$\delta^j_{i,k} = t^j_{i,k} - \tau_i$	Delay in completing T_i for M_j and patient k
$\psi^j_i = \mu^j_i - \tau_i$	Mean delay in completing T_i for M_j
$\eta^j_i = \frac{100}{N^j_i} \sum_k \mathbb{1}(\delta^j_{i,k})$	Percentage on-time completion for T_i and M_j

3 Results

Staff were educated about the standardised RTP workflow and trained in the use of tasks in the EMR to record carepath activity status.

3.1 Real-Time Tracking and Display of Workflow

Workflow progression according to treatment date, physician, type of treatment and treatment location were displayed in real-time on web-based dashboard as shown in Fig. 3. For every patient, task status and timeline were conveyed by means of color-coded due dates. Overall progress in the creation of a patient's treatment plan was conveyed through a progress bar.

3.2 Performance Measures

Data for $N = 85$ new patient treatments and 476 care path tasks that were completed in the EMR within 10 days of the CT simulation date were analyzed. As described previously, two treatment modalities, $M = \{3D, IMRT\}$, were considered with a breakdown of 54 and 31 patients, respectively. A summary of the calculated performance measures for the different tasks for 3D and IMRT treatments is given in Table 2. These results are described in more detail in the following sections.

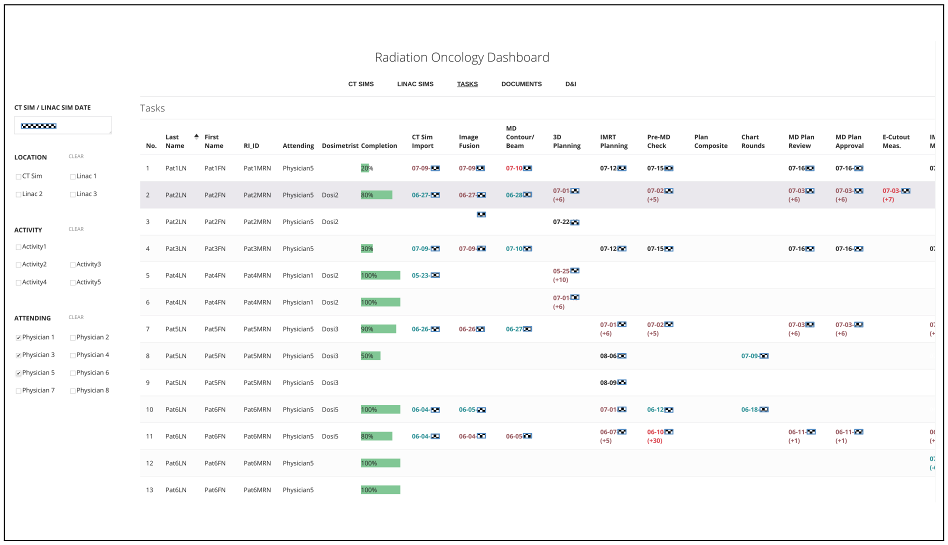

Fig. 3: **Real-time tracking of radiation treatment planning workflow.** A departmental web-based dashboard tracks carepath activities in the creation of a radiation treatment plan and the status of associated tasks, queried from the EMR, in real-time.

Table 2: **RTP performance measures**. The performance measures associated with the different tasks tracked for patients treated with 3D or IMRT radiation therapy are shown below.

i	Task	3D					IMRT				
		β_i^1 (%)	μ_i^1 (days)	σ_i^1 (days)	ψ_i^1 (days)	η_i^1 (%)	β_i^2 (%)	μ_i^2 (days)	σ_i^2 (days)	ψ_i^2 (days)	η_i^2 (%)
1	CT Import	100	-0.42	0.18	-0.42	96.3	100	-0.32	0.40	-0.32	87.1
2	Image Reg.	79.6	0.33	0.94	0.33	44.2	90.3	0.51	0.68	0.0.51	25.0
3	MD Contour	100	0.35	0.97	-0.65	87.0	100	1.41	0.91	0.41	32.3
4	Planning	87.0	3.47	2.11	0.47	34.0	67.7	5.98	1.45	2.98	23.8
5	MD Review	44.4	3.18	2.06	-1.82	87.5	22.6	5.25	1.54	0.25	42.9
6	MD Approval	42.6	3.23	2.09	-1.77	87.0	22.6	5.25	1.54	0.25	42.9
7	IMRT QA						83.9	6.06	2.11	1.06	46.2
8	Physics Review	92.6	3.94	2.31	-2.06	94.0	96.8	6.11	1.63	0.11	53.3

3.3 Compliance in Recording Task Completion

Compliance, β, in recording task completion ranged from 22% to 100% as shown in Table 2. Note that here, non-completion of the task does not indicate that the carepath activity was not completed, but rather that it was either not completed within 10 days or not recorded as having been completed in the EMR. Compliance was greatest for the CT Import task and least for the MD Review and MD Approval tasks.

3.4 Elapsed Time to Task Completion

Quantitative, longitudinal progression of the RTP workflow for 3D treatments is shown in Fig. 4 and for IMRT treatments in Fig. 5. The bubbles displayed are color-coded by staff role. The centre of the bubbles in the figures represents the average number of days, μ, to completion of a task post CT simulation. The diameter of the bubbles is proportional to the percentage times, η, the tasks were completed on time relative to the ideal timeline. The dotted line represents the ideal timeline for task completion.

The graphs permit evaluation of where bottlenecks are introduced in the clinic and help identify areas of improvement. The mean time (and standard deviation) from CT import to completion of the physics review for 3D and IMRT treatments, respectively, were 3.9 (2.3) and 6.1 (1.6) days. 3D task completion times were better than ideal, indicating that the timeline associated with the 3D RTP workflow is amenable to further refinement. For IMRT treatments, delays were introduced in the image registration and MD contour stages. The average time to completion of the physics review task, which was the last task in the RTP process, was close to the ideal completion time of 6 days.

3.5 On-time Performance Relative to Ideal Timeline

Average on-time performance relative to the ideal timeline was 75/7% (44.2% - 96.3%) for 3D plans and 44.2% (25-87.1%) for IMRT plans, with the lowest timeliness being for planning activities. Further analysis of the individual task completion times showed that the planning task was completed out-of-sequence by the dosimetrists. That is, tasks associated with planning activities were completed prior to the physics review rather than prior to the MD review as modelled in the standardised RTP workflow in Fig. 2, thus resulting in low on-time performance for this task.

3.6 Elapsed Time between Tasks

The average time elapsed between completion of the different tasks is listed in Table 3. This provides an estimate of the average time required to perform each task. The times to complete the planning, MD review and MD approval tasks were calculated relative to completion of the MD contour task. The times to complete the IMRT QA and the Physics review tasks were calculated with respect to MD approval. As can be seen, individual IMRT tasks require more time to complete than 3D tasks, reflecting the increased complexity associated with IMRT plans.

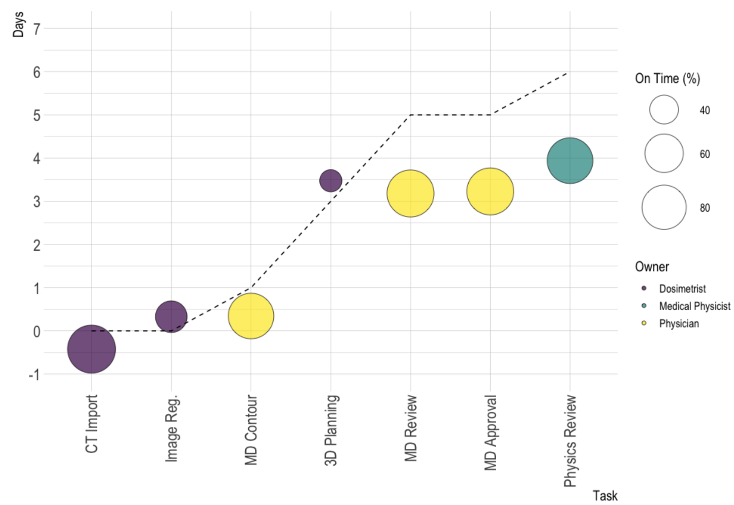

Fig. 4: **3D treatment planning workflow timeline.** The average number of days to completion for the different tasks in the 3D planning workflow is shown by staff role. The diameter of the bubble is proportional to on time compliance relative to the ideal timeline (dotted line).

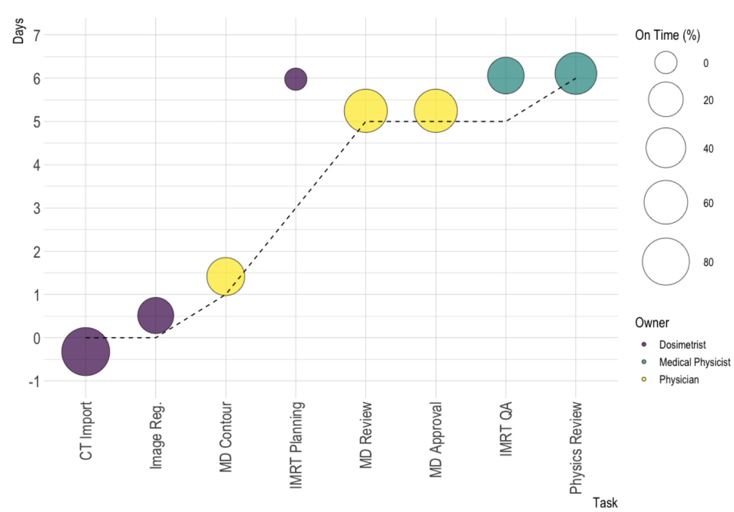

Fig. 5: **IMRT treatment planning workflow timeline.** The average number of days to task completion in the IMRT planning workflow colour-coded by staff role is shown. The diameter of the bubble is proportional to on-time compliance relative to the ideal timeline (dotted line).

Table 3: **Average time to complete a given task for 3D and IMRT treatments.** The negative value for CT import is to end-of-day on the day that the CT is acquired being considered as the start time. †Calculated relative to MD Contour. ‡ Calculated relative to MD Approval.

Modality	Task							
	CT Import	Image Reg.	MD Contour	Planning†	MD Review†	MD Approval†	IMRT QA‡	Physics Review‡
Ideal time (days)	-0.5	-0.5	1	2	4	4	1	1
3D actual time (days)	-0.42	0.75	0.76	3.1	2.8	2.85		0.47
IMRT actual time (days)	-0.32	0.83	0.90	4.56	3.83	3.83	0.81	0.86

4 Discussion

We have presented performance measures of the radiation treatment planning workflow for cancer patients. The measures describe the completion time and compliance rates in the completion of key carepath activities in a standardised RTP workflow.

Formulating, implementing and adoption of a standardised workflow in radiation oncology that can be tracked by the EMR and displayed in real-time on the departmental dashboard was challenging due to the complexity of the RTP process, the large number and interdisciplinary nature of the staff involved in the creation of a patient's treatment plan, and inherent limitations of the EMR. Ensuring effective communication amongst the stakeholders was key towards achieving a working solution.

Implementing an RTP process in the clinic that is event-driven and where progression to the next stage of planning is triggered by task completion relies on the timely completion of the tasks in the EMR by the owners of the task. It also relies on the tasks being completed in the correct sequence. This study has provided insight into how activities unfold in a busy clinical practice during the treatment planning process. It has helped us identify strengths in our clinical practice, for instance, on average the physics review is completed, and therefore patient treatment starts, within the ideal timeline. It has also helped identify limitations, for instance in the compliance of task completion for certain activities, the sequence of activity completion, and delays.

As patient loads increase and we move towards process automation in radiation oncology, optimal allocation of resources and an understanding of where bottlenecks and failure modes arise [3,8,11], the relationship between workload and staffing levels, as well as the impact of potential changes in workflow are crucial. The performance measures presented here are important for clinical practice improvement and process modelling particularly with respect to optimising allocation of resources and ensuring adequate staffing levels in a busy clinical setting. In future work, we will develop more advanced models of the radiation therapy workflow towards improving clinical practice and patient safety.

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