Design and Scheduling of Proton Therapy Treatment Centers

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Outline

- Motivation
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- Modeling the system
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- Conclusions

Motivation

- In 2012, an estimated 1.6 million Americans were diagnosed with cancer
- Approximately 60% of all U.S. patients with cancer are treated with radiation therapy, most of them with external beam radiation therapy
- Radiation therapy, while effective at destroying cancerous tissue, tends to irradiate healthy tissue in the process, causing unwanted side effects
- Proton therapy has the potential to deliver a lethal radiation dose to the tumor while delivering less radiation to adjacent tissue than other forms of radiation therapy

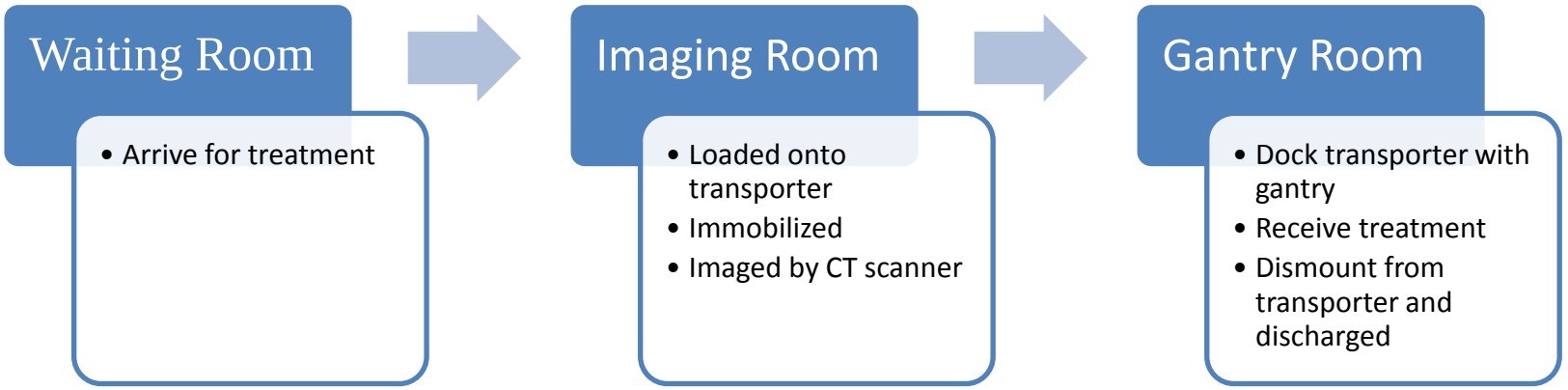
Motivation

- Given the large capital investment and scarcity of proton therapy treatment centers, it is important that each center treats as many patients as possible while minimizing patient wait times
- Schedules need to be constructed with awareness of the limiting constraints of the facility
- Schedules need to account for uncertainty in treatment time and should account for problems faced in an outpatient setting, such as patient tardiness and absenteeism

Proton Therapy

- A course of treatment typically has five treatments per week for three to five weeks
- A patient is immobilized and then transported through the treatment process on a motorized patient carrier that docks with the imaging and gantry equipment
- Before each treatment, a patient is imaged to ensure precise delivery of radiation
- A patient receives radiation from multiple beam angles to mitigate any incident radiation to healthy tissue

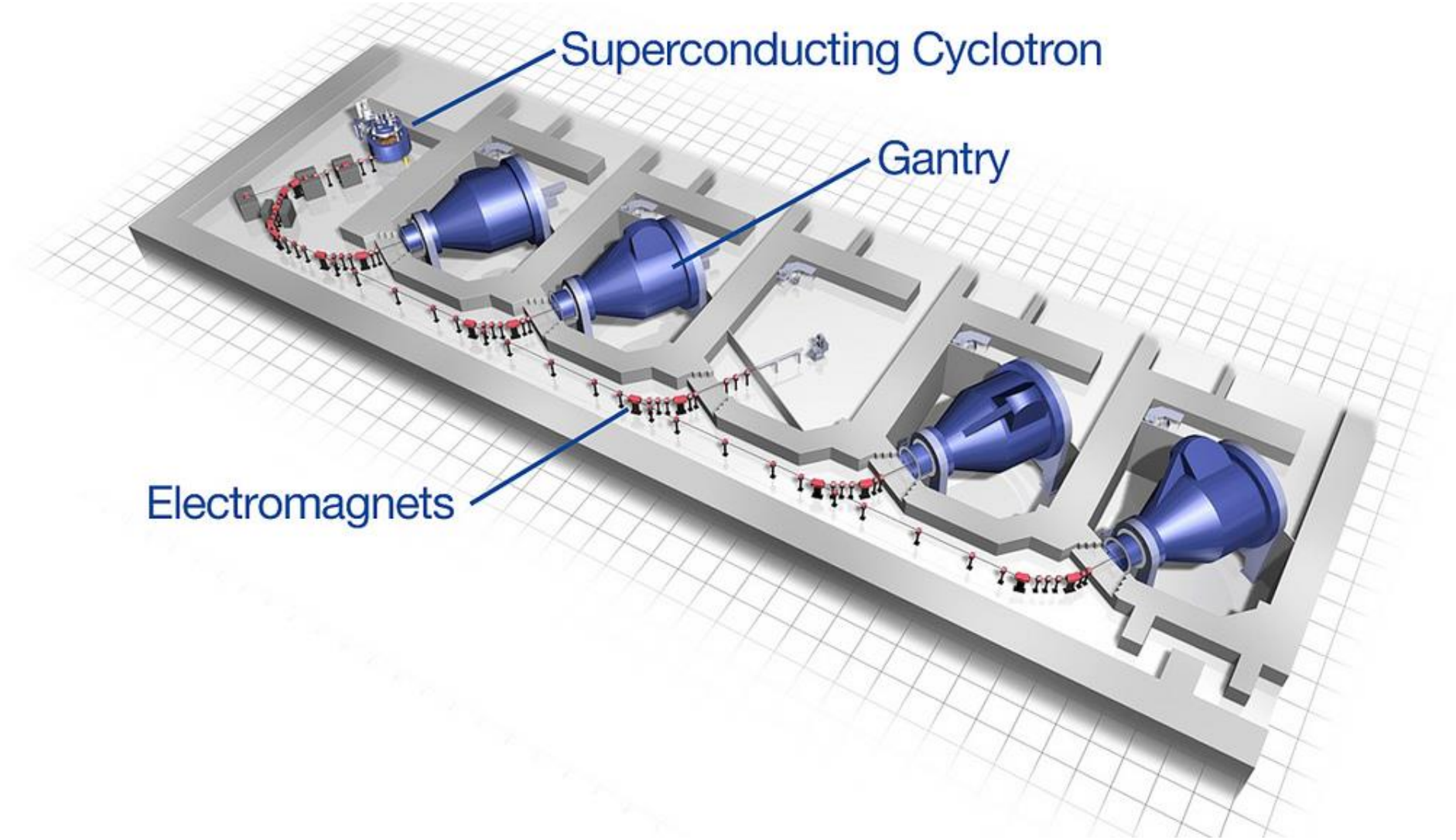
Patient Flow Through the System



X-ray Computed Tomography

- Scan is taken prior to every treatment
- Patient is immobilized in imaging room, then scanned
- Landmarks are placed to aid in the correct delivery of radiation

Facility Layout

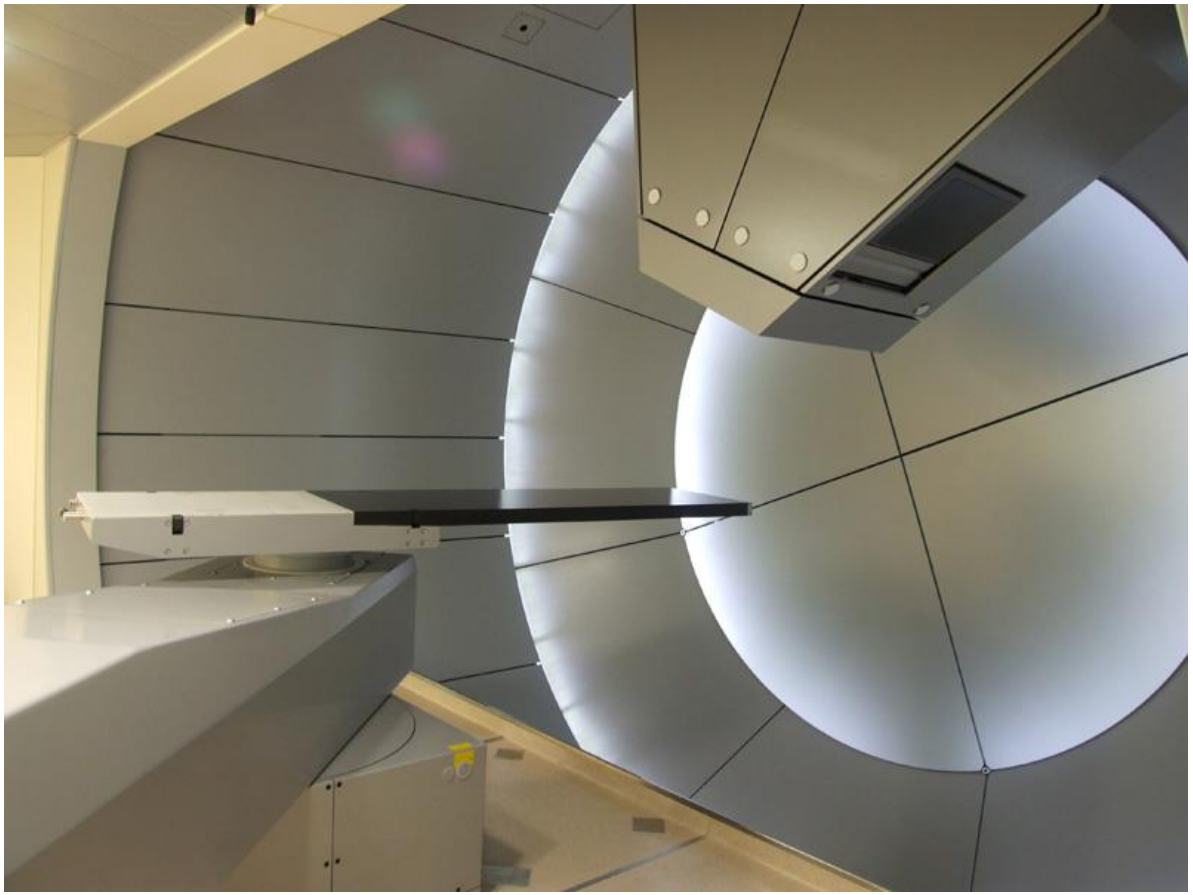


Cyclotron and Room Switching

- Cyclotron is able to deliver protons to a single gantry room at any point in time
- There is a single cyclotron, making it the limiting resource of the system

- Switching delivery of protons from one gantry room to another incurs a delay of one minute

The Gantry Room



- Gantry must be rotated between each beam angle, a process that takes approximately 90 seconds

Previous Work

Fava et al. (2012) simulate a comparison of remote positioning versus in-gantry positioning of patients for proton therapy centers

- Used plans with up to nine minutes of beam time
- Imposed strict limit of no more than three minutes of waiting during any stage of treatment
- Scheduled patients without considering their treatment plan

Simulation

- NetLogo 5.0.4, an open source multi-agent modeling programming language, was used to construct the simulation of patient treatment
- Treatment times were estimated based on Fava et al. (2012) and manufacturer specifications
- Triangular distributions were used to simulate the distribution of treatment times to ensure positive treatment times

Treatment Times

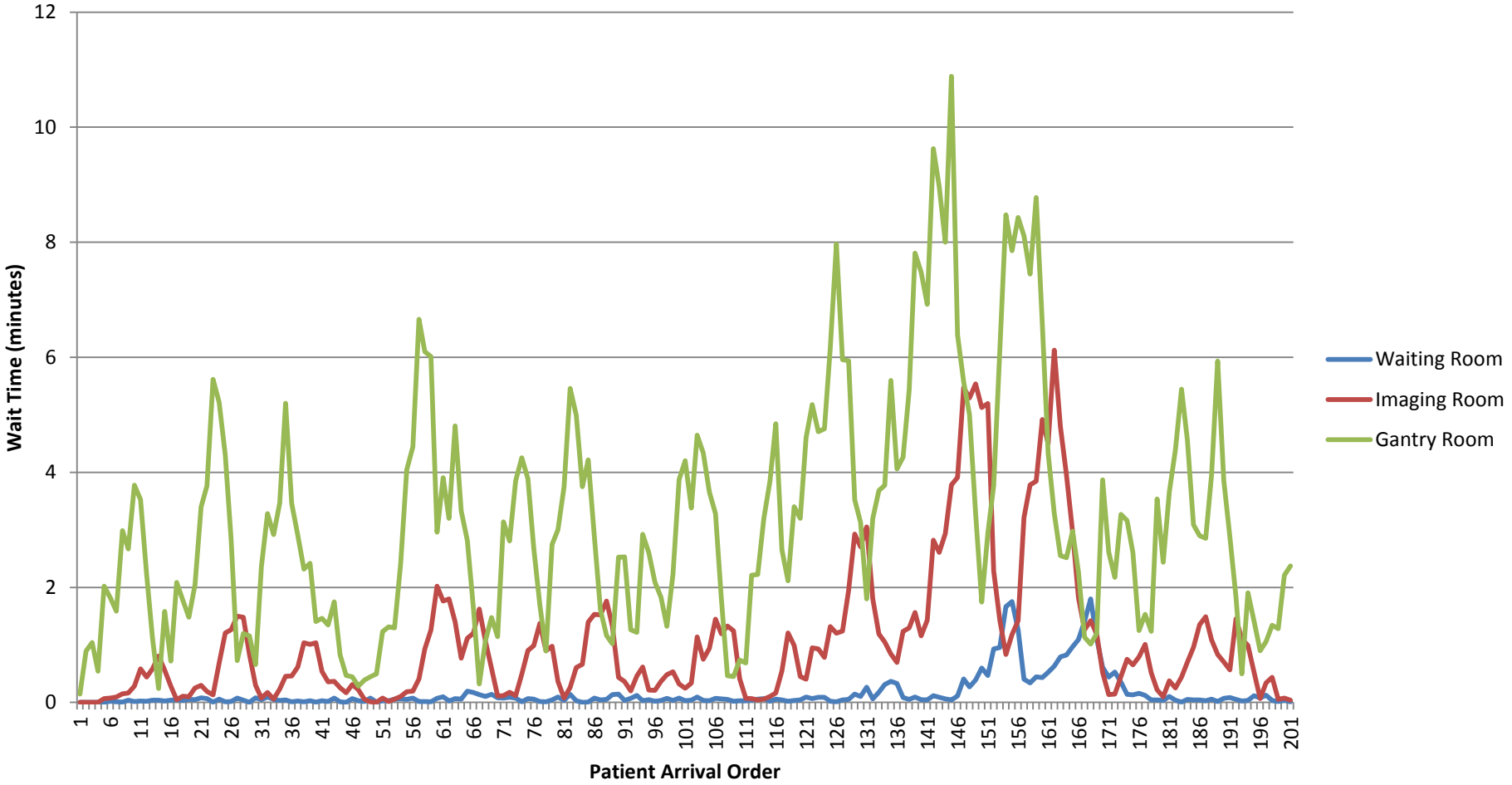
Treatment Steps	Mean Time (min)	Range of Values (min)
(1) Patient enters the facility	0.00	[0.00]
(2) Imaging	16.83	[8.50, 25.17]
(3) Move to gantry room	1.33	[1.33]
(4) Prepare for beam angles	6.67	[4.25, 9.08]
(5) First beam angle	1.00	[1.00]
(6) Move gantry arm	1.00	[1.00]
(7) Second beam angle	1.00	[1.00]
(8) Move gantry arm	1.00	[1.00]
(9) Third beam angle	1.00	[1.00]
(10) Discharge patient and reset gantry room	4.83	[2.83, 6.83]

Treatment times are based on Fava et al. (2012) and manufacturer estimates

Scheduling Patients

- A basic schedule has patients arriving at fixed intervals based on the average throughput of a proton treatment center
- Ignores information about a patient including treatment plan, which determines how many beams from the cyclotron are needed

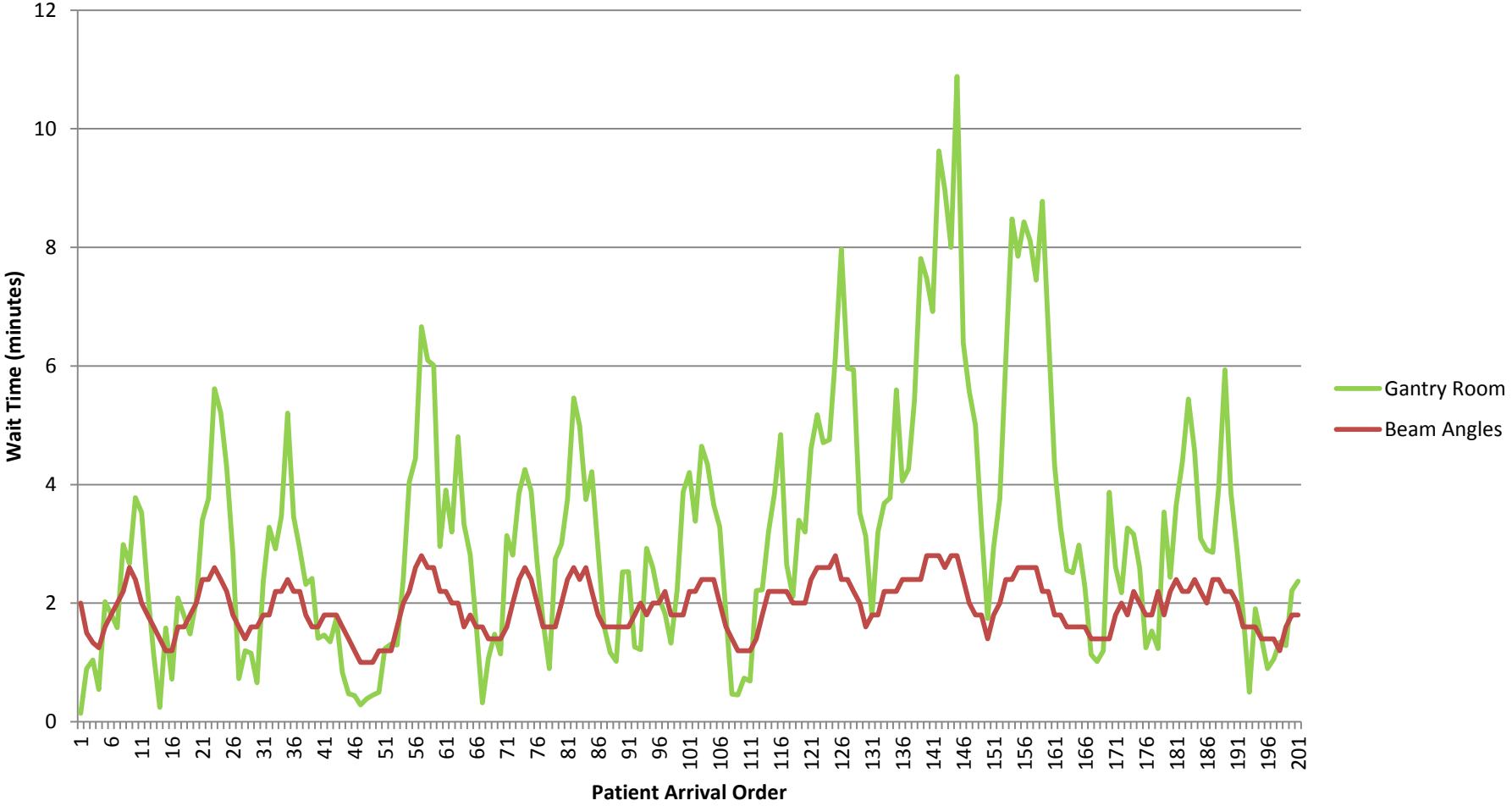
Patients Scheduled Without Accounting for Treatment Plan



Scheduling Patients

- There are large swings in the wait time experienced in the gantry room
- Long wait times in the gantry room lead to increased wait times in the imaging room
- How do the randomly ordered patient treatment plans affect the waiting time in the gantry room?

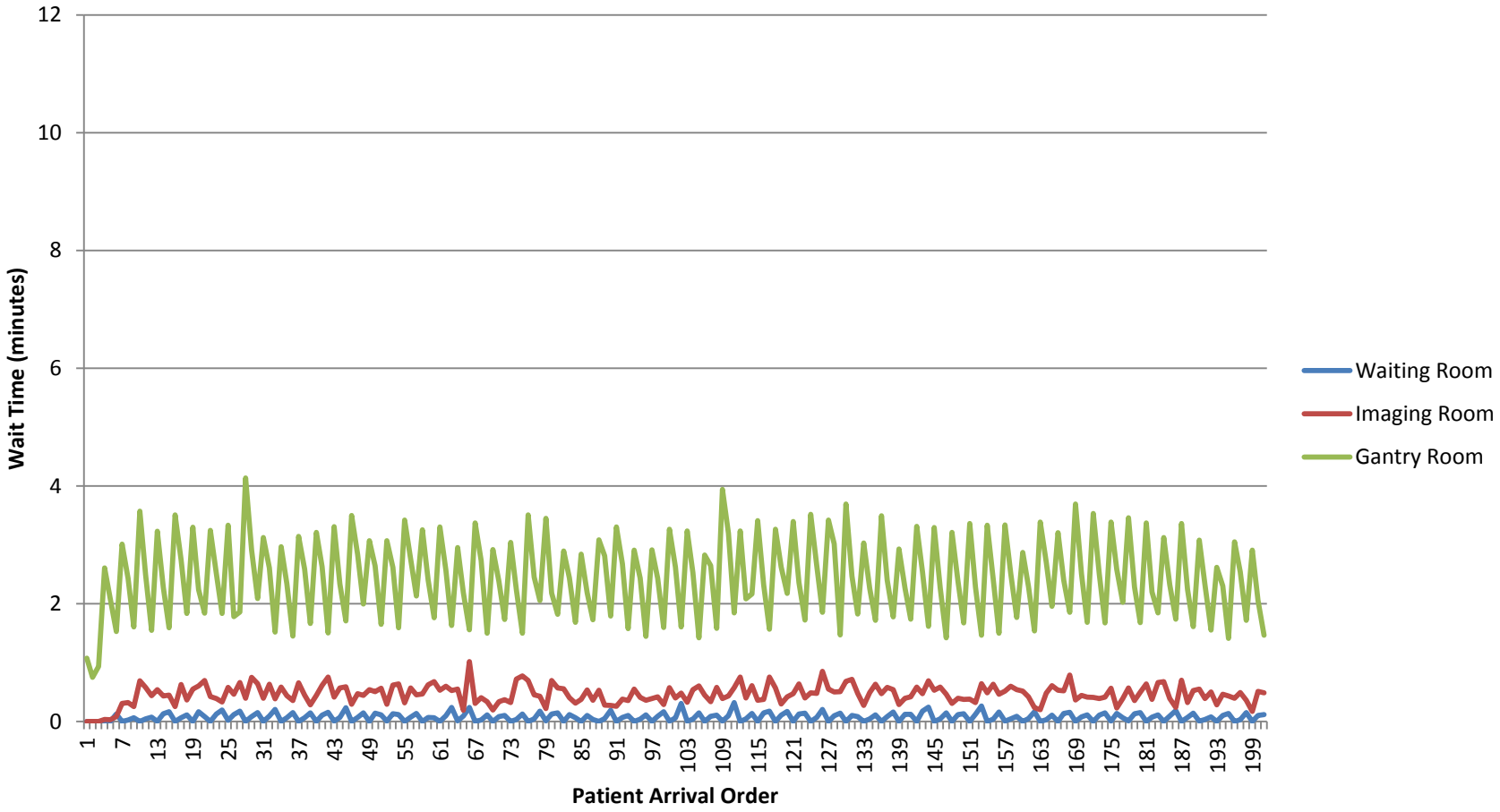
Wait Time in Gantry Room vs. Rolling Average of Beam Angles



Ordering By Treatment Plan

- Consecutive patients with multiple beam angle treatment plans lead to long gantry room waiting times
- Patient treatment plans are known prior to the scheduling of patients
- Cycling between patients with one, two, and three beam angle plans when scheduling will reduce congestion in the gantry room caused by several consecutive patients with two or three beam angle treatment plans

Wait Times for Ordered Patient Arrivals at Equal Intervals



Ordering By Treatment Plan

- The average time spent waiting by patients is reduced by over a minute per patient, a reduction of 30%
- The variance of total wait time is reduced by 30%
- The number of patients who have total wait times longer than 10 minutes is reduced by 80% and longer than 5 minutes by 37%
- Patients spending more than three minutes waiting in the gantry room is reduced by 24%

Ordering Patients Based on Treatment Plan

Beam Angles in Preceding Patient's Plan	Total Wait Time (minutes)	
	Random Order	Smart Ordering
1	3.07	2.90
2	4.23	2.17
3	5.43	3.81

- Note that while the patient experience is quicker and the variations in wait times are smaller, differences in wait time persist
- We adjust the time between patient arrivals to allow for more time after patients with multiple beams and less for patients with a single beam. The daily throughput and operation hours are not changed

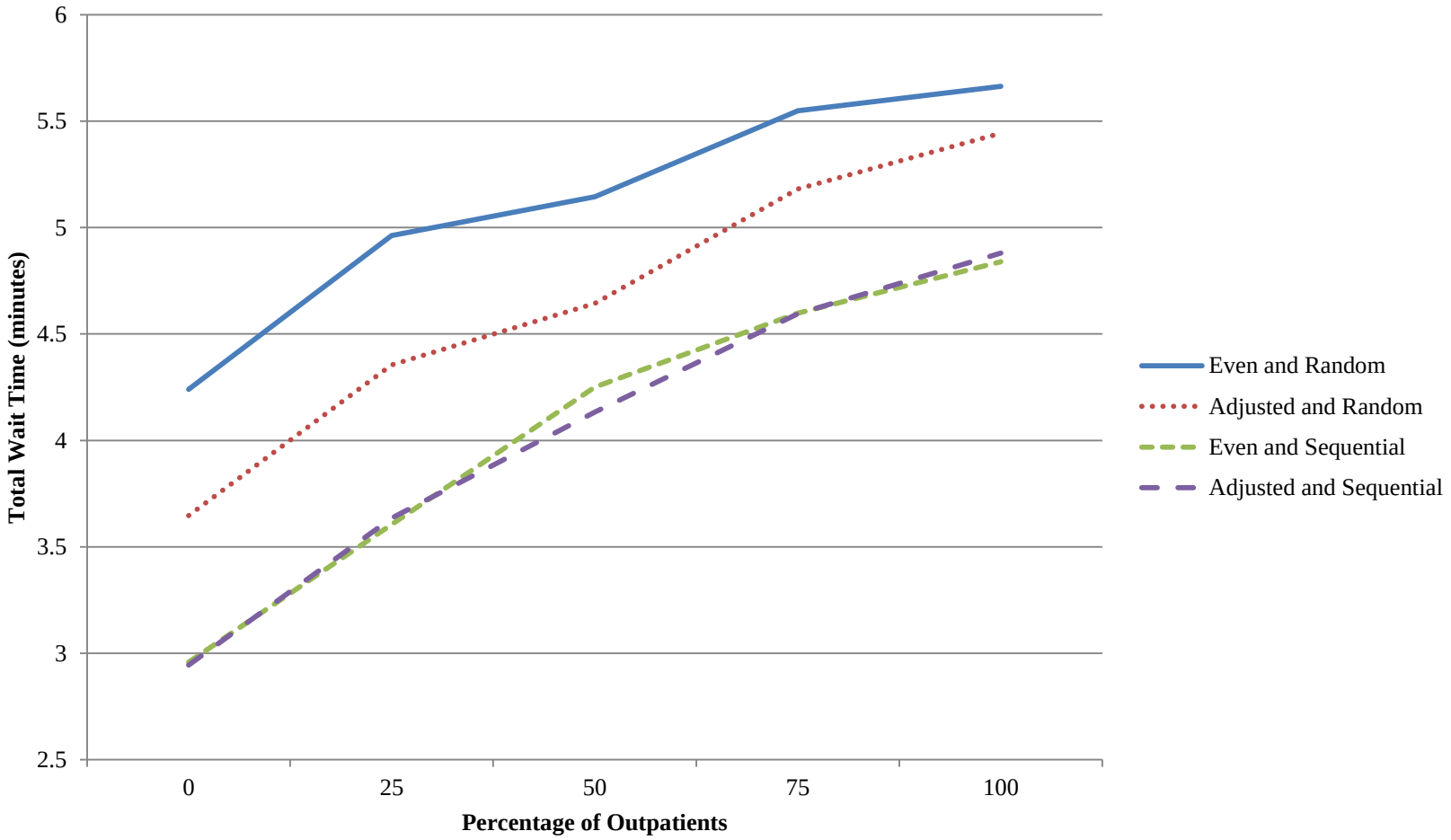
Comparison of Different Schedules Based on Patient Treatment Plans

	Waiting Room (minutes)	Imaging Room (minutes)	Gantry Room (minutes)	Total (minutes)
Even Spacing Random Order	0.10	0.94	3.20	4.24
Adjusted Spacing Random Order	0.56	0.62	2.46	3.65
Even Spacing Sequential Order	0.04	0.46	2.45	2.96
Adjusted Spacing Sequential Order	0.07	0.47	2.41	2.94

Patient Tardiness and Absenteeism

- Proton therapy is available as an outpatient procedure with most of the local patients commuting daily for treatment
- A fraction of the patients will be inpatients or will be staying from out of town specifically for treatment
- Patient tardiness and absenteeism are a major concern for outpatient procedures (Liu et al. 2010) and their effect on patient throughput and wait times may be significant
- Outpatients are assumed to have a 5% chance of absenteeism and otherwise arrive within 20 minutes of their scheduled arrival time

Change in Patient Wait Time as a Function of Percentage of Outpatients



Patient Tardiness and Absenteeism

- While ordering by treatment plan outperforms the other schedules at all mixtures of outpatients, the wait time experienced by patients is increased by 66%
- Scheduling outpatients for precise arrival throughout the day is unrealistic. Scheduling multiple patients to arrive every 15 minutes allows for some variance in arrival time with minimal overall disruption to patient wait times

Scheduling Multiple Patients on the Quarter Hour

Percentage of Outpatients	Waiting Room (minutes)	Imaging Room (minutes)	Gantry Room (minutes)	Total (minutes)
0	1.15	0.71	2.78	4.63
25	0.83	0.75	2.89	4.48
50	0.77	0.81	3.01	4.59
75	0.79	0.86	3.07	4.71
100	0.91	0.94	3.14	4.99

Conclusions

- Taking into account patient treatment plans when scheduling can reduce patient wait times up to 30%
- With high levels of patient tardiness and absenteeism, exact scheduling can have wait times up to 66% longer than when all patients arrive on schedule
- When treating only outpatients, scheduling patients to arrive on the quarter hour leads to a 2% decrease in performance over exact scheduling