A Discrete Event Simulation Model to Evaluate Operational Performance of a Colonoscopy Suite

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Background and Aims*. Colorectal cancer, a leading cause of cancer death, is preventable with colonoscopic screening. Colonoscopy cost is high, and optimizing resource utilization for colonoscopy is important. This study's aim is to evaluate resource allocation for optimal use of facilities for colonoscopy screening.* ***Method****. The authors used data from a computerized colonoscopy database to develop a discrete event simulation model of a colonoscopy suite. Operational configurations were compared by varying the number of endoscopists, procedure rooms, the patient arrival times, and procedure room turnaround time. Performance measures included the number of patients served during the clinic day and utilization of key resources. Further analysis included considering patient waiting time tradeoffs as well as the sensitivity of the system to procedure room turnaround time.* ***Results****. The maximum number of patients served is linearly related to the number of procedure rooms in the colonoscopy suite, with a fixed room to endoscopist ratio. Utilization of intake and recovery resources becomes more efficient as the number of procedure rooms increases, indicating the potential benefits of large colonoscopy suites. Procedure room turnaround time has a significant influence on patient throughput, procedure room utilization, and endoscopist utilization for varying ratios between 1:1 and 2:1 rooms per endoscopist. Finally, changes in the patient arrival schedule can reduce patient waiting time while not requiring a longer clinic day.* ***Conclusions****. Suite managers should keep a procedure room to endoscopist ratio between 1:1 and 2:1 while considering the utilization of related key resources as a decision factor as well. The sensitivity of the system to processes such as turnaround time should be evaluated before improvement efforts are made.* ***Key words:*** *colorectal cancer; colonoscopy; discrete event; simulation.* ***(Med Decis Making XXXX;XX:xx–x)***

Colorectal cancer is the second leading cause of cancer death in the United States, with 50,640 deaths and 148,810 new cases estimated in 2008.[1] Colonoscopy screening is an important prevention and detection method for colorectal cancer. It has been estimated that 17 million endoscopies were done in 2002 for colorectal cancer screening.[2] The high cost of health care delivery for colonoscopies motivates the consideration of best practices to improve operational performance of colonoscopy suites.

Careful planning of procedure rooms, staff, and other resources that make up the colonoscopy suite is integral to effective delivery of screenings. However, there is significant uncertainty about the time of activities required for colonoscopy, such as the intake process, the procedure, and patient recovery. This uncertainty makes resource planning a difficult task. Furthermore, a significant portion of the total costs are fixed (e.g., physical space, equipment, staff) and are incurred independent of average daily patient throughput through the suite. Modeling the colonoscopy suite is a helpful means of better

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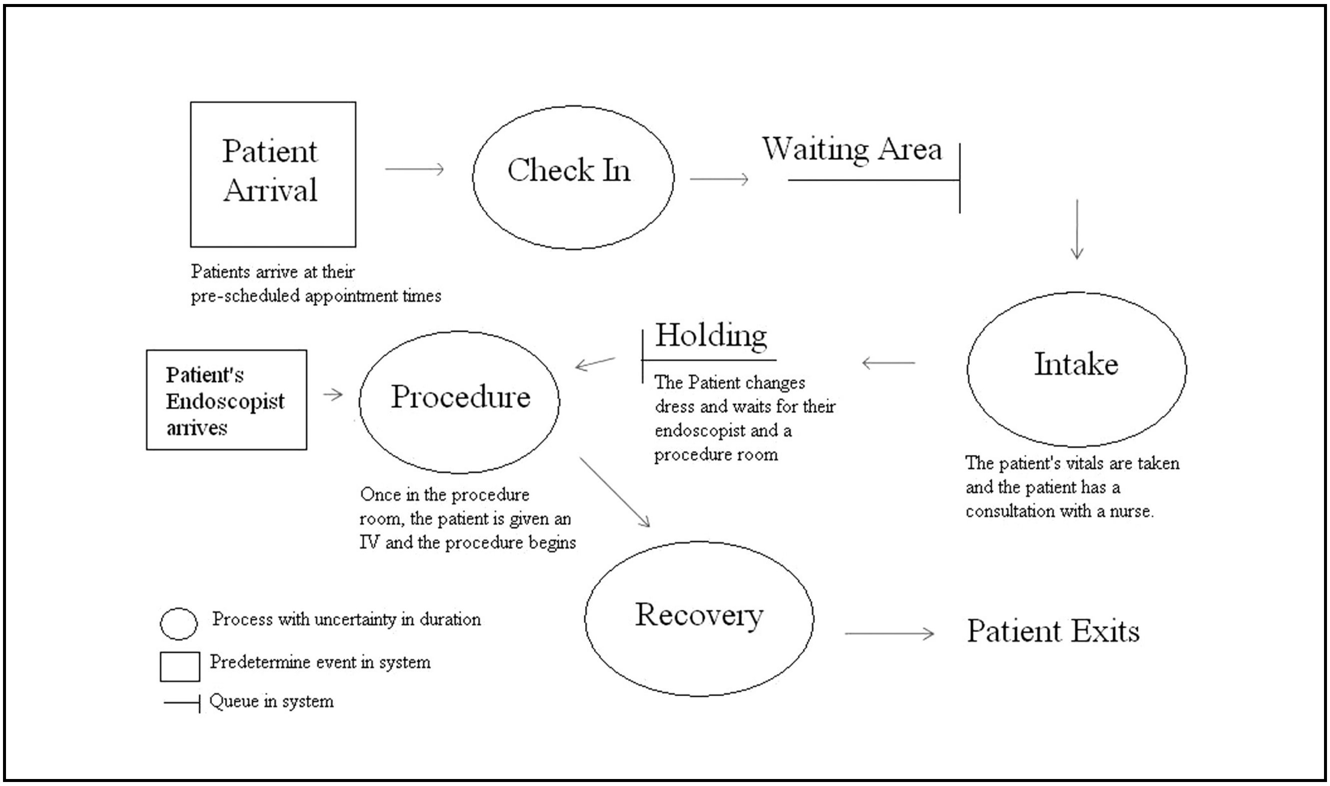

Figure 1 Schematic representation of the sequence and flow of activities for a particular patient within a colonoscopy practice.

understanding the interactions between the processes in the suite and how potential changes can influence its efficiency. Discrete event simulation[3] is a type of modeling from the field of systems engineering. A discrete event simulation is a computer-implemented quantitative model that is designed to emulate the process flow of a system.

The main questions we addressed though our simulation were as follows: 1) given a certain number of procedure rooms, how does varying the number of endoscopists operating within the suite affect patient throughput? 2) Are there economies of scale associated with a larger endoscopy suite? 3) What is the maximum achievable resource utilization? 4) Are there any recognizable relationships between these performance measures?

METHODS

Conceptual Model

Our simulation model was constructed based on the colonoscopy suite at Mayo Clinic in Rochester, Minnesota. Development of our simulation model began with the design of a conceptual model representing the typical operation of a colonoscopy suite. A team of subject matter experts and systems engineers mapped the flow of patients through actual stages of the system, including the patient waiting room, preparation rooms, procedure rooms, and recovery rooms. In the colonoscopy practice we studied, appointments can be made up to 12 weeks in advance. Schedules typically fill up within the last 48 h, and patients arrive at the colonoscopy suite according to a predetermined set of assigned appointment times. The conceptual model includes a base case of 4 endoscopists sharing 8 procedure rooms. The day begins at 7:30 AM and finishes at 5:00 PM. Figure 1 provides a summary of the activities that comprise a patient's flow through the colonoscopy suite. Following is a detailed description of the main activities that govern flow through the colonoscopy suite:

Intake. When patients arrive for their scheduled procedure, they are received at the check-in desk, where they are asked to have a seat in the lobby. At the patient's scheduled arrival time, 1 of 6 nurses from the intake area takes the patient from the lobby to an intake area. Following consultation with a nurse, the patient is taken to a room for a change of dress. Following changing, the patient is taken to 1 of 2 holding rooms where there are 10 patient seats. The patient waits until the nurse from the next available procedure room comes to transfer him or her.

Procedure. Following holding, a nurse from a procedure room walks the patient to the procedure. An IV is started, and the patient waits in the procedure room for the endoscopist to arrive. The procedure room activity begins when the endoscopist enters the room and ends when the patient leaves the procedure room. Subactivities include discussion of the procedure, sedation, insertion of colonoscope, and colonoscope removal. Following the procedure, cleanup and preparation for the next procedure in the room take approximately 10 to 15 min.

Recovery. Following the procedure, the patient is taken to the recovery area. The recovery area has 3 pods with 8 beds in each pod. As the patient is taken to recovery, the nurse checks the recovery display panel for directions on which pod the patient should be taken to in order to balance the load on each pod.

Data

Our simulation model is based on a data set ($n = 4024$ patients) collected and compiled over the year 2006, after obtaining appropriate research authorization. It is based on a single unit of 4 endoscopy rooms, representing a sample subset of the total number of procedures performed at the colonoscopy suite. The times at check-in, intake area arrival, procedure room arrival, recovery room arrival, and discharge were collected for each patient. These patient flow time data points were fed into an electronic system as they occurred. From these data, the probability distribution for the procedure time was fit using maximum likelihood estimation. The probability distributions for intake and recovery were based on sampling from empirical data. The highest 1% of outliers was excluded as unreasonable time durations, most likely due to a time miscalculation. The resulting distributions for intake, procedure, and recovery shown in Figure 2 have means and standard deviations of 14.63 (7.24), 23.55 (11.89), and 59.18 (18.18) mins, respectively.

Simulation Model

We developed our simulation model through an iterative process involving model construction, attaining feedback from those involved in the management of the colonoscopy suite, incorporating the feedback into the model, refinement, and validation. The discrete event simulation model was constructed by dividing the system into the 3 separate stages: intake, procedure, and recovery. Empirical data were used to model the intake, procedure, and recovery stages, and estimates for other process parameters were obtained from the suite manager. Model parameters and sources are organized in Table 1.

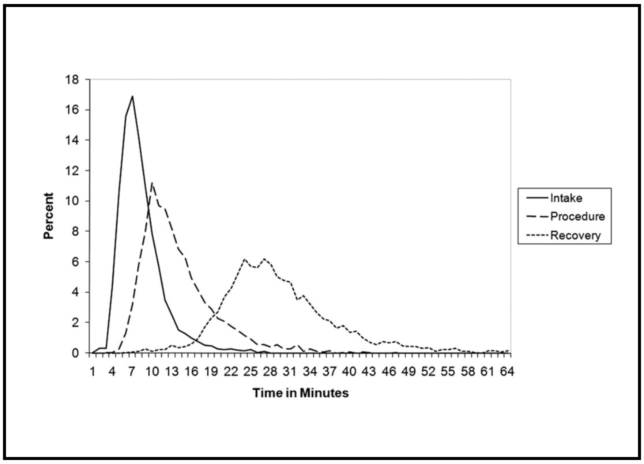

Figure 2 Distributions of duration times for intake, procedure, and recovery processes.

In our model, we assume that a finite number of procedure rooms and endoscopists are available, and patient flow is restricted based on their availability. Recovery beds and intake nurses were both given unlimited availability for the purpose of measuring maximum procedure room and endoscopist utilization in a stressed system based on a maximum number of procedures. The average utilization rates of recovery beds and intake nurses were then calculated as the average of the number of resources at peak utilization.

Patient schedules were generated by varying the amount of time between each patient's arrival between $(\mu - 2\sigma, \mu + 2\sigma)$, where μ represents the mean procedure time and σ is the standard deviation. We assume arrivals are deterministic, and all patients arrive on time and have undergone appropriate preparation for the colonoscopy. This may vary among clinical environments for a variety of reasons. We make this assumption for 2 reasons. First, it is consistent with the practice we studied where no-show rates are very low and most patients arrive at or before their appointment time. Second, it favors a more straightforward interpretation of our analysis of varying design and operating policies.

Table 1 Summary of Model Parameter Sources

Parameter	Time Distribution	Source
Patient arrival	Scheduled	MCCD
Check-in	Uniform [1,3]	Expert opinion
Intake	Empirical, mean = 14.63, standard deviation = 7.24	MCCD
Procedure	Lognormal + 3, mean = 23.55, standard deviation = 11.89	MCCD
Recovery	Empirical, mean = 59.18, standard deviation = 18.18	MCCD
Endoscopist turnaround	Triangular (3, 4, 5)	Expert opinion
Procedure room turnaround	Triangular (10, 15, 20)	Expert opinion
Transfer	Deterministic (0.5 –1.0)	Expert opinion

Note: All times reported in minutes. MCCD, Mayo Clinic Colonoscopy Database.

Table 2 Patient Throughput, Procedure Room Utilization, Endoscopist Utilization, Intake Utilization, and Recovery Utilization with Respect to Increasing Number of Procedure Rooms in the Endoscopy Suite (95% Confidence Interval)

Procedure Rooms/ Endoscopists	Patient Throughput (Number of Patients)	Procedure Room Utilization (%)	Endoscopist Utilization (%)	Intake Utilization (%)	Recovery Utilization (%)
4/3	46 (46, 46)	62 (62, 62)	82 (82, 82)	26 (26, 26)	41 (41, 41)
8/6	94 (94, 94)	63 (63, 63)	84 (84, 84)	28 (28, 28)	41 (41, 41)
12/9	142 (142, 143)	64 (64, 64)	85 (85, 85)	36 (36, 36)	42 (42, 42)
16/12	186 (186, 186)	62 (62, 62)	83 (83, 83)	48 (48, 48)	54 (54, 54)
20/15	236 (235, 236)	63 (63, 63)	84 (84, 84)	47 (47, 47)	58 (58, 58)

Validation

The model was built using Arena 10.0,[4] and all scenarios discussed in the Results section were run on a standard PC (Intel Core 2 Quad CPU, 2.39 GHz, 4 GB of RAM). Our validation of the model was based on a base case scenario corresponding to the typical operation of the clinic we studied. Calibrating the model using the sampled data resulted in total patient throughput rates that match closely with those observed in practice. Both patient throughput and the length of day for the clinic for different staffing configurations were presented to the suite manager, endoscopists, and experts familiar with the suite's operations. It was agreed that the data presented were consistent with expected outcomes of the configurations. Additional validation was done based on dividing the clinic day into 3 smaller 3-h shifts, in the manner the clinic schedule operates, and comparing daily throughput per endoscopist. On the basis of our observational data, the mean number of procedures done by an endoscopist during a shift was 5.33. Based on our simulation model results, presented in Table 2, the mean number of procedures per endoscopist per shift was 5.16 (0.12), 5.25 (0.45), 5.28 (0.67), 5.18 (0.15), and 5.25 (0.41) for the 5 scenarios presented in Table 2. The numbers in parentheses are the *P* values for 2-sided *t* tests for each scenario.

Simulation Analysis

Our numerical results include the base case and additional scenarios that were constructed by varying the number of procedure rooms and the number of endoscopists. Patient arrivals are based on a schedule where patients arrive in independent arrival streams for each endoscopist. Arrivals are spread out during the day by the mean procedure duration. Each of the scenarios was simulated for 500 replications to account for the stochastic nature of the intake, procedure, room and endoscopist turnaround, and recovery times. This number of scenarios created sufficiently tight confidence intervals relative to the mean. Base case procedure room turnaround times were based on expert estimates and assumed to be 15 min using a triangle distribution with parameters (10, 15, 20). Endoscopist turnaround time was based on a triangle distribution with parameters (3, 4, 5 min).

The results reported for each scenario include 1) the maximum number of patients who receive an endoscopy during the clinic day (7:30 AM to 5:00 PM), 2) mean utilization of procedure rooms throughout the day, and 3) mean utilization of endoscopists throughout the day. Total daily patient throughput is defined by the number of patients who leave recovery by 5:00 PM. The utilization of procedure rooms and endoscopists is defined as the time the room is used for colonoscopy procedures divided by the total time they are available (turnaround time is counted as available time but not used time).

RESULTS

Operational Performance Evaluation

Table 2 shows that, for a given procedure room to endoscopist ratio, the maximum number of patients who can be seen increases approximately linearly as the suite size increases in size. For example, 3 endoscopists who share 4 rooms can see a maximum of 46 patients during a clinic day, and 6 endoscopists who share 8 rooms can see a maximum of 94 patients and so on. The increasing utilizations of intake and recovery resources in Table 2 demonstrate the potential benefits of a larger suite. That is, as the suite size increases, the utilizations of the shared resources also increase. Table 2 also shows that procedure room and endoscopist utilizations remain approximately constant as the suite size increases because the ratio of procedure rooms to endoscopists is held constant.

On the basis of the results in Figure 3, we conclude that the maximum number of patients who can be seen on a given day is subject to diminishing returns when the number of endoscopists operating within a set number of procedure rooms increases. Furthermore, Figure 3 illustrates that both the procedure room utilization and endoscopist utilization converge to the same maximum utilization as endoscopists are added to a suite of 8 procedure rooms. This is intuitive because as endoscopists are added, we approach the situation where each endoscopist is confined to a single procedure room.

Sensitivity Analysis

Figure 4 illustrates the influence of turnaround time on performance measures relative to the base case assumption of a triangle distribution with parameters (10, 15, 20 min). In the figure, the percentage increase or decrease of a performance measure from base case is shown with the low and high assumptions for turnaround time corresponding to a mean of 10 and 25 min with parameters (5, 10, 15) and (20, 25, 30), respectively. The base case corresponds to a scenario with 8 procedure rooms open. For example, when procedure room turnaround time is assumed to be low, patient throughput increases 12% when there are 8 endoscopists and 5% when there are 6 endoscopists. That is, patient throughput is more sensitive to changes in procedure room turnaround time when the procedure rooms available are being used by more endoscopists. From Figure 4, we conclude that performance measures are quite sensitive to mean turnaround time when the number of endoscopists using the 8 procedure rooms is greater than 4. However, there is little discernible effect of reducing turnaround time for higher ratios (such as 2:1 illustrated in the figure). This indicates that the availability of a larger number of procedure rooms (2 or more per endoscopist) provides very little benefit.

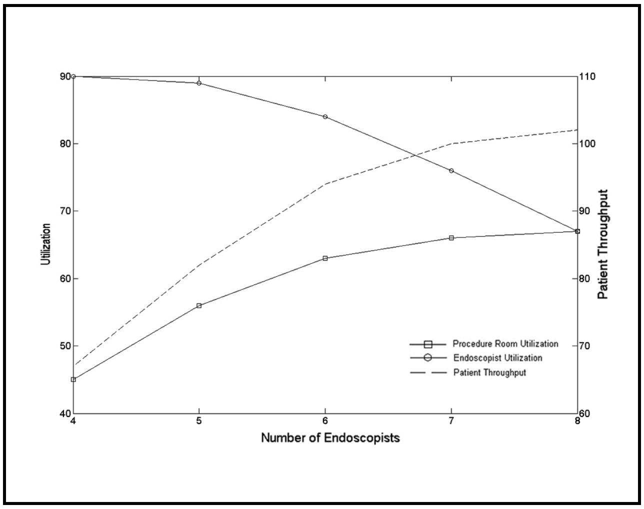

Figure 3 Expected procedure room and endoscopist utilization and patient throughput over time as a function of the number of endoscopists in the suite.

By increasing the number of procedure rooms in the simulation, we observe increased efficiencies in both intake nurses and recovery beds. As shown in Table 2, although procedure room and endoscopist utilizations remain constant, intake nurse and recovery bed mean utilizations increase more than 75% and 40%, respectively. Such results support potential efficiencies of having a large colonoscopy suite.

Patient Perspective

Measurable outcomes of this analysis can be extended to the patients' perspective as well. For instance,

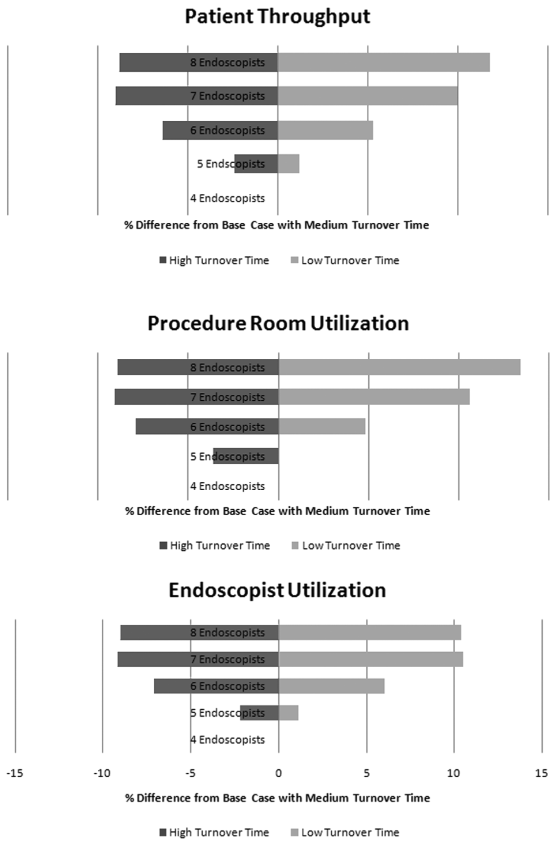

Figure 4 *Sensitivity analysis of performance measures with respect to the number of endoscopists staffing an 8-procedure room endoscopy suite.*

operational decisions about staffing of the endoscopy suite influence patient waiting time for a procedure. We found that the patient arrival schedule has the most significant effect on patient waiting and resource utilization. Figure 5 illustrates the tradeoff of expected patient waiting time and the expected length of the day (time to complete all scheduled colonoscopies). The base case in Figure 5 uses the mean duration as the patient interarrival time, which is a commonly used approach in practice. As interarrival times increase, expected patient waiting time decreases, whereas the expected length of day increases when interarrival times increase. Thus, these 2 criteria are competing. Figure 5 suggests that an optimal arrival schedule would be based on interarrival times that are greater than the mean procedure time.

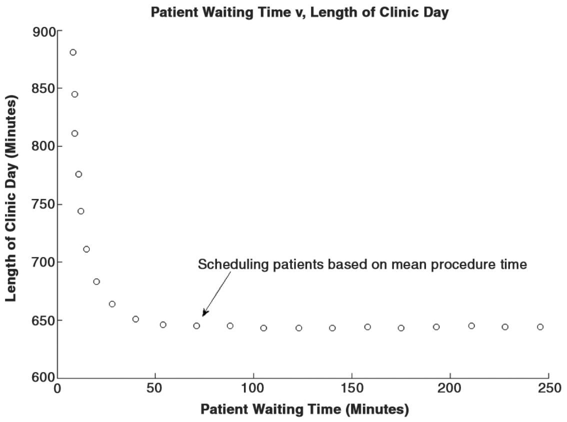

Figure 5 *Expected length of day (time to complete all cases) v. expected patient waiting time (averaged over all patients) with respect to the interarrival time for the patient arrival schedule.*

Recommendations

On the basis of our simulation, we made several recommendations to increase the operational efficiency of the colonoscopy suite. First, when considering how many procedure rooms to open or allocate, it should be noted that 2 procedure rooms per endoscopist is an upper bound. Thus, the optimal ratio of procedure rooms to endoscopists is no greater than 2:1. Having more than 2 procedure rooms per endoscopist results in low procedure room utilization with no increase in patient throughput. This threshold is dependent on the mean time per endoscopy v. the mean time for procedure room turnaround. Second, patient waiting time could be decreased from 71 to 40 min (44% decrease) by allowing as little as 5 additional min (2 data points to the left in Figure 5) between patient arrivals while only sacrificing 6 additional min (0.9% increase) to the length of the clinic day. Finally, depending on the procedure room to endoscopist ratio, focusing improvement efforts on procedure turnaround time could be beneficial as performance measures are very sensitive to that variable.

DISCUSSION

There is a rich history of the use of systems engineering methods to improve efficiency of service systems such as airlines, amusement parks, hotel chains, car rental agencies, and the natural gas and power industry. However, the use of systems engineering methods in health care has been more limited, and further research based on systems engineering principles is needed to improve and make known the potential benefits to health care delivery.[5] Some notable exceptions are recent papers that consider the use of discrete event simulation for planning of outpatient surgical suites,[6–10] primary care clinics,[11,12] a pediatric emergency department,[13] and various other health care clinics.[14]

We created a discrete event simulation model of a complete colonoscopy suite, including the check-in and intake process, the procedure itself, and recovery. Furthermore, our model uses a detailed representation of patient flow and critical resources (e.g., procedure rooms, endoscopist, intake nurses, recovery beds) to investigate the impact of uncertainty in process times and procedure room turnaround times on colonoscopy suite throughput and resource efficiency. Including such a level of detail in the simulation allowed us to gain further insight into how specific resources and structures of the suite affect the efficiency of each other as well as the operations of the suite as a whole.

Most notably, our simulation model contributes to the sparse applications of simulation models to evaluate parallel processing of procedures and the utilization of auxiliary resources (endoscopists) that have complex patterns of resource utilization depending on the presence of both patients and an available procedure room. Thus, our model allows us to investigate the relationships of key resources as the number of patients being served in parallel is varied. In addition, we explore how task performance within the system affects key decisions by examining the influence of procedure room turnaround time in the optimal number of procedure rooms. This integration of detailed operational processes for a colonoscopy suite to create a model of the system capable of answering operational policy-based questions related to overall system efficiency is an area of research that does not have a well-developed precedent in the literature.

The impact of reducing turnaround times for procedure rooms on all performance measures can be significant but is limited to staffing scenarios in which endoscopists have fewer than 2 procedure rooms. The optimal ratio is dependent on the mean time for colonoscopy v. turnaround time. Before focusing attention on improving such processes, considerations about the system improvement should be made.

The maximum achievable endoscopist utilization is 90%, and the maximum achievable procedure room utilization is 67%. This can be intuitively understood from the fact that the mean turnaround times for endoscopists and procedure rooms are approximately 10% and 33% of their used time per endoscopy, respectively. Thus, when averaging over a large number of days with multiple colonoscopies with random durations, the mean utilization approaches the mean time the resources (procedure room and endoscopist) are available.

Efficiency and patient satisfaction are both very important measures of a high-volume service such as a colonoscopy suite. Expected patient waiting time and operational performance measures, such as total time to complete all scheduled colonoscopies, are competing criteria (i.e., increasing one results in a decrease in the other). Thus, both need to be considered in the context of the managerial objectives when determining a patient arrival schedule.

Limitations

The limitations of this study mainly relate to extrapolating the results from this particular suite into the context of other practices. For example, although our assumption about patient arrivals being on time is supported by the data for this suite, such punctuality may not be the case in all suites, and overtime is a real challenge to improving operations in many suites. Furthermore, our assumption about perfect patient attendance and preparation is a departure from reality. Both decreasing the rate of no-shows and having a robust system that absorbs their effects are important aspects of making a suite operate efficiently.

CONCLUSIONS

The above findings are dependent on the mean and variance of activities within the endoscopy suite, which depends on a variety of factors, such as the experience level of the endoscopist and the complexity of typical cases. However, the simulation model we describe is transferable to any organization with a similar process flow and sufficiently large sample set of activity durations to calibrate the model. Furthermore, the model may be used to investigate how other factors influence performance measures, such as reductions in the mean and variance of intake and recovery time, and the effect of material resources constraints such as recovery beds, scopes, or supporting personnel. The application of these findings will potentially allow managers of colonoscopy suites to provide optimally effective staffing, determine the number of rooms required, and may encourage the design of large suites to take advantage of the economies of scale that can be gained in the intake and recovery areas. Ultimately, these data may lead to lower costs as facilities and staff are used more efficiently.

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