

Reorganizing the System of Care Surrounding Laparoscopic Surgery: A Cost-Effectiveness Analysis Using Discrete-Event Simulation

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Purpose. To determine the cost-effectiveness of a proposed reorganization of surgical and anesthesia care to balance patient volume and safety. **Methods.** Discrete-event simulation methods were used to compare current surgical practice with a new modular system in which patient care is handed off between 2 anesthesiologists. A health care system's perspective, using hospital and professional costs, was chosen for the cost-effectiveness analysis. Outcomes were patient throughput, flow time, wait time, and resource use. Sensitivity analyses were performed on staffing levels, mortality rates, process times, and scheduled patient volume. **Results.** The new strategy was more effective (average 4.41 patients/d [median = 5]

v. 4.29 [median = 4]) and had similar costs (average cost/patient/d = \$5327 v. \$5289) to the current strategy with an incremental cost-effectiveness of \$318/additional patient treated/d. Surgical mortality rate must be >4% or hand-off delay >15 min before the new strategy is no longer more effective. **Conclusion.** The proposed system is more cost-effective relative to current practice over a wide range of mortality rates, hand-off times, and scheduled patient volumes. **Key words:** computer simulation; discrete event simulation; anesthesia; cost-effectiveness. (*Med Decis Making* 2004;24:461-471)

The primary goal of the surgical care process is to provide the safest, most effective, and most efficient care possible. However, a potential dilemma arises when surgery departments try to increase patient volume without compromising patient safety. For this analysis, we define "safe" care as care with the fewest

avoidable medical errors¹⁻³ and "efficient" care as treating the maximum possible number of patients in a given period of time and/or using the least amount of resources.

Improved safety has been one of the most significant advances in surgical care in recent times. With anesthesiologists leading the way, medically related system errors and anesthesia-related deaths have fallen from ~1:10,000 to less than 1:1,000,000.^{1,2,4} Currently, most hospital surgery protocols dictate an individual anesthesiologist remain with and be responsible for the surgical patient from anesthesia induction through surgery and recovery. An unfortunate consequence, from a productivity perspective, is that occasionally the operating room (OR) and surgeon stand idle. This is because the surgeon must wait for the anesthesiologist to finish with the postsurgery recovering patient before she or he is free to start anesthesia care on the next. In such a system, the anesthesia protocol limits throughput and potentially becomes a policy "bottleneck" on OR efficiency. Treating more patients per unit time then implies either more anesthesia staff or less time spent with each individual patient, creating a conflict for de-

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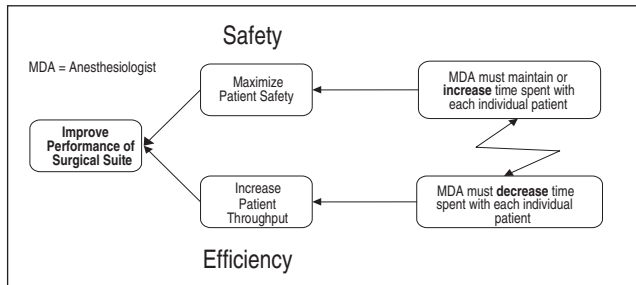


Figure 1 Surgery system conflict.

cision makers (Figure 1). Resolving the conflict with additional staff is difficult unless it can be demonstrated that increased staffing either increases marginal revenue for the hospital or substantially improves outcomes, such as patient throughput and/or patient safety; otherwise, a new approach should be sought.

The purpose of this analysis is to examine the effect of radically redesigning the delivery of anesthesia care and to determine the effect of the proposed change on efficiency and surgical safety. We focused on one common example procedure: laparoscopic cholecystectomy. Laparoscopic cholecystectomy is one of the most common surgical procedures performed today and also one of the newest. Therefore, we believe it is fairly representative of the new surgical innovations currently driving the reexamination of surgical systems and processes. We chose to analyze this problem from a health care system perspective, including both hospital and clinical staffing costs, because this is the organizational level that would be most directly affected by such changes.

The OR of the Future Project (ORF) is an initiative based at the Massachusetts General Hospital, a teaching hospital in Boston, the aim of which is to serve as a laboratory for new OR technologies and processes such as proposed above. The study design of the ORF project is iterative. A proposed process or technology is modeled before implementation and then tested in the experimental OR and evaluated. Lessons learned are then used to identify and model new potential interventions. The initial analysis performed here served as part of the preimplementation modeling efforts.

METHODS

We performed a cost-effectiveness analysis comparing current practice with several staffing strategies (physicians and nurses) for anesthesia coverage. A computer simulation was built to compare the current

and proposed surgical care processes, from patient arrival at the surgical suite through discharge.

Modeling Method

A discrete-event simulation (DES) modeling approach was chosen. DES is a computer-modeling methodology designed to capture flow time, waiting time, competition for resources, and the interdependency of events providing insight into the simulated systems dynamics. Systems simulated using DES may undergo discrete and abrupt changes at variable times. For example, patients may enter the modeled system at randomly chosen intervals, and processes may take randomly chosen amounts of time. The probability of events, the duration of processes, and the rate at which people may enter the system are also typically derived from stochastic draws from either theoretical or empirically derived distributions. Finally, DES allows simulated patients within the system to interact and/or compete with each other for the available resources. These interactions in turn can instigate further effects in the system.

The model was developed using SIMAN, a general-purpose DES language, on the Arena™ software platform.⁵⁻⁸ Alternative simulation scenarios were statistically analyzed using the Process Analyzer, which is embedded within the Arena platform.

Strategy Description

The model follows patients from admission through induction of anesthesia, surgery, and recovery (Figures 2a, 2b). Patients may suffer procedure- or anesthesia-related death. Patients may progress from laparoscopic to open cholecystectomy if there is a complication during the laparoscopic procedure. Alternate therapies such as emergent endoscopic retrograde cholangiopancreatography were not considered since these are not standard emergent responses to failed laparoscopic cholecystectomy. In the model of the current staffing strategy, both nurses (RN) and anesthesiologists (MDA) are present at anesthesia induction and accompany the patient from induction through recovery. In the current strategy, a new patient cannot be induced until both the RN and MDA have finished with the current patient. In the model of the new staffing strategy, 2 MDAs work in tandem with anesthesia care separated into 2 parts. The 1st MDA is responsible for anesthesia induction. The patient's care is then transferred from the inducing MDA to the 2nd MDA, who is then responsible for the patient's intraoperative monitoring and recovery. The

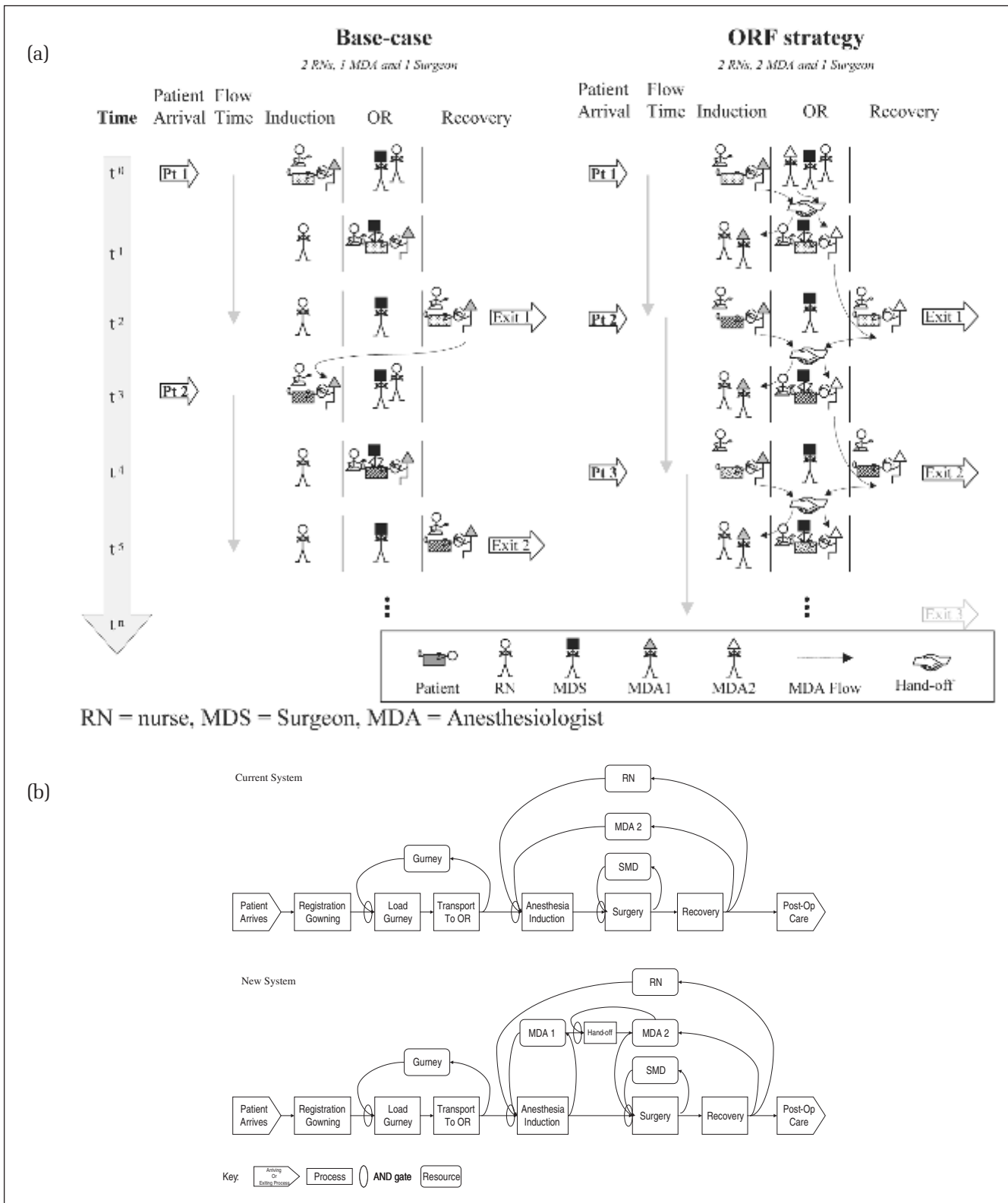


Figure 2 (a) Schematic of current and proposed anesthesia processes. (b) Flowchart of current and proposed anesthesia processes. Note: RN = nurse; MDS = surgeon; MDA = anesthesiologist; OR = operating room.

Table 1 Timing Data from Hospital OR Surgery Scheduling Database (in minutes)

	\bar{x}	<i>SD</i>	Distribution	
			Function	Form
Time between patient arrivals (interarrival time)	110	20	Normal	DSS ^a
Time into room to time ready for surgeon	16.6	11.7	Log norm	DSS
Time procedure start to end	99.5	89.9	Log norm	DSS
Procedure end to leave OR	14.3	10.6	Erlang	DSS
Leave OR to PACU	11.3	5.7	Erlang	DSS
Enter PACU to leave PACU	181	134	Gamma	DSS
Total flow time	318	178	Weibull	DSS

Note: OR = operating room; PACU = postoperative care unit. $n = 526$ cases.
a. Hospital OR scheduling database, Dynamic Scheduling System™.

handoff of the patient requires both MDAs and cannot occur unless the 2nd MDA is free.

A 10-h workday was modeled (e.g., 7 AM to 5 PM). The hospital's ability to staff postoperative and ward beds and the scheduling of surgical patients were assumed to remain unchanged across strategies. The time between patient arrivals (i.e., the interarrival time) was modeled as a stochastic draw derived from the distribution of interarrival times for our hospital's OR. Specifically, patients arrived at the OR with a mean interarrival time of 110 min ($SD = 20$ min). Alternate scheduling strategies^{9,10} were not explored in this particular model. To simulate current patient scheduling decision rules, patients were allowed to enter the model if they arrived within the 10-h workday minus the average time for the operation (i.e., there had to be enough time left on average to perform the final operation). Otherwise, the patient was considered rescheduled. If the waiting time of the currently prepared but not as yet anesthetized patient exceeded 2 h, then subsequent arriving patients were rescheduled for another day until such time as the waiting time again dropped below 2 h. These rules were based on the expert opinion of the surgical scheduling staff. The operative day ended when the last patient allowed into the system finished surgery and was sent to the postoperative care unit (PACU). The patient's total OR flow time was the time from arrival to discharge to the PACU.

Process time data, length of stay data, and cost data were modeled as univariate statistical distributions

within the model. These data (Table 1) were estimated from literature review or empirically from our hospital databases. Distributions were fit using the Input Analyzer within the Arena™ software platform (a software product developed by Systems Modeling™ [now Rockwell Software, West Allis, WI]) to standard distributions such as normal, log normal, erlang, weibull, etc. The fitting process estimates distribution parameters and provides both visual and statistical goodness-of-fit results.

The model was analyzed from a health care delivery system perspective (i.e., using hospital and professional staff costs) and focused on the outcomes of patient flow time, throughput, waiting time, and costs.

The base-case patient was a 45-year-old woman with acute cholecystitis. Costs for the base-case staffing strategy included the professional fees of 2 RNs, 1 MDA, and 1 surgeon. Staffing and hospital costs were estimated from national data (Table 2). Strategies were compared on the following outcome measures: patient throughput (patients processed per day), flow time (time needed to transit the system), and waiting time. Sensitivity analyses were performed varying staff composition, operative mortality, conversion to open cholecystectomy, and the time needed to transfer care from 1 MDA to the next (Table 3). The measure of potential benefit was the incremental cost-effectiveness ratio, which is the change in cost of providing care divided by the change in health outcome of concern, for example, patients treated per day.

The perspective chosen for the analysis was the health care system's perspective as we are examining the effect of changing how care is delivered within a hospital with different staffing rather than the type of care delivered. Posthospital outcomes and costs were assumed to be the same for each strategy because the surgery itself was the same.

Model Assumptions

In developing the model, we made several simplifying assumptions. First, because only the process of delivering care within the OR was being changed, the capacity to handle patient output (discharge home or remain in hospital) was assumed to be the same as in the current environment and also to remain constant through the analyses. Second, only cholecystectomy was examined, meaning the OR system was modeled as if it were dedicated only to this procedure. Third, only physician anesthesiologists were modeled as MDAs, filling the anesthesia role, an assumption necessary so that the anesthesia clinicians could legally hand off care of the patient to one another. Fourth, specific pro-

Table 2 Cost Data

	Annual Salary				SD	Distribution Function Form	Reference
	\bar{x}	Median	25th %	75th %			
Salary costs (\$1000) ^a							
General surgery MD	270	246	190	326	113	Triangular	
Anesthesiology MD	290	280	231	336	95	Triangular	20, 21
Anesthesiology CRNA	98	96	89	105	15	Triangular	
Operating room nurse	46	45	42	48			
	Weighted Mean	Minimum	Maximum			Distribution Function Form	Reference
Hospital costs							
Open cholecystectomy	9843	4772	11,373			Triangular	16
Laparoscopic cholecystectomy	6503	3821	7858			Triangular	16
Intensive care unit costs per day	2616	1746	3487			Triangular	16

a. From the Bureau of Labor Statistics (2002; <http://www.bls.gov>), Medical Group Management Association (2002; <http://www.mgma.org/>), Association of American Medical Colleges (2002; <http://www.aamc.org/>), and www.kellyservices.com.

cess times, such as the time spent operating and the time needed to induce and wake patients, were assumed to be independent of the staffing or organizational strategy followed.

To focus on the effect of the processes surrounding the surgery itself, we assumed that there was only 1 surgeon present at any given time, although this might change from day to day or through the day, and only 1 OR available in each model, that is, each had a capacity of 1. There were no other ORs running in parallel where nursing or anesthesia staff might be pulled to or from. This assumption was made for several reasons. First, it isolates the effect of the strategy we are looking at, and for a given type of operation, the staffing mix within a given OR tends to remain constant even though staff may turn over between shifts. Second, we are analyzing an elective procedure, not an emergency one. Emergencies are among the most likely reasons to abruptly change OR staff mix.

Finally, and most important, we assumed that the system operated on a first-come, first-served basis with the patient interarrival time approximating how patients are actually scheduled on a given day. The interarrival time modeled as a stochastic arrival process based on data from our hospital's scheduling system and expert opinion. We did not assume any other scheduling systems⁹⁻¹⁴ other than the one described in the strategy description section. In the model, more patients may be scheduled per day by shortening the interarrival time between patients. In the real world, only the patients scheduled are operated on, and they receive their surgery no matter how late it is in the day.

Table 3 Mortality and Morbidity Probability Estimates

	Open	Lap	Reference
Operative mortality	0.02	0.002	22-25
Major nonfatal operative complication	0.01	0.03	22, 25, 26
Conversion to open cholecystectomy	—	0.05 [.04 to .08]	22, 25-27

In a first-come, first-served model, we are able to stress the system to its potential limit, thereby determining how many people might be served without risking a patients' health or denial of service.

Data

Medicare data, data derived from a literature review, and data from our hospital's surgical scheduling system were used to determine the best estimates for patient arrival rates, process times, outcomes, costs, and so on. These are reported in Tables 1 through 3.

Process Data

Surgical process time data, for example, surgery duration or the time from registration to the start of surgery, were obtained primarily from the Massachusetts General Hospital OR administration's Dynamic Scheduling SystemTM (Table 1). This system records the

scheduled start time for each procedure, the actual start time, the completion time, and the type and frequency of delays. Additional data were collected manually where specific timing data were not recorded in the Dynamic Scheduling System™. Length of stay was derived from hospital databases for all laparoscopic and open cholecystectomies performed in our institution from 1998 through 2000. The length of stay for patients who suffered a complication resulting in open cholecystectomy was 2.89 ($SD = 3.12$). The mean length of stay for patients who were treated as outpatients was 0.58 days ($SD = 0.5$).

The anesthesia hand-off time is the period of time in which both clinicians are simultaneously caring for the patient and engaging in the transfer of information relevant to the smooth assumption of care by the clinician who is receiving the patient. The duration of hand-off delays was derived from the opinion of anesthesiologists. There is no handoff in the standard care model as the MDA and nurse remain with the patient through all 3 steps of anesthesia coverage.

The model's process performance was validated in development by comparing predicted operational outcomes (total flow time and total wait time) using the current strategy to historic total flow time and total wait time derived from the hospital's surgical scheduling system database. These data were not used in the construction of the model and were reserved for this analysis. The performance of the model was not statistically different from the reserved historic data set. The model's face validity was confirmed by the surgeons and anesthesiologists associated with the project.

Probability Data

The base-case operative mortality probability was derived from a systematic review of the literature, as well as an examination of our hospital records via Transition Systems Inc. (a subsidiary of Eclypsis, Inc.). These risks and the risk of the laparoscopic procedure evolving into an open cholecystectomy are presented in Table 3. These data are derived from a review of the literature and a review of hospital records (526 cases) from 2000 through 2002.

Cost Data

The health care system costs used in the analysis are hospital costs and clinical labor costs. Hospital costs were broken down into cost of hospitalization and intensive care unit (ICU) costs. Patients who died a surgical death were assumed to incur the equivalent cost of 5 days in the ICU.¹⁵ Clinical labor costs were identified as surgeon time, anesthesiologist time, and nursing

time. Clinical salary costs were derived from the Bureau of Labor Statistics, Medical Group Management Association, American Association of Medical Colleges, and the American Medical Association (Table 2). All costs were calculated in year 2000 dollars.

Hospital reimbursements were used as proxies for hospital cost, specifically, the Medicare inpatient hospital operating costs (Medicare Provider Analysis and Review [MEDPAR]) for the diagnostic-related groups describing laparoscopic cholecystectomy with and without complications and open cholecystectomy with and without complications. These data are provided by the Centers for Medicare and Medicaid Services Bureau of Data Management and Strategy from the 100% MEDPAR inpatient hospital fiscal year 1999 and were updated in June 2000 for total Medicare reimbursements and number of discharges.¹⁶ The average hospital operating costs for both laparoscopic and open cholecystectomies were derived by taking total reimbursements for each procedure with and without complications divided by the number of discharges in each category. The minimum hospital operating costs were estimated by taking the weighted average reimbursement for procedures without complications. The maximum hospital operating costs were estimated using the weighted average reimbursement for those with complications. Postoperative hospitalization and intensive care costs were derived as above (Table 2). Discounting was not used as the analysis was performed from the health care system perspective and the time horizon was in hours to days. The costs for each specific replication (individual model run) were derived by randomly sampling the cost distributions for staff and material as each patient passed through the system.

Outcomes

The model was analyzed primarily from the health care system perspective. The outcome measures examined in the model are throughput (the number of patients treated per day), flow time (transit time from admission through discharge), waiting time (time from patient arrival to start of surgery), and staff utilization (busy time/total time available), which is also a marker for safety and serious medical error (Table 3).

Sensitivity Analyses

The model parameters were varied systematically over wide ranges to examine the effect the proposed process might have on the system's performance. The central questions addressed through sensitivity analysis were as follows: 1) how safe must the proposed system be for it to remain relatively cost-effective com-

pared to current practice? 2) how short must the handoff of patient care between anesthesiologists be for the proposed system to be relatively cost-effective? and 3) is the new system relatively cost-effective for low-volume hospitals? For the 1st question, we varied the operative mortality rate of the proposed system. For the 2nd question, we varied the time needed to transfer anesthesia care from the 1st MDA to the next. For the 3rd question, we compared the systems head to head, with regard to patient throughput per day, flow time, and waiting time while varying the patient arrival rate.

Statistics

The model was evaluated as a terminating system using a 10-h replication period. The output from each simulation replication was treated as an experimental sample. The independence of replications was achieved by using different random numbers for each replication. The number of replications chosen for the initial analysis to test for significant difference between strategies (950 replications) was the minimum needed for all the 95% confidence intervals to be within 5% of the mean for all performance measures: flow time, wait time, throughput, and staff utilization. If statistical difference is demonstrated, the model is re-run with sufficient replications to ensure that all performance measures are statistically different. This method of analysis then allows us to compare the magnitude of their difference between strategies. It was assumed that all the outcome variables were approximately normally distributed. Normal-quantile plots were used to determine the normality of the experimental output of the 2 models before comparing the results with standard statistical techniques such as Student's *t* test.

RESULTS

Performance Validity

The validity of the model was further tested after the experimental trial was completed by comparing its predicted performance against the reality of the new system. The model performance was tested against 2 time intervals. First, an intermediate time interval was measured in the prospective trial but not specifically tested in the primary analysis: start of anesthesia care to time of extubation. Second, one that was tested in the original analysis was wait time, which is defined as the start of anesthesia care to the start of surgery. An additional layer of rigor was added by testing the model's performance against all surgery types performed in the experimental room. If the model was true to the

Table 4 Base-Case Differences in Operational Outcomes

	Current Average	New Average
Patients treated per day (throughput)	4.29	4.41
Flowtime/patient (registration to exit home)	333.90	339.35
Waiting time (registration to start of surgery)	56.07	58.42
Last completed surgery	590.86	606.35
Staff utilization (busy time/scheduled time)		
Operating room/surgeon	0.66	0.68
Anesthesiologist	0.80	0.49
Nurse	0.40	0.49

Note: For analysis comparing magnitude of difference of outcome measures (all $P < 0.05$), the number replications = 2500.

perioperative changes, then despite changing the surgery duration to the distribution experienced in the ORF ($\bar{x} = 63.6$ min, $SD = 44.8$ min), the model should predict the length of these time intervals in the experiment. The results were median wait times of 69.8 min (model v. 66.3 min prospective trial, $P = ns$) and 150.2 min (model v. 146.1 min prospective, $P = ns$) for the new intermediate test interval.

Base-Case Cost-Effectiveness

The base-case cost-effectiveness analysis was performed from the health care system perspective. The initial analysis using 950 replications demonstrated that the base-case strategy and the proposed strategy were statistically different in the designated outcome measures. The model was then run for 2500 replications for each strategy to compare the magnitude of the difference between strategies. Compared to the current system, the proposed system is both more effective (Table 4) and less costly. The new process results in an average of 4.41 patients cared for per day (median = 5) in a 10-h day versus 4.29/d (median = 4; Figure 3). The cost per patient cared for per day was on average \$5327 for the proposed system as compared to \$5289 for the current system. If the current nonmodular system had the same level of staffing as the proposed system, that is, with 2 MDAs, 2 RNs, and 1 surgeon (SMD) but was organizationally unchanged, it would also treat on average 4.3 patients/d (median = 4), although MDA utilization would halve. This intermediate strategy had the

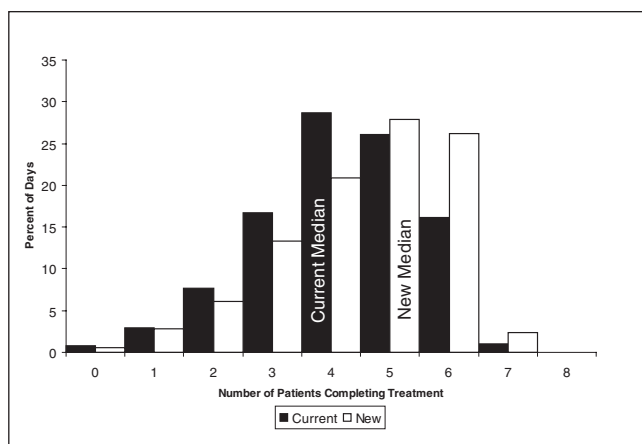


Figure 3 Distribution of patients treatable per day.

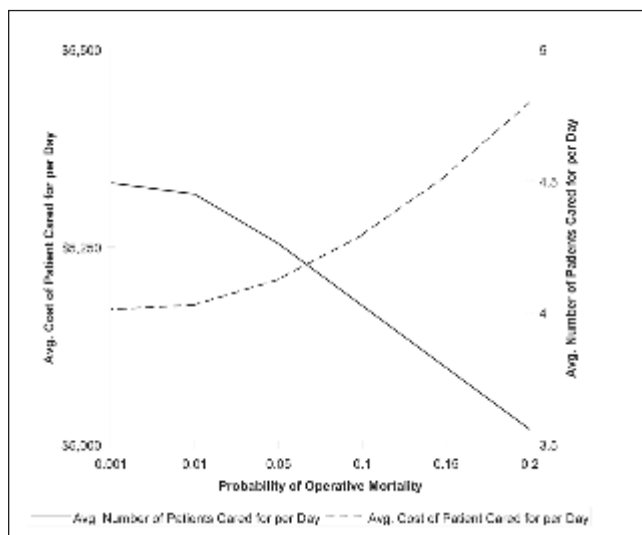


Figure 4 Sensitivity analysis of probability of operative mortality (range = .001-.2).

Note: Patient interarrival time held constant at 110 min. The current operative mortality for laparoscopic cholecystectomy generally is substantially less than 1% (25).

same staffing costs as the new system but was less effective and therefore was a dominated strategy. For the new strategy, the incremental cost-effectiveness ratio was \$318 per additional patient cared for per day. If one extends the analysis to include the cost of the patients' lost labor during hospitalization and convalescence, the proposed system becomes even more cost-effective relative to the current system.

Sensitivity Analysis Results

The results of the sensitivity analyses are shown in Figures 4 through 6. Figure 4 shows the sensitivity

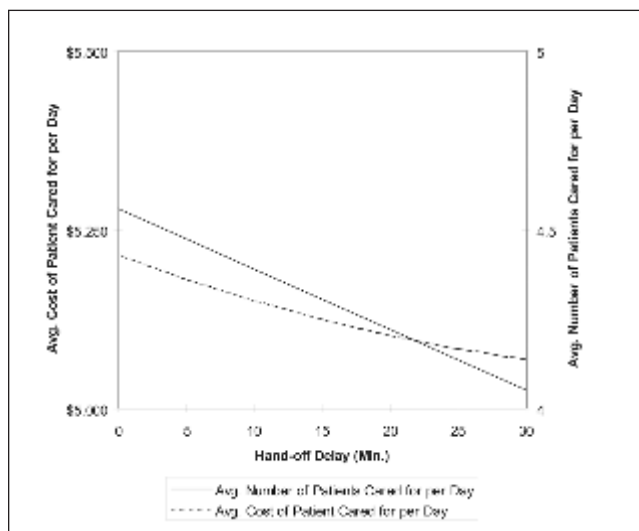


Figure 5 Sensitivity analysis of hand-off delay between MDA 1 and MDA 2 from 0 to 30 min.

Note: Patient interarrival time held constant at 110 min. MDA = anesthesiologist.

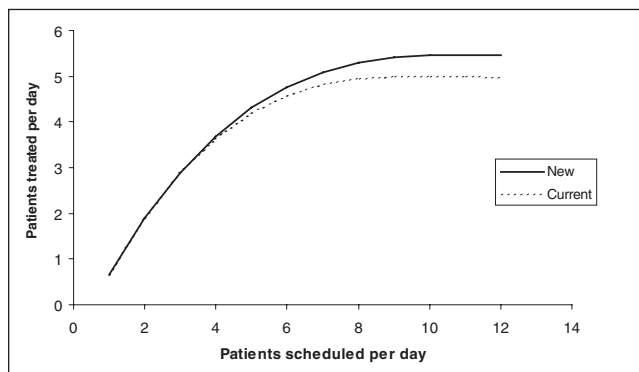


Figure 6 Number of patients treated per day (patient throughput) versus number of patients scheduled per day (new v. current).

analysis examining the effect of increasing the surgical mortality associated with the new process. Surgical mortality must exceed 4% before the throughput of the new organizational/staffing strategy is no longer greater than current practice. Figure 5 shows the results of the sensitivity analysis on the time needed to transfer the care of the patient between anesthesiologists. The hand-off time must exceed 15 min before patient throughput is less than current practice, which has no handoff, and remains cost saving.

For the analyses examining different daily patient volumes, the interarrival time for patients was modeled as an exponential distribution with a mean value selected based on prescribed number of patients to be scheduled per day. Using an exponential distribution to specify the interarrival time for this analysis simpli-

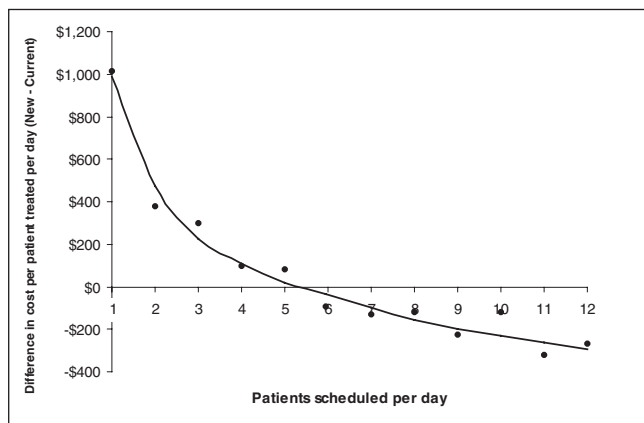


Figure 7 Difference in cost per patient treated per day between strategies (new v. current) as the number of patients scheduled is increased from 1 to 12 patients per day.

fies the sensitivity analysis by allowing us to systematically vary only 1 variable. For example, if one wished to schedule 10 patients per day in a 10-h day, the mean value for the exponential distribution would be 60 min. In the sensitivity analyses examining the effect of patient volume, we examined the relative cost per patient treated between the new and old system and at what point the system becomes saturated. For high patient volumes (>6 patients per day), the proposed single OR system has an average throughput of approximately 5.58 patients per day as compared to 5.04 patients per day for the current system (Figure 6). At lower scheduled volumes, the marginal additional cost per patient of the new system peaks at approximately \$1000 per patient (fitted value) and steadily declines to become cost saving at scheduled volumes of 5 or more patients per day (Figure 7).

DISCUSSION

DES provides an excellent test bed with which to evaluate the cost-effectiveness analysis of alternative systems of care, particularly when resource constraints and the interdependence of events are important. The proposed strategy using 2 MDAs and 2 RNs with a handoff of patient care between 2 MDAs is more effective and less expensive than the current system, over a wide range of hand-off times and mortality rates. Although there are higher fixed staff costs in the new strategy with 2 MDAs, 2 RNs, and 1 SMD versus the current strategy with 1 MDA, 2 RNs, and 1 SMD, these costs are spread over more patients, thus reducing the total cost per patient treated. The new system's increased speed of processing patients appears to make

up for its higher cost per minute. For low patient volumes, as might be found in a smaller community hospital, the proposed system is only modestly more expensive per patient than the current system is. For higher volumes of patients (≥ 5 patients per day), the new system's capacity to process patients less expensively is significantly greater than the current system. The sensitivity analysis on operative mortality, a marker for safety and serious medical error, indicates that the proposed procedural change would have to increase the operative mortality risk by more than 20 times the expected current rate before fewer patients are treated successfully than with standard practice. It may also be hypothesized that a system with 2 MDAs involved may actually increase the reliability and safety of patient care over that of a system with 1 MDA.

The perspective chosen for this analysis was that of the health care system, the frame of reference of the decision makers who might implement these changes. Evaluating the same problem from the societal perspective is considerably more difficult. To do so would require modeling the effects of these local perioperative changes on society as a whole, a nonterminating dynamic system.⁵⁻⁸ In a societal health care system model, persons in the population pool become ill, use health care resources either appropriately or not, and either die—thus exiting the system—or return to the general population pool where their illness may recur. Therefore, to measure the societal cost-effectiveness of changing the perioperative process means determining the net change in resource use and survival spread out over the whole presenting population and would require modeling the prevalence of cholecystitis in the general population, the presentation rate of patients with symptoms consistent with cholecystitis, the sensitivity and specificity of the screening procedures for cholecystitis, the presentation rate of clinical conditions that might arise in society resulting in patients competing for the use of the same OR (almost any general surgery), and the posttreatment recurrence rate of all these diseases. For the purpose of the present analysis, to help decision makers understand process and technology changes in the OR, a societal perspective analysis was not necessary.

From the health care system perspective, who is allowed to bill for the care a patient receives is very important. If this procedural change were to be implemented, current reimbursement procedures would need to be reexamined. Currently, insurance coverage typically pays for specific services rendered. If a service is spread over 2 or more providers, there is often a problem determining who gets paid and how much. Several solutions suggest themselves. One possibility

is for anesthesia or surgery departments to place anesthesia providers on salary and contract with payers for treating blocks of patients, thus allowing them to determine their own internal allocation of resources. This is similar in concept to federal block grants to states. Another alternative might be to make the billing procedures themselves more modular to fit the nature of the service better.

In general, improvements to a system may have 1 of 3 effects: to increase desired throughput, reduce production costs, or both. The proposed system increases the capacity to treat patients and controls the variability in patient interarrival time and use of the surgeon's time. This improved effectiveness is achieved in large part through buffering.⁷ A buffer may be thought of as a small dynamic queue between 2 processes that removes the handoff between them. In the new strategy, the inducing MDA acts as a single patient buffer between arriving patients and the operating surgeon. The buffer works by almost always having a patient ready for the surgeon as soon as the surgeon is free and if the surgeon is busy, allowing the next patient to enter the system.

The new system appears to work best when scheduled patient volume is greater than or equal to 5 patients per day. However, scheduling high patient volumes may incur unexpected costs,¹⁷ particularly by running the risk of keeping more and more patients waiting. Too long a wait and patient satisfaction may suffer, and patients may leave to be treated elsewhere. In our analysis, the waiting time rises much more rapidly in the current system than in the proposed one. The new system achieves similar or better volumes with less waiting, shorter flow times, and increased surgeon utilization. In addition, reduced waiting and faster transit times through the system may lead to greater patient satisfaction and improved revenue. It must be cautioned, though, that increased productivity related to increased utilization may also risk increasing staff burnout,¹⁸ especially if it does not at the same time improve job satisfaction. Burnout may potentially add downstream costs in the form of the need to hire and train new staff.

Although it may appear that the proposed system diverges radically from the standard protocol of 1 MDA following 1 patient through anesthesia induction to recovery, in fact, ad hoc versions of the hand-off strategy occur informally with some frequency. Anesthesiologists are often asked to split their time between more than 1 operating room, relying on residents, nurse practitioners, or certified nurse anesthetists to monitor the patient when they are otherwise occupied. An additional benefit to formalizing the new system is that it

should allow anesthesiologists to be compensated for the additional work that they often do to increase OR productivity.

Like all models, this model is a simplification of reality. One of our major assumptions was that we were comparing only one operating room to another. In an environment with a capacity of 1, any delays in the system may be magnified. In reality, most institutions have more than 1 OR running in parallel. The occasional idle room can sometimes act as reserve capacity. In very efficient surgery departments, some of the variance in patient interarrival time and surgeon utilization may be buffered by having multiple simultaneously active operating rooms, anesthesiologists covering more than 1 room, and staggered start times. In addition, highly efficient and knowledgeable charge nurses also take into account information such as the complexity of the proposed surgery and the skill of the surgeon when allocating time slots. But even in such an environment, as in our hospital, patients may wait more than 2 h from registration to surgery, and the number of operating rooms available is limited. The proposed system should improve the capacity of each individual OR and reduce patient waiting time and flow time.

Limitations

Finally, several study limitations must be noted. One of the most important is the limited availability of timing data from national sources. Relatively few studies have focused on the process of care as their primary concern except as a source of error,^{1,3,19} and process data are not readily available as they are typically proprietary. Another limitation is that the study focused on a single procedure rather than a large variety of procedures, although laparoscopic cholecystectomy was felt to be both common and representative. Another limitation was the assumption of a fixed 10-h day, which may or may not be reflective of practice at various institutions. Finally, assuming a stochastic process to determine interarrival times for patients does not take into account the full effect of human judgment in scheduling. We feel, though, the scheduling decision rules incorporated in the model fairly approximate reality. The distributions used are based on the scheduling data at a large high-volume sophisticated institution. Finally, although a given sophisticated admissions staff might, on a given day, be able to better fill the OR schedule, there is no avoiding case-to-case randomness or the variability in staff scheduling skill.

CONCLUSION

The proposed system should expand the capacity of each individual OR and consequently the capacity of surgery departments in general. Because the new strategy is a departure from standard practice, if implemented, it will likely require a reexamination of the reimbursement of both physician and hospital services. It is anticipated that the procedures modeled will be put to trial in the near future in a live experiment within our institution as part of a larger effort to redesign the surgical care process, after which we hope to report both the actual costs and effectiveness (throughput, safety, etc.) of the working system and how well the modeling effort anticipated them.

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