



Since January 2020 Elsevier has created a COVID-19 resource centre with free information in English and Mandarin on the novel coronavirus COVID-19. The COVID-19 resource centre is hosted on Elsevier Connect, the company's public news and information website.

Elsevier hereby grants permission to make all its COVID-19-related research that is available on the COVID-19 resource centre - including this research content - immediately available in PubMed Central and other publicly funded repositories, such as the WHO COVID database with rights for unrestricted research re-use and analyses in any form or by any means with acknowledgement of the original source. These permissions are granted for free by Elsevier for as long as the COVID-19 resource centre remains active.



ELSEVIER

Contents lists available at ScienceDirect

Journal of Clinical Anesthesia

journal homepage: www.elsevier.com/locate/jclinane

Original Contribution

Caseload is increased by resequencing cases before and on the day of surgery at ambulatory surgery centers where initial patient recovery is in operating rooms and cleanup times are longer than typical

Zhengli Wang (PhD Candidate)^a, Franklin Dexter (MD PhD FASA)^{b,*}, Stefanos A. Zenios (PhD)^a^a Stanford Graduate School of Business, United States of America^b University of Iowa, United States of America

A B S T R A C T

Study objective: The coronavirus disease 2019 (COVID-19) pandemic impacts operating room (OR) management in regions with high prevalence (e.g., > 1.0% of asymptomatic patients testing positive). Cases with aerosol producing procedures are isolated to a few ORs, initial phase I recovery of those patients is in the ORs, and multimodal environmental decontamination applied. We quantified the potential increase in productivity from also resequencing these cases among those 2 or 3 ORs.

Design: Computer simulation provided sample sizes requiring > 100 years experimentally. Resequencing was limited to changes in the start times of surgeons' lists of cases.

Setting: Ambulatory surgery center or hospital outpatient department.

Main results: With case resequencing applied before and on the day of surgery, there were 5.6% and 5.5% more cases per OR per day for the 2 ORs and 3 ORs, respectively, both standard errors (SE) < 0.1%. Resequencing cases among ORs to start cases earlier permitted increases in the hours into which cases could be scheduled from 10.5 to 11.0 h, while assuring > 90% probability of each OR finishing within the prespecified 12-h shift. Thus, the additional cases were all scheduled before the day of surgery. The greater allocated time also resulted in less overutilized time, a mean of 4.2 min per OR per day for 2 ORs (SE 0.5) and 6.3 min per OR per day for 3 ORs (SE 0.4). The benefit could be achieved while limiting application of resequencing to days when the OR with the fewest estimated hours of cases was ≤ 8 h.

Conclusions: Some ambulatory surgery ORs have unusually long OR times and/or room cleanup times (e.g., infection control efforts because of the pandemic). Resequencing cases before and on the day of surgery should be considered, because moving 1 or 2 cases occasionally has little to no cost with substantive benefit.

1. Introduction

The coronavirus disease 2019 (COVID-19) pandemic has substantial impact on operating room (OR) management for surgical procedures with aerosol production (e.g., navigational bronchoscopy) [1,2]. Previous OR management scientific studies provide guidance for mitigation of the effect on ambulatory surgery of asymptomatic patients testing false negative (i.e., with unrecognized COVID-19) [3–5]. For anesthesiologists, facilities, etc., in regions with low prevalence of COVID-19, likely there would rarely be adverse consequence to following normal perioperative infection control protocols [3,6]. However, in regions with higher prevalence (e.g., > 1.0% of asymptomatic patients testing positive), managerial changes are warranted, especially for surgical suites with open, multiple bay phase I post-anesthesia care units [3]. First, isolate cases with aerosol producing procedures to a few ORs, thereby reducing their impact on other cases, patients, surgeons,

etc. [3]. Second, as feasible, have staff including anesthesiologists work longer work hours (e.g., 12-h shifts) to reduce the numbers exposed to an asymptomatic patient testing false negative for COVID-19, to reduce the queues of patients needing essential surgery, and to reduce use of personal protective equipment [2,3,7]. Third, have patients' initial phase I recovery be in the OR, with "initial" meaning the period of coughing and disorientation [3]. Patient coughing and extubation results in extensive environmental contamination [2,8]. Previous managerial epidemiology, clinical trials, and observational studies can be applied to reduce that period (e.g., at most Japanese hospitals all recovery is in the OR with the anesthesiologist, and for much less time than typical for US phase I recovery) [9,10,11]. Fourth, use multimodal environmental decontamination after each such case with aerosol production [2,3,8]. Previous studies provided guidance on how to plan housekeeping teams to reduce the long turnover times [12,13,14,15].

Potentially, productivity could be increased further by resequencing

* Corresponding author at: Division of Management Consulting, Department of Anesthesia, University of Iowa, 200 Hawkins Drive, 6-JCP, Iowa City, IA 52242, United States of America.

E-mail address: Franklin-Dexter@UIowa.edu (F. Dexter).

URL: <https://FranklinDexter.net> (F. Dexter).

<https://doi.org/10.1016/j.jclinane.2020.110024>

Received 11 July 2020; Received in revised form 3 August 2020; Accepted 7 August 2020

Available online 11 August 2020

0952-8180/ © 2020 Elsevier Inc. All rights reserved.

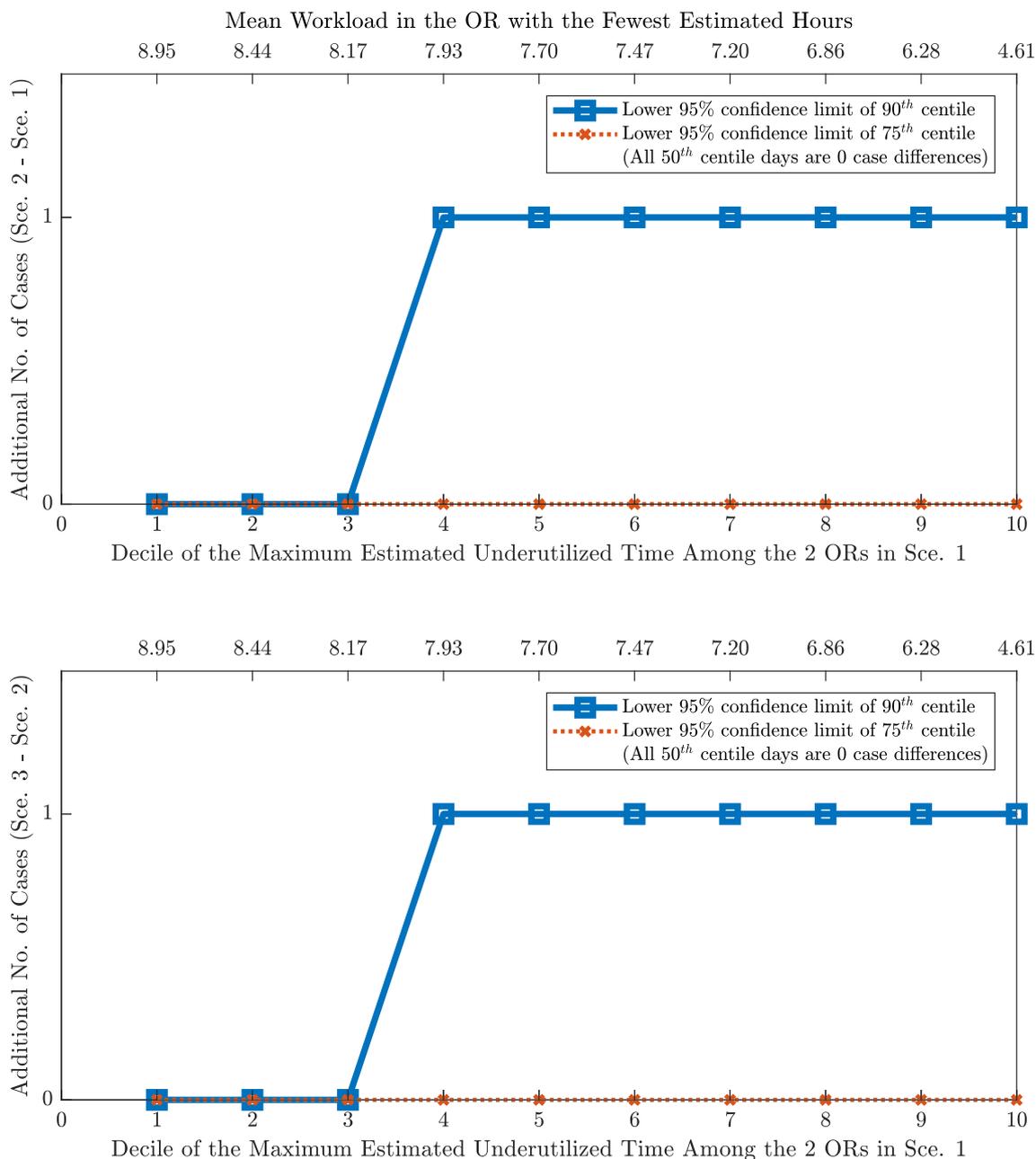


Fig. 1. Comparisons of the three scenarios for the setting of 2 ORs with patients having initial recovery in their OR and longer than typical turnover times. How we generated the figures and 95% one-sided confidence limits are described in Section 2.5. The Scenario 1 is baseline. Scenario 2 includes resequencing the cases before they have started (e.g., during huddle). Scenario 3 uses Scenario 2 and in addition resequencing of the cases whenever a case finishes, a patient finishes initial recovery, and/or a turnover time ends. An extra case was scheduled before the day of surgery, and thus performed, on at least 1/10th of days, and overall on 1 out of 7 days (Table 4). This figure shows that the manager can limit application of resequencing to days when the least filled OR has fewer than 8 h of cases.

cases the day before surgery and on the day of surgery. The objective would be to do more cases by better packing surgeons' lists of cases into the ORs dedicated to aerosol producing procedures. Because of the pandemic, both with temporary shutdown of elective surgery and with lower productivity of the ORs for these specific procedures, resequencing cases to optimize packing may be fruitful.

2. Methods

2.1. Overview

We performed simulations for both 2-OR and 3-OR settings. For each of the two settings, 20,000 simulated workdays were used to

obtain the precisions needed for Figs. 1 and 2, as explained below. For each simulated workday, we performed pairwise comparisons between three scenarios. Experimental models (e.g., every third day rotating among Scenarios 1, 2, 3) would have taken 3 times longer (i.e., 480 years, where $480 \cong 2 \text{ settings} \times 20,000 \text{ days} \times 3 \text{ scenarios}$). Simulations were performed using Matlab 2017b (The Mathworks Inc., Natick, MA). Computer code is available at <https://FDshort.com/Wang2020>.

Table 1 summarizes specific features of the model and refers to the corresponding section of the Methods. We urge readers interested in the OR management and less so the mathematical modeling to rely on the Table 1. Subsequently read the Results and Discussion.

We considered the OR time for each surgical case to be the sum of its

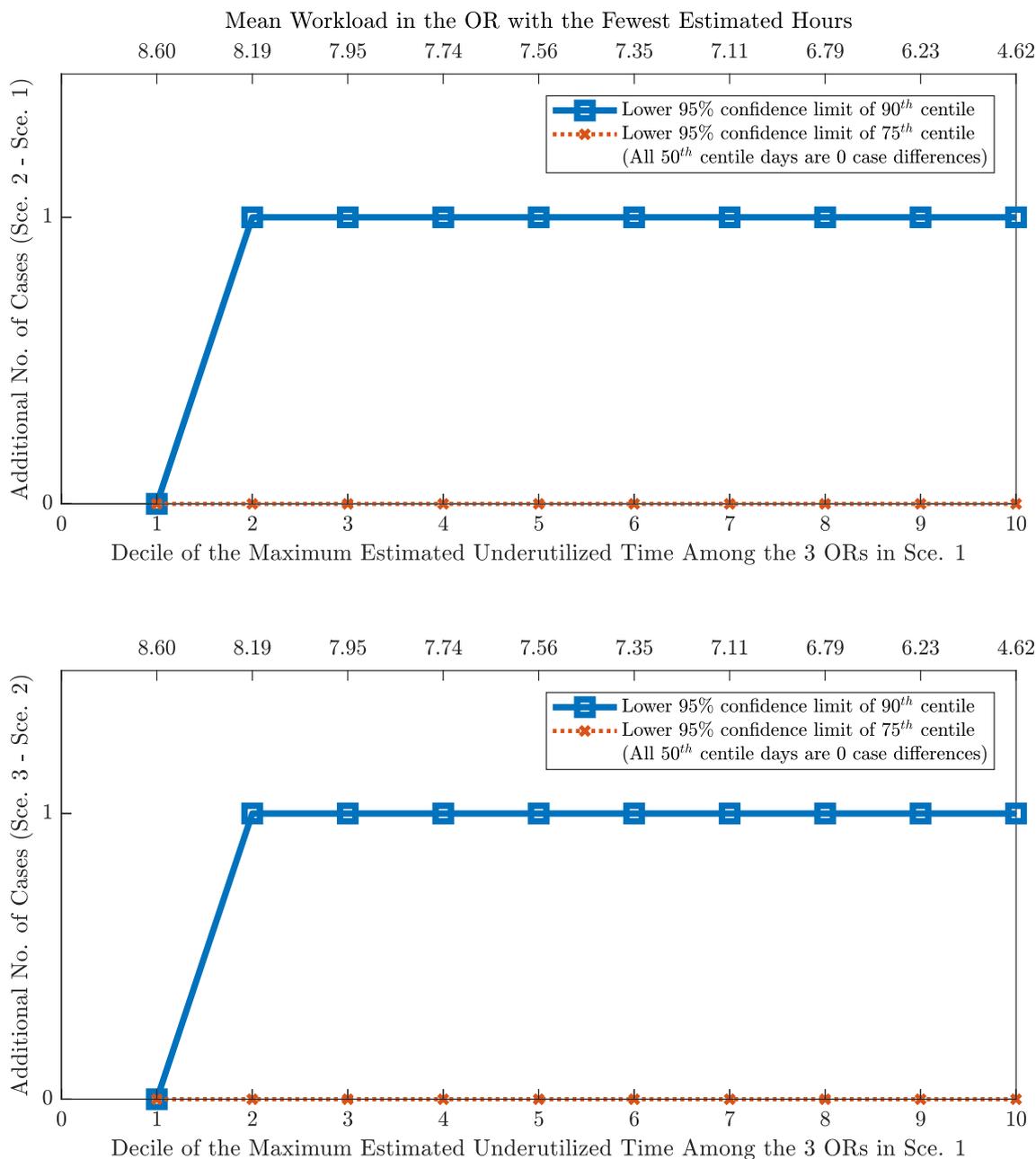


Fig. 2. Comparisons of the three scenarios for the setting of 3 ORs with patients having initial recovery in their OR and longer than typical turnover times. Please see the Fig. 1 legend for details. This figure shows that the manager can limit application of resequencing to days when the least filled OR has fewer than 8 h 15 min of cases.

regular OR time, initial phase I post-anesthesia recovery time in the OR, and subsequent turnover time. The evening of the workday before surgery, we are presented with an initial surgical schedule, which includes, for each of the 2 or 3 ORs, the number of cases by surgeon, the sequence of those cases in its OR, and the estimated regular OR times, initial recovery times, and turnover times. The details of how we obtained the initial OR schedule is presented, below, in Section 2.3.

2.1.1. Scenario 1, baseline scenario

Scenario 1 involves performing the cases in their ORs in the cases' original sequence.

2.1.2. Scenario 2, cases are resequenced before any case has started

Cases are resequenced the night before surgery (e.g., 6:30 PM) and/or early the day of surgery (e.g., 6:30 AM). Even at a hospital surgical

suite, cases scheduled between 7:00 PM and 6:59 AM the next working day influenced only 0.2% (standard error [SE] 0.1%) of OR-date combinations [16]. Therefore, Scenario 2 modeled decisions made at either times. Scenario 2 used so-called offline sequencing, meaning that the cases in the 2 or 3 ORs were considered for resequencing before the cases had started [17–19].

The offline resequencing proceeded in 3 steps from the schedule in Scenario 1.

First, if a surgeon had multiple cases, we kept those cases in their original sequence (i.e., functionally the order potentially requested by the surgeon). For purposes of all subsequent resequencing steps, we treated each surgeon's list of cases as being one long case (i.e., no split among ORs or with gap introduced between the surgeon's cases).

Second, we considered two changes. (1) Move one OR's case to the end of the same day in another OR. (2) Swap any pair of cases between

Table 1

Highlights of model features and relationship with pandemic, explanations and scientific references being in the listed sections.

Highlights of model features	Section
2-OR and 3-OR settings were simulated, suitable numbers of rooms when surgical procedures with aerosol production have been isolated to the fewest rooms possible and for the longest hours appropriate to minimize disruption to as many surgeons, patients, and ORs, as feasible.	2.1
Scenario 1 represented the baseline, with no case resequencing performed. The two other scenarios were compared with this scenario.	2.1.1
Scenario 2 considered case resequencing the night before surgery (e.g., 6:30 PM) and/or early the day of surgery (e.g., 6:30 AM). Each surgeon's cases were kept in their original, consecutive sequence without splitting between ORs. Cases were moved between ORs only if this would reduce the latest finish time among all ORs by at least 30 min.	2.1.2
Scenario 3 applied case resequencing per Scenario 2, but in addition applied the process on the day of surgery whenever a task had ended (e.g., patient begins initial phase I post-anesthesia care unit time in the OR, appropriate for the pandemic).	2.1.3
Mean case durations matched the US national average for hospital outpatient surgery departments, the latter used because the ORs under consideration are those for lower airway surgery during a pandemic. The proportional variation between estimated and actual duration used was that for cases with few historical data, appropriate because the pandemic resulted in changes in workflow.	2.2.1
Period of initial post-anesthesia care unit recovery was in the OR to avoid environmental contamination (e.g., from sputum during tracheal extubation). The time in the OR for initial recovery was brief, modeled after a Japanese hospital with no phase I unit, with anesthesiologists caring for the patient after extubation.	2.2.2
Median turnover times used were appropriate for hospital surgical suites, not ambulatory surgery center, because multimodal cleaning applied. There is dual risk of environmental contamination, from the aerosol producing procedure and tracheal extubation of the patient.	2.2.3
Cases per surgeon were chosen based on probability distributions from all Iowa hospitals, among days when a surgeon had at least one ambulatory surgery case. The probability of case cancellation was as observed for small hospitals, the focus being on hospital outpatient departments, because the model was for lower airway surgery during pandemic. Multiple efforts were made to schedule each add-on cases, matching scenario of long queues of patients seeking care, postponed because of acute phase of pandemic. However, no add-on cases were scheduled on the day of surgery, reflecting that modeling was for outpatient surgery only.	2.3

ORs, regardless of the sequence of those cases in their ORs. If any of the two changes resulted in a decrease in the latest finish time of one or more ORs, we performed the change and tentatively modified the OR schedule.

This second step was then repeated multiple times until no additional change would reduce the estimated latest finish time for any of the 2 or 3 ORs.

Third, we compared the OR schedule from the third step to the initial OR schedule from Scenario 1. If the tentative, new OR schedule from the third step would decrease the overall latest estimated finish time among the ORs by at least 30 min, the new OR schedule was adopted. We used 30 min based on prior survey of OR physician directors [20,21].

2.1.3. Scenario 3, cases were resequenced before and on the day of surgery

Scenario 3 started with the OR schedule from Scenario 2 and added online resequencing on the day of surgery. "Online" means that changes were made whenever a task ended [17,22]. The online resequencing worked as follows. Whenever, in any of the 2 or 3 ORs, a regular OR case ended, initial phase I post-anesthesia care unit time in the OR ceased, or turnover was completed, resequencing was contemplated. The resequencing heuristic used was the same three steps as for Scenario 2 but limited to cases not yet started. As for Scenario 2, we did not inconvenience surgeons by creating any gaps between their cases.

2.1.4. Generation of the Tables 2, 3, 4, and 5

Scenarios 1, 2, and 3 were compared pairwise by day. For each day, all the cases performed in Scenario 1 were present in Scenario 2, with Scenario 2 occasionally an extra case(s). Similarly, all the cases performed in Scenario 2 were present in Scenario 3, with Scenario 3 occasionally having an extra case(s). Therefore, Tables 3, 4, and 5 and Figs. 1 and 2 show pairwise comparisons among scenarios, feasible because we use simulation.

For each of the scenarios, we first had to calculate the allocated OR time (i.e., the hours into which cases would be scheduled). We did this by simulating 1000 days for each of multiple candidate values for the allocated OR times, 9.5 to 11.5 h in 15-min increments. Exhaustive search was used, trying all options to select the largest allocated time with at least 90% of the observed OR-days finishing within the 12-h workday (See Section 1).

The best allocated time for Scenarios 1,2 and 3 were 10.50, 10.75 and 11.00 h, respectively, for both 2-OR and 3-OR settings. We then simulated 20,000 days for each scenario using that associated allocated OR time to produce the tables and figures.

Table 2

Simulated endpoints from the baseline (Scenario 1), no resequencing of cases among surgeons.

Endpoint, with corresponding calculated mean	2 operating rooms ^a	3 operating rooms ^a
Workload per room (hours) ^b	8.9	9.0
Standard deviation of workload among rooms (hours)	2.1	2.3
Raw utilization (%) ^c	69.5	70.5
Adjusted utilization (%) ^c	80.5	81.4
Under-utilized time per room per day (hours) ^c	2.0	2.0
Over-utilized time per room per day (hours) ^c	0.4	0.4
Rooms with over-utilized time (%) ^b	25.2	25.8
Cases per surgeon per day	1.5	1.5
Cases per room per day	2.9	2.9
Standard deviation of cases per room per day	0.8	0.9

^a The standard errors of the mean among the 20,000 simulated days were < 0.02 h, 0.02 cases, or 0.3%, respectively.

^b As an example of the simulations, "workload per room" was the mean among 20,000 simulated days of the (mean among the 2 or 3 rooms of the total hours of cases, initial recovery times, and turnovers). The final turnover was excluded. By arithmetic, this was the same as the mean among 40,000 or 60,000 room days.

^c The allocated time of 10.5 h was, for both 2 or 3 rooms, the largest hours in 15 min increments such that at least 90.0% of 1000 simulated days' rooms had the last case's initial phase I recovery time ending within 12 h from the start of the workday. Therefore, the quantities with this listed footnote were not obtainable directly from an analytical formula for solution to the newsvendor problem.

2.2. Parameter distributions

2.2.1. Regular OR times

By the regular OR time, we mean the anesthesia induction time, surgical time, and the period from end of surgery until when the patient normally would exit the OR for phase I recovery in the post-anesthesia care unit. These estimated durations were treated as following a two-parameter log-normal distribution. Validity of this model for collection of cases at surgical suites was shown in References [23–26].

The US national average OR times for hospital outpatient surgery departments was 2.25 h [27]. The mean for ambulatory procedures in general was 1.02 h [28]. Our interest would be lower airway surgery, and thus we used the longer estimate. The standard deviation in the log scale of OR times at the University of Iowa was 0.725 [23]. Combining these two estimates, mean 135 min in the time scale and standard deviation of 0.725 in the log scale, the corresponding mean in the log

Table 3

Means of differences between Scenario 3 with modification of start times of surgeons' lists of cases both on and before the day of surgery versus the baseline, Scenario 1 listed in Table 2.

Endpoint, with corresponding calculated mean	2 operating rooms ^a	3 operating rooms ^a
Workload per room (hours)	0.5	0.5
Standard deviation of workload among rooms (hours)	-0.7	-0.7
Raw utilization (%) ^b	0.7	0.8
Adjusted utilization (%) ^b	1.4	1.8
Under-utilized time per room per day (hours) ^b	-0.1	-0.1
Over-utilized time per room per day (hours) ^b	-0.1	-0.1
Rooms with over-utilized time (%) ^b	-2.6	-4.1
Cases per surgeon per day	0.0	0.0
Cases per room per day moved ≥ 30 min later	0.4	0.6
Cases per room per day	0.1	0.1
(Preceding row)/(cases per room per day in Scenario 1), %	5.6	5.5

^a The standard errors of the mean among the 20,000 simulated days were < 0.02 h, 0.01 cases, or 0.32%, respectively.

^b The allocated time of 11.00 h was chosen to assure there was ≥ 90% probability of each room's last case ending within 12 h from the start of the workday, excluding the final case cleanup. Therefore, these quantities were not obtainable directly from an analytical formula for solution to the newsvendor problem.

scale was 0.55; for formula see page 889 of Reference [29].

The realized duration was

$$X \cdot \varepsilon,$$

where $\ln(\varepsilon)/0.27$ follows a t-distribution with 4.64 degrees of freedom, restricted between 0.322 and 3.106. For explanation, from References [30,31], realized OR times equaled:

$$X * \exp\left(t[2\alpha] \sqrt{\frac{\beta}{\alpha} \left(\frac{1 + \tau}{\tau}\right)}\right).$$

We used $(\alpha, \beta) = (2.32, 0.142)$, the median of 3 teaching hospitals' estimates [32]. We used $\tau = 5.51$, again the median from among the 3 hospitals [32]. This gives

$$X * \exp(0.27 * t[4.64]).$$

However,

$$\varepsilon = \exp(0.27 * t[4.64])$$

has an infinite expectation. Therefore, we restricted ε to be between 0.322 and 3.106, representing the 0.5th and 99.5th percentiles. We rejected any randomly selected value of ε outside that range, and when so redrew another realization to be used instead. The resulting expected value of ε was close to 1.00, as desired.

The realized regular OR times had mean 2.37 h and standard deviations of 2.23 h. The mean of 2.37 was, effectively, prespecified, as above. However, very long cases often failed to be assigned to an OR, see Section 2.3, below. Among performed cases, the realized durations

had mean 2.19 h and standard deviation 1.95 h. To evaluate the validity of the standard deviation of 1.95 h, a series of 35 hospitals' cases' standard deviations ranged from 0.48 to 2.78 h [33]. Our value was within this range, as desired.

2.2.2. Initial phase I post-anesthesia care unit recovery time in ORs

At a Japanese hospital with no phase I post-anesthesia care unit, all patients recovered in the OR where they had surgery under the continued care of their anesthesiologist. The 16 consecutive patients undergoing gynecological laparoscopic surgery had median 0.37 h from end of surgery until discharge to the ward [10]. We used that duration as the estimated time for initial phase I recovery in the OR.

To obtain realized initial recovery times, we relied on the observation that estimated recovery times followed a three-parameter log-normal distribution with shift 0.04 h and standard deviation in the log scale equaling 0.65 [34]. The mean in the log scale was estimated using maximum likelihood estimation to obtain the prespecified median time. The realized mean and standard deviation in the time scale were 0.45 h and 0.30 h, respectively.

2.2.3. Turnover times

For a 5 OR multidisciplinary hospital, median turnover times were 40 min [14]. We used that duration, 0.67 h, as the estimated, deliberately long median. As explained in Section 1, we are simulating outpatient surgery departments but applying multimodal environmental decontamination after each case with aerosol production [2,3,8].

Turnover times were modeled using two-parameter log-normal

Table 4

Means of differences between Scenario 2 with modification start times of surgeons' lists of cases before the day of surgery versus the baseline, Scenario 1 listed in Table 2.

Endpoint, with corresponding calculated mean	2 operating rooms ^a	3 operating rooms ^a
Workload per room (hours)	0.2	0.3
Standard deviation of workload among rooms (hours)	-0.4	-0.3
Raw utilization (%) ^b	0.2	0.4
Adjusted utilization (%) ^b	0.6	0.8
Under-utilized time per room per day (hours) ^b	0.0	0.0
Over-utilized time per room per day (hours) ^b	0.0	0.0
Rooms with over-utilized time (%) ^b	-1.9	-2.2
Cases per surgeon per day	0.0	0.0
Cases per room per day moved ≥ 30 min later	0.3	0.4
Cases per room per day	0.1	0.1
(Preceding row)/(cases per room per day in Scenario 1), %	2.9	2.8

^a The standard errors of the mean among the 20,000 simulated days were < 0.02 h, 0.02 cases, or 0.32%, respectively.

^b The allocated time of 10.75 h was chosen to assure there was ≥ 90% probability of each room's last case ending within 12 h from the start of the workday, excluding the final case cleanup. Therefore, these quantities were not obtainable directly from an analytical formula for solution to the newsvendor problem.

Table 5

Means of differences between Scenario 3 with modification of start times of surgeons' lists of cases both on and before the day of surgery versus Scenario 2 with modification only before the day of surgery.

Endpoint, with corresponding calculated mean	2 operating rooms ^a	3 operating rooms ^a
Workload per room (hours)	0.2	0.2
Standard deviation of workload among rooms (hours)	-0.3	-0.4
Raw utilization (%) ^b	0.4	0.5
Adjusted utilization (%) ^b	0.8	1.0
Under-utilized time per room per day (hours) ^b	0.0	-0.1
Over-utilized time per room per day (hours) ^b	0.0	-0.1
Rooms with over-utilized time (%) ^b	-0.7	-1.9
Cases per surgeon per day	0.0	0.0
Cases per room per day moved ≥ 30 min later	0.4	0.6
Cases per room per day	0.1	0.1
(Preceding row)/(cases per room per day in Scenario 2), %	2.7	2.6

^a The standard errors of the mean among the 20,000 simulated days were < 0.02 h, 0.01 cases, or 0.32%, respectively.

^b The allocated time of 11.00 h was chosen to assure there was $\geq 90\%$ probability of each room's last case ending within 12 h from the start of the workday, excluding the final case cleanup. Therefore, these quantities were not obtainable directly from an analytical formula for solution to the newsvendor problem.

distributions [35]. We used the median of the standard deviations in the log scale among 4 studied hospitals, 0.583 [35]. We then used maximum likelihood estimation to estimate the mean in the log scale, 0.41, to achieve median equal to the prespecified 40 min. Because turnover times longer than 1.50 h are uncommon, we set a maximum duration equal to that time [12]. The realized mean and standard deviation in the time scale were 0.75 h and 0.38 h, respectively.

2.2.4. Random number generation

Uniform random numbers in the interval (0,1) were generated using Matlab's mcg16807 multiplicative congruential generator, with multiplier 16,807 and modulo $2^{31}-1$ [36]. Log-normally distributed random numbers were obtained by generating normally distributed numbers via the Matlab's randn function, and then taking the exponential. The randn function derived standard normal random variates using the polar algorithm and the output of mcg16807 [37]. The t-distributed random numbers were obtained using the Matlab trnd function, using transformation of the standard normal random variate [38]. To assure reproducibility, we used the Matlab rng function to set the seed equal to 1.

2.3. Initial OR schedule (i.e., Scenario 1)

OR schedules are created over weeks to months, usually by individual surgeons. However, among 117 hospitals in Iowa, on days when a surgeon performed at least one outpatient surgery case, the most common number of cases performed was one [39]. Therefore, our approach was first to generate cases, and then to assign the cases to surgeons. To create realistic schedules for an ambulatory surgery center [3], the assignment process was supplemented with case cancellations and additions before the day of surgery [16,40].

Cases were generated sequentially, each with independent and identically distributed estimated regular OR times, initial phase I post-anesthesia recovery times, and turnover times. Each case was assigned to the OR with the least remaining time (i.e., so-called "BestFit") [23,40]. The addition of cases was terminated when a new case would not fit into any of the 2 or 3 ORs based on the allocated OR time. For selection of the allocated time, see Section 2.1.4, above.

Cases were assigned to surgeons, with all cases of a surgeon being in the same OR. For the first surgeon, a uniform distributed random number between 0 and 1 was generated that corresponded to percentiles in Table 3 of Reference [39]. That table shows all Iowa surgeons' facility-days number of cases and intraoperative relative value units of work [39]. The surgeon's hours of OR time that day was estimated by multiplying the relative value units by 22/83.5, assuming the maximum observed 83.5 units in the table represented 2 ORs each for 11 h (Table 2). Using linear interpolation, we obtained a randomly selected

number of cases and total OR hours. If there were at least that count of cases in the OR, we chose the subset of the selected numbers of cases such that the total work hours in this subset were closest to the selected hours. If there were multiple possible combinations of cases, we chose one combination randomly. The chosen cases were removed from the list of cases available to be assigned to other surgeons in the OR. Then, the same process was repeated for subsequent surgeons until all cases had been assigned to a surgeon.

Each case had independent probability of 5.0% of being cancelled. The probability of 5.0% was obtained from a national survey in Germany of small to mid-sized community hospitals [41]. For each cancelled case, an add-on case was generated. If the estimated total workload of the OR including the add-on case would be within the allocated OR time, we assigned the add-on case to be the last one in that OR. If not, new add-on cases were generated until one of them could be inserted into the OR. We stopped after 10 generation attempts. Each add-on case was assigned to a new surgeon. That was done because many surgeons with a backlog of cases were being represented for the pandemic (see Section 1) [3]. We did not include clustering of cancellations by surgeon for that same reason [42].

In each OR, cases were rearranged so that the cases belonging to the same surgeon were in consecutive order. This was achieved as follows. Surgeons were indexed arbitrarily when they were assigned cases. Starting from the surgeon with the smallest index and assigned to the OR, all his/her cases were put at the start of the schedule in that OR. Then, consideration was made for the surgeon with the second smallest index, with all his/her cases put after the cases of the first surgeon, and so forth.

Each existing case in each OR was again cancelled independently and with a probability of 0.05. No add-on cases would arrive. At this point, a preliminary schedule on the day of surgery was known. The estimated start times of each case was then computed.

2.4. Check of the validity of simulated ORs

Table 2 lists characteristics of the simulated ORs. Mean workload, adjusted utilization, etc., have face validity for the design of 12-h staff scheduling and each OR having $< 10\%$ probability of exceeding those work hours (again, see Section 1) [2,3].

The simulated standard deviations of hours of cases and turnovers among ORs were 2.07 h for 2 ORs and 2.29 h for 3 ORs, both SE = 0.01 h (Table 2). Marcon & Dexter showed a range among 34 hospital ORs of 1.80 to 3.79 h, median 2.86 h [33]. Our calculations being within that range but less than the median was as desired because we were simulating fewer ORs than would be present at most hospitals.

The simulations resulted in an average 1.54 and 1.52 cases per

surgeon per day for the 2 ORs and 3 ORs, respectively, both $SE < 0.01$ (Table 2). These statistics matched data from 117 hospitals in Iowa [39]. On days when a surgeon performed at least one outpatient surgical case, 54% of the surgeon lists had 1 case and 77% had 1 or 2 cases [39].

2.5. Generation of Figs. 1 and 2

To create the figures, we first sorted the 20,000 days of Scenario 1 in descending sequence of the OR with the least estimated workload. These 20,000 workloads were then partitioned into 10 deciles (e.g., the 2000 days in the 1st decile had the greatest estimated workloads for the ORs on each date having the fewest estimated hours). The decile number was plotted along the bottom, horizontal axes. Within each decile, the mean of the estimated workload was computed and plotted along the upper horizontal axis. For each of the 2000 workdays in the decile, the difference in the total number of cases of that day was computed between Scenario 3 vs Scenario 2 (lower pane), or between Scenario 2 vs Scenario 1 (upper pane). The 2000 differences were sorted in ascending sequence. The lower 95% conservative confidence limit was calculated for the 90th, 75th and 50th percentiles. The conservative limits were obtained using binomial distribution. For example, the lower 95% confidence limit for the 90th percentile of the 2000 sorted differences was the 1777th value. These very large sample sizes, impractical for experimentation, were necessary because the cases performed per day are discrete distributions with little heterogeneity among days (Table 2, standard deviations among ORs of 0.79 cases per day for 2 ORs and 0.89 cases per day for 3 ORs, both $SE < 0.01$).

3. Results

With case resequencing applied before and on the day of surgery, there were increases averaging 1 case per OR every 7 days (Table 3). Proportionately, that was 5.6% and 5.5% more cases per OR per day for the 2 ORs and 3 ORs, respectively, both $SE < 0.1\%$. The additional cases could be scheduled before the day of surgery because resequencing cases among ORs to start cases earlier permitted increases in the allocated time (i.e., the hours into which cases could be scheduled), from 10.5 to 11.0 h (Table 3 footnote b). The greater allocated time also resulted in less overutilized time, a mean of 4.2 min per OR per day for 2 ORs ($SE 0.5$ min) and 6.3 min per OR per day for 3 ORs ($SE 0.4$ min).

Table 4 and Fig. 1 show the incremental effects of resequencing cases only before the day of surgery. Table 5 and Fig. 2 show the incremental effects of also resequencing cases on the day of surgery. Figs. 1 and 2 show that the manager can achieve the benefits while limiting application of resequencing to when the OR with the fewest estimated hours of cases has fewer than 8 h (2 ORs) or 8 h 15 min (3 ORs).

4. Discussion

Changes in case scheduling alone that obtain even 1.0% increases in caseload have been treated as important [40], because such increases are obtained at negligible cost. We simulated no change in anesthetic drugs [10,11] or extra housekeepers [12,13,15], OR nurses, or nurse anesthetists [43]. We similarly simulated no change in each surgeon's list of cases (i.e., each surgeon was maintained within one OR and without gaps between cases). Still, the smaller increase of 5.5% was greater than the annual growth in surgical cases at 85.6% of Florida hospitals and 95.4% of Iowa hospitals [44]. Even larger increases in productivity can be accrued with using an extra OR (e.g., 4 ORs for 3 ORs of cases) [43], but with the expense of more staff (e.g., another anesthesiologist). Conveniently, our results suggest that managers need not review all ORs for opportunities to change case start times, only when there is at least one OR estimated to have 8 or fewer hours of

cases.

Strengths of our study were that we made multiple decisions that resulted in our deliberately underestimating the maximum potential benefit of case rescheduling. First, Scenario 3 considered only changes made once tasks had finished (e.g., patient exits OR), and did not rely on statistical methods for predicting the time remaining in ongoing cases [45,46]. Second, we only moved cases to start sooner if the change in overutilized time was at least 30 min. We did that because many OR managers consider smaller changes not to warrant the effort of contacting surgeons, evaluating if the move is feasible because of constraints, etc. [20,21]. A facility aiming to reduce the queue of patients from the shutdown of elective surgery because of the acute phase of the pandemic could be more aggressive. Third, we considered only having extra elective, scheduled cases, not add-on cases that may not be completed [47,48]. However, hospitals may have options to perform an extra add-on case (e.g., tracheal stent placement) during the regular workday in the outpatient ORs rather than late at night in the hospital ORs. Add-on cases would considerably increase benefit of case resequencing, because there were on average 2.0 h of under-utilized time per OR per day (Table 2). Fourth, by limiting consideration to all cases scheduled before the day of surgery, and in a few ORs designated for aerosol producing procedures, staff assignment decisions can be made to achieve reductions in turnover times [49]. Our lack of consideration of such opportunities in the model deliberately resulted in our underestimating potential benefits to case resequencing. Fifth, we assured a $> 90\%$ probability of staff working a 12-h shift to finish on-time. At hospitals, OR personnel on call routinely work more hours, but that was not what we planned.

We limited our study to ambulatory surgery, following-up on our previous study of the economics of ambulatory surgery centers and hospital outpatient departments after the acute phase of the pandemic [3]. Second, we considered cases with longer than normal OR times and turnover times [3]. Our results do not apply to typical outpatient surgery cases, pre-pandemic. Third, and most importantly, there will not be more cases performed if there are not cases waiting to be done because of unavailable OR time. Before the shutdown of elective surgery, that was not the situation at many facilities. For example, the United States' 2010 national ambulatory surgery survey included outpatient surgery performed at hospitals and unaffiliated free-standing surgery centers [28]. There was 64% ($SE 1\%$) of all operating room time completed before 12 noon, and 90% ($SE 1\%$) before 3:00 PM [28]. Our results depend on the human factor of patients and surgeons choosing to perform as many cases as possible.

Funding

None.

CRedit authorship contribution statement

Zhengli Wang:Methodology, Software, Validation, Formal analysis, Investigation, Data curation, Writing - original draft, Writing - review & editing, Visualization.**Franklin Dexter:**Conceptualization, Methodology, Validation, Formal analysis, Writing - original draft, Writing - review & editing, Visualization, Supervision.**Stefanos A. Zenios:**Methodology, Investigation, Resources, Writing - review & editing, Supervision.

Declaration of competing interest

None.

References

- [1] Kohanski MA, Lo JL, Waring MS. Review of indoor aerosol generation, transport and control in the context of COVID-19. *Int Forum Allergy Rhinol* 2020. <https://doi.org/>

- 10.1002/alr.22661. ePub.
- [2] Dexter F, Parra MC, Brown JR, Loftus RW. Perioperative COVID-19 defense: an evidence-based approach for optimization of infection control and operating room management. *Anesth Analg* 2020;131:37–42.
 - [3] Dexter F, Elhakim M, Loftus RW, Seering MS, Epstein RH. Strategies for daily operating room management of ambulatory surgery centers following resolution of the acute phase of the COVID-19 pandemic. *J Clin Anesth* 2020;109:854–64.
 - [4] Böger B, Fachi MM, Vilhena RO, de Fátima Cobre A, Tonin FS, Pontarolo R. Systematic review with meta-analysis of the accuracy of diagnostic tests for COVID-19. *Am J Infect Control* 2020. <https://doi.org/10.1016/j.ajic.2020.07.011>. ePub.
 - [5] Long DR, Sunshine JE, Van Cleve W. Considerations for assessing risk of provider exposure to SARS-CoV-2 after a negative test. *Anesthesiology* 2020;133:483–5.
 - [6] Shah A, Walkoff LA, Kuzo RS, Callstrom MR, Brown MJ, Kendrick ML, et al. The utility of chest CT and RT-PCR screening of asymptomatic patients for SARS-CoV-2 (COVID-19) prior to semi-urgent or urgent hospital procedures. *Infect Control Hosp Epidemiol* 2020. <https://doi.org/10.1017/ice.2020.331>. ePub.
 - [7] Mascha EJ, Schober P, Schefold JC, Stueber F, Luedi MM. Staffing with disease based epidemiologic indices may reduce shortage of intensive care unit staff during the COVID-19 pandemic. *Anesth Analg* 2020;131:24–30.
 - [8] Sellens P, Wellbelove Z, Wright D. Testing contamination and cleaning effectiveness in theatre during the COVID-19 pandemic using UV fluorescent powder. *Anaesthesia* 2020. <https://doi.org/10.1111/anae.15200>. ePub.
 - [9] Sento Y, Suzuki T, Suzuki Y, Scott DA, Sobue K. The past, present and future of the postanesthesia care unit (PACU) in Japan. *J Anesth* 2017;31:601–7.
 - [10] Thenuwara KN, Yoshi T, Nakata Y, Dexter F. Time to recovery after general anesthesia at hospitals with and without a phase I post-anesthesia care unit: a historical cohort study. *Can J Anesth* 2018(12):1296–302.
 - [11] Dexter F, Bayman EO, Epstein RH. Statistical modeling of average and variability of time to extubation for meta-analysis comparing desflurane to sevoflurane. *Anesth Analg* 2010;110:570–80.
 - [12] Dexter F, Epstein RH, Marcon E, Ledolter J. Estimating the incidence of prolonged turnover times and delays by time of day. *Anesthesiology* 2005;102:1242–8.
 - [13] Dexter F, Marcon E, Aker J, Epstein RH. Numbers of simultaneous turnovers calculated from anesthesia or operating room information management system data. *Anesth Analg* 2009;109:900–5.
 - [14] Wang J, Dexter F, Yang K. A behavioral study of daily mean turnover times and first case of the day start tardiness. *Anesth Analg* 2013;116:1333–41.
 - [15] Gul S. A stochastic programming approach for appointment scheduling under limited availability of surgery turnover teams. *Serv Sci* 2018;10:277–88.
 - [16] Dexter F, Shi P, Epstein RH. Descriptive study of case scheduling and cancellations within 1 week of the day of surgery. *Anesth Analg* 2012;115:1188–95.
 - [17] Dexter F, Macario A, Traub RD. Which algorithm for scheduling add-on elective cases maximizes operating room utilization? Use of bin packing algorithms and fuzzy constraints in operating room management. *Anesthesiology* 1999;91:1491–500.
 - [18] Hans E, Wullink G, van Houdenhoven M, Kazemier G. Robust surgery loading. *Eur J Oper Res* 2008;185:1038–50.
 - [19] Bandi C, Gupta D. Operating room staffing and scheduling. *Manuf Serv Oper Manag* 2020. <https://doi.org/10.1287/msom.2019.0781>. ePub.
 - [20] Dexter F, Smith TC, Tatman DJ, Macario A. Physicians' perceptions of minimum time that should be saved to move a surgical case from one operating room to another: internet-based survey of the Association of Anesthesia Clinical Directors' (AACD) members. *J Clin Anesth* 2003;15:206–10.
 - [21] Dexter F, Epstein RD, Traub RD, Xiao Y. Making management decisions on the day of surgery based on operating room efficiency and patient waiting times. *Anesthesiology* 2004;101:1444–53.
 - [22] Dexter F, Wachtel RE, Epstein RH. Decreasing the hours that anesthesiologist and nurse anesthetists work late by making decisions to reduce the hours of over-utilized operating room time. *Anesth Analg* 2016;122:831–42.
 - [23] Dexter F, Macario A, Traub RD, Hopwood M, Lubarsky DA. An operating room scheduling strategy to maximize the use of operating room block time - computer simulation of patient scheduling and survey of patients' preferences for surgical waiting time. *Anesth Analg* 1999;89:7–20.
 - [24] May JH, Strum DP, Vargas LG. Fitting the lognormal distribution to surgical procedure times. *Decis Sci* 2000;31:129–48.
 - [25] Dexter F, Epstein RH, Bayman EO, Ledolter J. Estimating surgical case durations and making comparisons among facilities: identifying facilities with lower anesthesia professional fees. *Anesth Analg* 2013;116:1103–15.
 - [26] Taaffe K, Pearce B, Ritchie G. Using kernel density estimation to model surgical procedure duration. *Int J Oper Res* 2020;28:401–18.
 - [27] Hair B, Hussey P, Wynn B. A comparison of ambulatory perioperative times in hospitals and freestanding centers. *Am J Surg* 2012;204:23–7.
 - [28] Dexter F, Epstein RH, Rodriguez LI. Throughout the United States, pediatric patients undergoing ambulatory surgery enter the operating room and are discharged earlier in the day than are adults. *Perioper Care Oper Room Manag* 2019;16:100076.
 - [29] Ledolter J, Dexter F, Epstein RH. Analysis of variance of communication latencies in anesthesia: comparing means of multiple lognormal distributions. *Anesth Analg* 2011;113:888–96.
 - [30] Dexter F, Ledolter J. Bayesian prediction bounds and comparisons of operating room times even for procedures with few or no historic data. *Anesthesiology* 2005;103:1259–67.
 - [31] Dexter F, Bayman EO, Pattillo JCS, Schwenk ES, Epstein RH. Influence of parameter uncertainty on the tardiness of the start of a surgical case following a preceding surgical case performed by a different surgeon. *Perioper Care Oper Room Manag* 2018;13:12–7.
 - [32] Dexter F, Ledolter J, Tiwari V, Epstein RH. Value of a scheduled duration quantified in terms of equivalent numbers of historical cases. *Anesth Analg* 2013;117:204–9.
 - [33] Marcon E, Dexter F. An observational study of surgeons' sequencing of cases and its impact on postanesthesia care unit and holding area staffing requirements at hospitals. *Anesth Analg* 2007;105:119–26.
 - [34] Dexter F, Traub RD, Penning DH. Statistical analysis by Monte-Carlo simulation of the impact of administrative and medical delays in discharge from the post-anesthesia care unit on total patient care hours. *Anesth Analg* 2001;92:1222–5.
 - [35] Dexter F, Abouleish AE, Epstein RH, Whitten CW, Lubarsky DA. Use of operating room information system data to predict the impact of reducing turnover times on staffing costs. *Anesth Analg* 2003;97:1119–26.
 - [36] Park SK, Miller KW. Random number generators: good ones are hard to find. *Commun ACM* 1998;31:1192–201.
 - [37] Thomas DB, Luk W, Leong PH, Villasenor JD. Gaussian random number generators. *ACM Computing Surveys (CSUR)* 2007;39(4):22–3.
 - [38] Gentle JE. Random number generation and Monte Carlo methods. Springer Science & Business Media; 2006. p. 185–6.
 - [39] Dexter F, Jarvie C, Epstein RH. At most hospitals in the state of Iowa, most surgeons' daily lists of elective cases include only 1 or 2 cases: individual surgeons' percentage operating room utilization is a consistently unreliable metric. *J Clin Anesth* 2017;42:88–92.
 - [40] Shi P, Dexter F, Epstein RH. Comparing policies for case scheduling within one day of surgery by Markov chain models. *Anesth Analg* 2016;122:526–38.
 - [41] Schuster M, Neumann C, Neumann K, Braun J, Geldner G, Martin J, et al. The effect of hospital size and surgical service on case cancellation in elective surgery: results from a prospective multicenter study. *Anesth Analg* 2011;113:578–85.
 - [42] Dexter F, Maxbauer T, Stout C, Archbold L, Epstein RH. Relative influence on total cancelled operating room time from patients who are inpatients or outpatients preoperatively. *Anesth Analg* 2014;118:1072–80.
 - [43] Marjamaa RA, Torkki PM, Hirvensalo EJ, Kirvelä OA. What is the best workflow for an operating room? A simulation study of five scenarios. *Health Care Manag Sci* 2009;12:142–6.
 - [44] Dexter F, Jarvie C, Epstein RH. Heterogeneity among hospitals statewide in percentage shares of the annual growth of surgical caseloads of inpatient and outpatient major therapeutic procedures. *J Clin Anesth* 2018;49:126–30.
 - [45] Dexter F, Epstein RH, Lee JD, Ledolter J. Automatic updating of times remaining in surgical cases using Bayesian analysis of historical case duration data and instant messaging updates from anesthesia providers. *Anesth Analg* 2009;108:929–40.
 - [46] Tiwari V, Dexter F, Rothman BS, Ehrenfeld JM, Epstein RH. Explanation for the near constant mean time remaining in surgical cases exceeding their estimated duration, necessary for appropriate display on electronic white boards. *Anesth Analg* 2013;117:487–93.
 - [47] Dexter F, Coffin S, Tinker JH. Decreases in anesthesia-controlled time cannot permit one additional surgical operation to be scheduled during the workday. *Anesth Analg* 1995;81:1263–8.
 - [48] Dexter F, Macario A. Decrease in case duration required to complete an additional case during regularly scheduled hours in an operating room suite - a computer simulation study. *Anesth Analg* 1999;88:72–6.
 - [49] Doll D, Kauf P, Wiefelich K, Schiffer R, Luedi MM. Implications of perioperative team setups for operating room management decisions. *Anesth Analg* 2017;124:262–9.