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Statistical Method for Predicting When Patients Should Be Ready on the Day of Surgery

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Background: **Previously, mathematical theory was developed for determining when a patient should be ready for surgery on the day of surgery. To apply this theory, a method is needed to predict the earliest start time of the case.**

Methods: **The authors calculated a time estimate such that the probability is 0.05 that the preceding case in the patient's operating room (OR) will be finished before the patient is ready for surgery. This implies there will be a 5% risk of OR personnel being idle and waiting for the patient. This 0.05 value was chosen by considering the relative cost valuation of an average patient's time to that of an average surgical team based on national salary data. Case duration data from a surgical services information system were used to test different statistical methods to estimate earliest start times.**

Results: **Simulations found that 0.05 prediction bounds, calculated assuming case durations followed log-normal distributions, achieved actual risks for the OR staff to wait for patients of 0.050 to 0.053 (SEM = 0.001). Nonparametric prediction bounds performed no better than the parametric method. Having patients ready a fixed number of hours before the scheduled starts of their operations is not reliable. If the preceding case in an OR had been underway for 0.5 to 1.5 h, the parametric 0.05 prediction bounds for the time remaining achieved actual risks for OR staff waiting of 0.055 to 0.058 (SEM = 0.001).**

Conclusion: **The earliest start time of a case can be estimated using the 0.05 prediction bound for the duration of the preceding case. The authors show 0.05 prediction bounds can be estimated accurately assuming that case durations follow log-normal distributions. (Key words: Operating room management; operating room scheduling; perioperative scheduling.)**

WHAT should be a surgical suite's policy for telling a patient at what time the patient should arrive at the surgical suite on the day of surgery? Although each surgical case typically has a scheduled start time, it is not clear if the patient should be told to arrive at the surgical suite 2 h before this scheduled start time, or if some longer or briefer length of time would be more appropriate. There are three facets to this question. First, will the patient arrive punctually? Second, once the patient has arrived at the surgical suite, how much time will be required for the patient to be prepared for surgery (*e.g.,* to change into a hospital gown and receive medications)? Third, will the preceding case or cases in the operating room (OR) in which the patient is to have surgery finish early, on time, or late? Provided the patient has already undergone preoperative evaluation,[1,2] the facet resulting in the greatest likelihood of a long patient waiting time on the day of surgery is the variability in the duration of the preceding case or cases.[3]

Ideally, a patient would arrive at the surgical suite, be prepared for surgery, and be ready for surgery just as the preceding case in his or her OR is completed.[4] The patient would then have the short waiting time he or she wants.[1,5–7] In addition, the OR staff would not incur idle time waiting for the patient. In this context, the "staff" include one or more surgeons, anesthesiologists, nurses, and OR technicians. However, if the patient is ready earlier than the time at which the preceding case in his or her OR finishes, then the patient will incur some waiting time while the preceding case is completed and the room is cleaned. This patient will likely be less satisfied.[1,5–7] In contrast, if the patient arrives after the completion of the preceding case in his or her OR, the staff working in the OR will have to wait for the patient.

Weiss showed that the determination of when to have patients arrive on the day of surgery is equivalent to specifying quantitatively the relative cost of patients' waiting time compared with the cost of the staff's idle time.[4] The logic is, in effect, that if there is a high cost for some undesired activity, then the probability of that activity occurring should be made as low as possible. For example, at some surgical suites the cost of the staff's idle time is considered to be large relative to the cost of the patients' waiting time. At such surgical suites, the probability of having the OR staff wait for the patient should be made low by having the patients arrive early. The surgical suite could implement this policy by instructing all patients to stop eating and drinking at midnight and arrive sufficiently early in the morning to be ready for surgery at the start of the regularly scheduled OR day.[5] As a result of the policy, patients who are not scheduled for the first case in each OR have a long waiting time, are thirsty, and can be dissatisfied with their care.[1,5–7] However, the policy ensures that staff working in the surgical suite virtually never wait for patients.

Weiss showed how, in theory, a surgical suite should determine when a patient should be ready for surgery on the day of surgery.[4] Based on the surgical suite's relative

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valuation[1] of patients' waiting time to staff's idle time, each patient should be ready for surgery some optimal number of hours before the scheduled end of the preceding case in the patient's OR. Weiss showed that these values need to be estimated, but did not investigate how to calculate them.[4] Our goal was to use actual data from a surgical suite to test different statistical methods that can be used to estimate the earliest start time of a case so that Weiss' theory can be implemented in surgical suites.

Methods

Review of the Previously Developed Theory for Determining When a Patient Should Be Ready on the Day of Surgery

Weiss[4] showed that there is an optimal method for balancing the cost of a patient waiting for the preceding case in his or her OR to be completed with the cost of OR staff waiting for the patient. Let us suppose that the cost of the patient waiting equals C_{pt} per hour. The cost of the OR staff waiting for the patient, once the staff have finished caring for the preceding patient in the OR, equals C_{OR} per hour. The expected total cost for patient and staff waiting equals the number of hours the patient waits multiplied by C_{pt} plus the number of hours the OR staff wait multiplied by C_{OR}. Weiss showed that to minimize this expected total cost, the time that the patient should be available for surgery is the τth percentile of the cumulative distribution function of the duration of the preceding case in the patient's OR, where $\tau = C_{pt}/(C_{OR} + C_{pt})$.[4] To minimize the expected total cost for patient and staff waiting, the risk that the OR staff should accept in having to wait for the patient equals τ.[4] For example, suppose that $\tau = 0.05$ and the preceding case in the OR is a cholecystectomy. Then, the patient would be asked to arrive sufficiently early so that he or she can be ready for surgery at the time that corresponds to the 0.05 percentile of the durations of cholecystectomies performed at the surgical suite. There would be a 0.05 chance that the OR staff would finish the cholecystectomy and have to wait for the next patient.

We give an example of how these principles[4] would be applied to determine when a patient whose case is preceded by a cholecystectomy should be ready for surgery. Figure 1 shows a histogram of the durations of the 552 cases scheduled to be a cholecystectomy in the data set (described in *Case Duration Data Used in this Study*). The data are plotted with a logarithmic axis. A normal distribution curve, with its characteristic bell shape, is superimposed. The 0.05 percentile of case duration, which equals 1.7 h, is marked with an arrow. When determining when to have the second patient in the OR be ready for surgery, the duration of the cholecystectomy could be expected to be 1.7 h. By having the second patient available for surgery 1.7 h after the start of the cholecystectomy, the risk of the OR staff having to wait for the second patient to be ready would be 0.05. Thus, when using the 0.05 percentile, the "earliest start time" of the second case would be 1.7 h after the cholecystectomy was started.

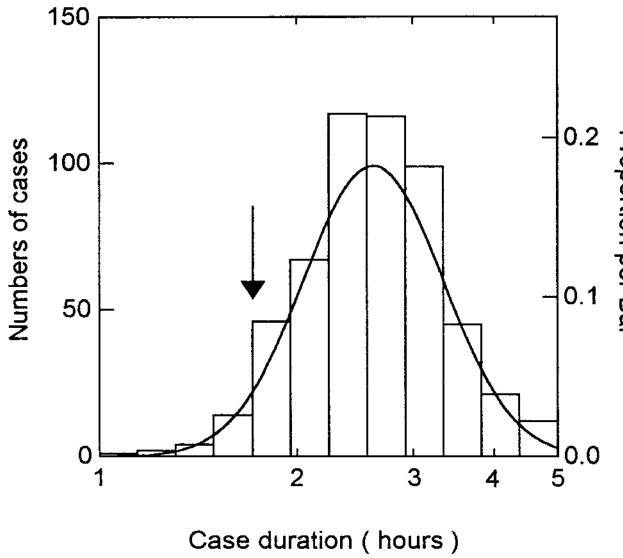

Fig. 1. Histogram of the durations of the 552 cases scheduled to be a cholecystectomy in the data set. The data are plotted with a logarithmic axis. A normal distribution curve is superimposed. The arrow marks the 0.05 percentile of case duration.

When there are hundreds of previous cases of the same scheduled procedure, an appropriate interpretation of the 0.05 percentile is that the risk is 0.05 of a patient not being ready for surgery when the OR team is available having completed the preceding case in the OR. However, in many instances there are only a few (*e.g.,* two) previous case durations of the same scheduled procedure available to predict the duration of a future case.[8,9] When there are small numbers of previous cases, "*prediction bounds*," not percentiles, are relevant. A prediction bound for a single future observation is a value that will, with a specified degree of confidence, be exceeded by the next randomly selected observation from a population. The specified degree of confidence then equals one minus the prediction bound. Thus, a 0.05 prediction bound provides a 0.05 risk of the OR staff waiting for the patient. For small numbers of cases, the value for the 0.05 prediction bound can differ substantially from the value of the 0.05 percentile.

A prediction bound incorporates two sources of variability in an estimate for the duration of a case. First, there is variability intrinsic to the scheduled procedure, as shown in figure 1. This source of variability exists whether there are two previous cases' durations or hundreds of previous cases' durations. Second, there is variability in the estimates of the parameters. Because of the small number of previous cases' durations available to estimate the parameters, the estimated values of the parameters may differ from what they would have been had there been hundreds of previous cases' durations

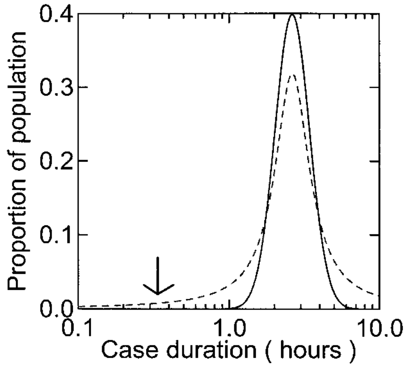

Fig. 2. Probability distributions for the duration of a future cholecystectomy based on a priori data from two (dotted curve) or 552 (solid curve) previous case durations. Both curves use values for the sample mean and standard deviation of the logarithms of case duration obtained using the 552 previous cases. The arrow marks the 0.05 prediction bound for case duration based on there being data from two previous cases.

available. For example, the two curves in figure 2 show the probability distributions for the duration of a future cholecystectomy based on *a priori* data from two or 552 previous case durations. Both curves use values for the sample mean and standard deviation of the logarithms of case duration that were obtained using the 552 previous cases. Both curves were drawn assuming that the logarithms of case durations follow a normal distribution. The solid curve for 552 previous cases is the same as the one shown in figure 1. The dotted curve, in contrast, gives the probability distribution obtained assuming that the mean and standard deviations were obtained from only two previous cases' durations. The use of only two previous cases' durations resulted in greater uncertainty in the accuracy of the duration of the future case. Consequently, the dotted curve in figure 2 is wider than the solid curve. Whereas the 0.05 prediction bound using 552 cases equals the 0.05 percentile or 1.7 h (fig. 1), the 0.05 prediction bound using two cases equals 0.3 h (fig. 2).

The focus of this paper was to test different statistical methods to calculate 0.05 prediction bounds for case duration.

Rationale for Choosing $\tau = 0.05$

We used a value of $\tau = 0.05$ in our study based, in part, on the salaries of patients and OR staff. Using recent median annual salaries in the United States, the value‡ of $C_{OR} \cong \$549,780$ for a surgical team with an anesthesiologist, a general surgeon, two OR nurses, and a full-time equivalent housekeeper (representing the work of, for example, unit assistants and central sterilization personnel in caring for the patient). As recommended by the Panel on Cost-effectiveness in Health and Medicine,[10] to value patients' time we used the average wage rate of people older than 16 years in the United States: $C_{pt} \cong \$27,196$.‡ Then, $\tau = \$27,196/(\$549,780 + \$27,196) \cong 0.05$.

Higher or lower values of τ may be appropriate because the valuation of patients' *versus* OR staff's time varies among hospitals and countries, among other situations. However, based on the salary argument, we think that setting the risk that the OR suite staff will wait for the patient at $\tau = 0.05$ is a reasonable compromise between the value of patients' and OR staff's time.

Case Duration Data Used in this Study

We tested statistical methods to calculate 0.05 prediction bounds using case duration data from the University of Iowa. The cases were performed between July 1, 1994, and July 1, 1997, at the tertiary surgical suite or ambulatory surgery center. "Case duration" was defined as the time from when the patient entered the OR in which he or she had surgery to the time he or she left the OR. Entrance and exit times from the OR were recorded by OR nurses when the patients entered and exited from the OR using clocks that were synchronized throughout all ORs in these two surgical suites. Two checks were applied to the times by the OR information system when a dedicated data entry clerk entered the data later that day. First, the entrance and exit times had to concur temporally with other recorded times for that case (*e.g.*, the time of induction of anesthesia). Second, the calculated case durations were compared automatically to the durations of previously performed cases of the same procedure. Discrepancies were addressed the next working day with the OR nurse or nurses who recorded the times.

The cases were classified based on their 8,808 different scheduled procedures. If a procedure was scheduled with more than one Current Procedural Terminology (CPT) code, that combination of scheduled codes was considered to characterize a unique scheduled procedure. The observed number of different scheduled procedures was reasonable compared with other surgical suites in the United States.[9] We classified each case by its scheduled (*vs.* actual) procedure code because (1) for a future case for which a prediction bound is being calculated, only the scheduled procedure would be known, and (2) for some surgeons and scheduled procedures, the actual procedures occasionally differed from the scheduled procedures.[11]

Among the 48,257 cases, 37,699 of the procedures were elective. There were 18,409 series of consecutive elective surgeries in the same OR on the same day with no turnover times exceeding 1 h. We used these series of consecutive elective cases in part to study the expected number of cases preceding a case in an OR on the day of surgery.

We also used the data to calculate the percentages of cases whose earliest start times can be estimated using

‡ Sites accessed June 12, 1999: http://www.pohly.com/salary_anes.shtml, http://www.aana.com/library/costeffect.asp, http://www.pohly.com/salary_gene.shtml, http://www.nurseweek.com/features/97-12/earnsrvy.html, ftp://ftp.bls.gov/pub/special.requests/lf/aat39.txt, and ftp://ftp.bls.gov/pub/special.requests/lf/aat39.txt

2.5 yr of historical case duration data. This was necessary to determine whether each of the statistical methods to calculate 0.05 prediction bounds would be useful if the method were accurate. We compared the scheduled procedures of the first 2.5 yr of cases to the scheduled procedures for the last 0.5 yr of cases. During the first 2.5 yr, there were 40,112 cases. Of the 8,145 operations performed in the last 0.5 yr, 3,717 were elective cases preceded by another elective case in the same OR on the same day with the turnover time not exceeding 1 h. The cases performed in these 3,717 patients were compared with the procedures of the 40,112 patients from the first 2.5 yr.

Testing Prediction Bounds Assuming that the Logarithms of Case Durations Follow a Normal Distribution ("Parametric Method")

When the natural logarithms of case durations follow a normal distribution, the 0.05 prediction bound equals[8,12]

$$\exp(\bar{T} + s \cdot \sqrt{1 + 1/N} \cdot T^{-1}[N - 1, 0.05]) \qquad (1)$$

where $\bar{T}$ = the mean of the natural logarithms of the N previous case durations, s = the standard deviation of the natural logarithms of the N previous case durations, and $T^{-1}[N - 1, \tau]$ = the τth percentile of the Student *t* cumulative distribution function with (N − 1) degrees of freedom. To calculate this parametric prediction bound, case durations must be available from at least two previous cases of the same scheduled procedure because $N \geq 2$ is needed to calculate the standard deviation.

For example, we used this equation to calculate the location of the arrows in figures 1 and 2. The value of $= T^{-1}[552 - 1, 0.05] = -1.648$. For N = 552, $\bar{T} = 0.967$, and s = 0.266, the 0.05 prediction bound equaled $\exp(0.967 + 0.266 \cdot \sqrt{1 + 1/552} \cdot [-1.648]) = 1.7$ h. When the 552 case durations were sorted and the 0.05 percentile was found empirically, the value also equaled 1.7 h. The value of $T^{-1}[2 - 1, 0.05] = -6.314$. For N = 2, the 0.05 prediction bound equaled $\exp(0.967 + 0.266 \cdot \sqrt{1 + 1/2} \cdot [-6.314]) = 0.3$ h.

This parametric equation for the 0.05 prediction bound assumes that the logarithms of previous cases' durations follow a normal distribution. This assumption may not hold sufficiently well for the 0.05 prediction bounds to be accurate. To determine the accuracy of 0.05 parametric prediction bounds, we analyzed the data set in the manner we previously reported.[8,13]

Testing 0.05 Prediction Bounds Calculated Using the Nonparametric Method

We repeated the analysis that we performed for parametric 0.05 prediction bounds using nonparametric 0.05 prediction bounds. The nonparametric method has the advantage of not assuming that logarithms of case durations are normally distributed. These nonparametric bounds were calculated using the approach described by Beran *et al.*[14] Provided $N \geq 19$, the 0.05 nonparametric prediction bound equals the $(0.05(N + 1) - 1)/(N - 1)$ percentile of the N numbers.[14]

Testing 0.05 Prediction Bounds Calculated by Having Each Patient Ready for Surgery at a Fixed Number of Hours before the Scheduled End of the Preceding Case in the Operating Room

An economically rational strategy for scheduling elective cases is to use the mean of the durations of previous cases of the same scheduled procedure to predict the duration of a future case.[15] A corresponding strategy for the problem considered in this study is to subtract a specified number of hours from the mean of previous cases' durations. We studied this strategy because it is a method currently used by surgical suites.

We considered the rule whereby patients are asked to arrive sufficiently early to be ready for surgery 1.5 h before the scheduled end of the preceding case in the OR. If the mean of previous cases of the same scheduled procedure type was briefer than 1.5 h, then the patient would be asked to arrive sufficiently early to be ready when the preceding case in the OR starts. We used 1.5 h because we found by trial and error that it gave a risk of the OR staff waiting for the patient of 0.050 ± 0.001 when applied to all cases in the data set.

Testing the Parametric Method When Applied to More than One Preceding Case in the Same Operating Room

A case may be preceded in its OR by two cases and the turnover time between the two cases. In the data set, there were 11,444 pairs of consecutive elective cases in the same OR on the same day with no turnover time exceeding 1 h and with at least two previous cases of the same scheduled procedure for each of the two cases in the series. We evaluated two strategies for predicting the time to complete the pairs of cases.

The actual time to complete a pair of cases and the turnover time between the pair of cases was compared with the sum of the 0.05 prediction bounds for each of the two cases and the turnover time, using the method of analysis that we reported previously.[8,13] The 0.05 prediction bound for the turnover time equaled 10 min by both parametric and nonparametric methods. This method needed to be tested in part because we assumed[15] that the durations of the two cases in each pair were statistically independent.

The 0.05 prediction bound for the time to complete a pair of cases and the turnover time between the pair of cases was also estimated by Monte-Carlo computer simulation. A duration for each of the two cases in the pair was obtained by making a random draw from its appropriate Student *t* distribution (equation 1). The process

Table 1. Percentages of Cases Whose Earliest Start Times Can Be Estimated Using 2.5 yr of Historical Case Duration Data

Number of Previous Cases Used to Predict the Duration of the Preceding Case in the Same Operating Room	Percentages of Cases (Mean ± Standard Error)	
	Limiting Consideration to Cases that Were Preceded by Another Elective Case (N = 3,717)	Including Cases that Were a "First-Start" in an Operating Room (N = 8,145)
19 or more	62.4 ± 0.8	82.8 ± 0.4
2 or more	84.5 ± 0.6	92.6 ± 0.3
1 or more	88.5 ± 0.5	94.7 ± 0.2

was repeated thousands of times, until the 99% two-sided confidence interval for the 0.05 quintile for the sum of the durations was less than 5 min.[16] Student *t*-distributed random numbers were generated by the T3T* algorithm.[17]

If the time that a patient would be asked to be ready for surgery equals the sum of the three 0.05 prediction bounds, and if the resulting risk of the OR staff waiting for the patient is less than 0.05, then the sum of 0.05 prediction bounds would be the earliest time the patient needs to be ready for surgery. On the day of surgery, the patient could call the surgical suite or *vice versa* to learn how much later than the original estimate he or she should arrive at the surgical suite. We show in the Appendix that the $\tau = 0.05$ prediction bound for the duration of a case based on the number of hours (d) because the case started equals

$$\exp(\bar{T} + s\sqrt{1 + 1/N} \cdot T^{-1}(N - 1, \tau + (1 - \tau) \cdot T\left(N - 1, \frac{\ln(d) - \bar{T}}{s\sqrt{1 + 1/N}}\right))). \quad (2)$$

We tested this method for cases in the data set with durations that were at least d = 0.5, 1.0, or 1.5 h long.

Results

Characteristics of Surgical Cases

The mean ± SD of the number of cases in each series of elective cases in an OR was 2.0 ± 1.1 cases, with an SEM of 0.01 cases. Among the elective cases, 87 ± 0.2% were preceded by zero or one case.

To calculate a 0.05 percentile empirically necessitates that there be at least 19 previous case durations because 0.05 = 1/(19 + 1). Table 1, row 1, shows that with 2.5 yr of historical data, 19 or more previous cases of the same scheduled procedure type would be available to calculate a 0.05 percentile for 62 ± 1% of elective cases preceded by another elective case in the same OR on the same day.

Table 1, row 2, shows that, with 2.5 yr of data, clerks could use parametric methods to determine when patients should be ready for surgery for 84 ± 1% of cases preceded by another case in the same OR on the same day.§

Calculation of Prediction Bounds for the Duration of the Preceding Case in the Operating Room

Table 2 shows the percentage of cases for which the OR staff would have to wait for the patient.

The first column shows the results when the parametric method was used. The 0.05 prediction bounds achieved an actual risk of 0.053 ± 0.001 for the OR staff to wait for the patient. If the minimum number of previous cases used to calculate the parametric prediction bounds was 19 instead of 2, then the achieved risk was more accurate at 0.050 ± 0.001.

The second column shows results for the nonparametric method. It performed no better than the parametric method.

In the third column we provide results from when we estimated the 0.05 prediction bound by having each patient ready for surgery 1.5 h before the scheduled end of the preceding case in the OR. By design, the overall risk of the OR staff waiting for the patient equaled 0.050 ± 0.001. Increasing the minimum number of previous cases from at least two to at least 19 caused the risk to change from 0.050 ± 0.001 to 0.035 ± 0.001. This was because of the marked dependence of the risk of the OR staff waiting for the patient on the mean of previous cases' durations. When the mean of previous cases' durations was less than or equal to 1.5 h, the patient was (by definition) always available when the preceding case in the OR was completed. The risk of the OR staff waiting for the patient always equaled 0.000. When the mean of previous cases' durations was longer than 3.5 h, the risk was 0.143 ± 0.004 for two or more previous cases and 0.100 ± 0.004 for 19 or more previous cases. The improvement in the accuracy of the prediction bounds for the longer case durations, which was achieved by increas-

§ Adding to this percentage the cases that were "first-starts" in an OR, parametric methods could be used to determine when 93 ± 0.3% of patients should be ready for surgery (table 1, row 2, column 2). This 93% value can be increased further. We consider an OR with two scheduled cases. The first case has one or zero previous case durations of the same scheduled procedure(s). The second case has many previous cases of the same scheduled procedure(s). The sequence of cases can be switched so that the case with historical case duration data is performed first. Specifically, cases were switched if (1) a case was followed in the same OR on the day of surgery by another elective case; (2) the first of the two cases was of a scheduled procedure that in 2.5 yr no more than one case of the same scheduled procedure had been performed; (3) the case that followed the case was of a scheduled procedure with two or more previous cases of the same scheduled procedure type; and (4) the case that followed was itself not followed by another case. Making such switches increased the percentage of cases for which the parametric method could be used to 95 ± 0.2%.

Table 2. Comparison of Statistical Methods' Abilities to Predict the Correct Answer (5%) that the Risk Was 0.05 that Case Duration Would Be Briefer than Expected

Number of Previous Cases	Mean Case Duration (h)	Parametric Method*	Nonparametric Method*	Mean Minus 1.5 h*	Sample Size
1 or more	All			5.4 ± 0.1	38,454
	≤1.5			0.0 ± 0.0	6,716
	1.5–3.5			2.4 ± 0.1	21,726
	>3.5			15.6 ± 0.4	10,012
2 or more	All	5.3 ± 0.1		5.0 ± 0.1	35,625
	≤1.5	4.8 ± 0.3		0.0 ± 0.0	6,155
	1.5–3.5	5.2 ± 0.2		2.4 ± 0.1	20,338
	>3.5	5.7 ± 0.2		14.3 ± 0.4	9,132
19 or more	All	5.0 ± 0.1	5.1 ± 0.2	3.5 ± 0.1	21,755
	≤1.5	5.0 ± 0.3	4.4 ± 0.3	0.0 ± 0.0	4,132
	1.5–3.5	5.1 ± 0.2	5.5 ± 0.2	2.2 ± 0.1	12,718
	>3.5	4.9 ± 0.3	4.7 ± 0.2	10.0 ± 0.4	4,905

* Percentage of cases (± standard error) that would be delayed using the different methods of predicting the earliest starting time.

ing the number of previous cases, had the effect of worsening the overall accuracy of the method.

Application of the Parametric Method to More than One Preceding Case in the Same Operating Room

If the patient having surgery after two preceding cases and a turnover was ready for surgery at the time corresponding to the sum of the three 0.05 prediction bounds, the risk of the OR staff waiting for the patient would be 0.016 ± 0.001. If computer simulation were used, the risk of the OR staff waiting would be 0.059 ± 0.001.

If the patient contacts the surgical suite on the day of surgery, the 0.05 prediction bound for the duration of the first of two preceding cases could be adjusted based on the number of hours since the case started. If this preceding case in the OR had been underway for 0.5, 1.0, or 1.5 h, then the 0.05 prediction bounds achieved actual risks for the OR staff to wait for the patient of 0.055 ± 0.001, 0.058 ± 0.001, and 0.056 ± 0.001, respectively.

Discussion

Implications of Findings

Weiss showed previously that, based on a surgical suite's relative valuation[1] of patients' waiting time to staff's idle time, there is an optimal number of hours before the scheduled end of the preceding case in a patient's OR that the patient should be ready for surgery.[4] We used actual case duration data to test statistical methods to estimate the earliest start time of a case so that Weiss' theory can be programmed into surgical services information systems.

The parametric method to calculate prediction bounds assumes that the logarithms of case durations follow a normal distribution. Although this assumption may not be strictly satisfied, figure 1 suggested that for cholecystectomies the logarithms of previous cases' durations can follow a distribution that is close to being normally distributed. Case durations have been found to be log-normally distributed,[18] and statistical methods that assume case durations follow log-normal distributions have been used successfully in applications.[8,13] Therefore, we suspected that the parametric equation for the 0.05 prediction bound would perform sufficiently well for the risk that the OR staff would wait for the patient to be approximately 0.05 if the patient were ready for surgery at the time specified by the 0.05 prediction bound. We found that 0.05 prediction bounds calculated using the parametric method achieved actual risks of 0.053 ± 0.001 for the OR staff to wait for the patient, which we consider to be very accurate.

We found that the parametric method was preferable to having patients ready for surgery a fixed number of hours before the scheduled end of the preceding case in the OR. First, when the latter method was used, increasing the minimum number of preceding cases from at least two to at least 19 caused the risk to change from 0.050 ± 0.001 to 0.035 ± 0.001. In contrast, the parametric method became more accurate. Second, there was a large dependence of the risk of the OR staff waiting for the patient on the mean of previous cases' durations.

Updating the Earliest Start Time for Series of Successive Cases

Among surgical suites in the United States, there was an average of 2.0 cases per OR each work day.[19] In our data set, the mean number of cases in each series of elective cases in an OR was also 2.0 cases. 87% of patients had zero or one preceding case in their OR.

Some surgical suites have scheduled delays between series of cases (*e.g.,* a morning and afternoon session separated by lunch). When there is a scheduled delay, the cases after the delay start as if there were no preceding cases in the OR. The use of scheduled delays in surgical suites increases the applicability of statistical methods for zero or one preceding cases.

Nevertheless, a method is needed to choose the times at which the patients with two or more preceding cases should be ready for surgery. We showed that when there are a series of successive cases in an OR, the sum of 0.05 prediction bounds can be used before the day of surgery as the earliest time the patient needs to be ready forsurgery.‖ This approach is conservative from the patient's perspective, in that the risk of the OR staff waiting for the patient is less than 0.05.

An alternative approach is for the 0.05 prediction bound for a series of cases to be calculated by using Monte-Carlo computer simulation. However, for many cases, there are only a few previous cases of the same scheduled procedure type (table 1).[9] With a small number of cases, the Student *t* densities had long lower tails (fig. 2). It is the lower tail that is used for calculating 0.05 prediction bounds. Due to the long lower tails, hundreds of thousands of Student *t*-distributed random numbers had to be generated for the precision of the estimate to be within 5 min. Thus, although this method yielded accurate results, the computational effort was substantial compared with the use of equation 1, which may make this approach less practical.

On the day of surgery, the patient can call the surgical suite or *vice versa* so that the patient can get an updated time to arrive at the surgical suite based on the updated earliest start time of the first of two preceding cases in the patient's OR. We found that the parametric method can accurately predict the 0.05 prediction bound for the time remaining in a case. If this method is used, patients may then have shorter waits while maintaining the risk that OR staff will be idle at less than 0.05. Our experience is that this concept is readily understandable by hospital staff and patients. Updating a patient's arrival time may be helpful if the second of two preceding cases has not started when the patient calls. Having the patient call may also be particularly useful if the number of previous cases' durations available to estimate the parameters for the prediction bound for the first of the two preceding cases is small, and as such, the 0.05 prediction bound is very brief, as in figure 2.

Updating the start time provides flexibility to the surgical suite in moving cases from one OR to another while maintaining a relative valuation of patients' waiting time to staff idle time of 0.05. We found that updating the start time can be straightforward for patients who live close to the surgical suite, are staying at hotels near the hospital, or are coming to the surgical suite from a ward or intensive care unit.

‖ Alternatively, the durations of previous "common" pairs of cases could, in theory, be used directly in the analytical expression for the 0.05 prediction bound. However, there were few "common" pairs of cases. Among the 3,717 pairs of cases with a turnover time in the 0.5-yr data set, only 26 ± 1% of the pairs had two or more like pairs in the earlier 2.5 yr of data.

Time that Patients Should Arrive at the Surgical Suite versus *the Time that They Should Be Ready for Surgery*

We focused on predicting the time when a patient needs to be ready for surgery. Based on the estimated earliest start time of a patient's case, a clerk will need to decide when the patient should arrive at the surgical suite. The difference between the estimated earliest start time and the time at which the patient should be asked to arrive varies among surgical suites because of differences in average patient punctuality, time necessary to change into a hospital gown, availability of medications, and turnover times, among other factors. For long preceding cases in the patient's OR, variability in these factors is relatively unimportant compared with the variability in the duration of the preceding case.[3] For brief preceding cases, variability in these factors may be important.

Cancellation on the Day of Surgery of a Preceding Case

The theory developed to balance the cost of a patient waiting on the day of surgery *versus* the cost of OR staff waiting for the patient assumes that the preceding case is performed.[4] Institutions with a high percentage of cancellations can incorporate the risk of cancellation into its decision-making regarding when patients should be ready for surgery. For example, if the proportion of appropriately scheduled cases that cancel on the day of surgery equals 0.03, then a 0.02 prediction bound would be used instead of a 0.05 prediction bound to maintain the risk of the OR staff waiting for the patient at 0.05. If an OR has a cancellation rate greater than 0.05, then even if every patient scheduled for elective surgery who shows up were to be ready for surgery at the start of the workday, the risk of the OR staff waiting for a patient would always exceed 0.05.

Other Applications of Predicting Earliest Start Times of Cases

We found that there are other ways that 0.05 prediction bounds for preceding cases in ORs can be used. First, family members and friends of patients in the hospital need to decide when to come to the hospital on the day of surgery. Second, the equation for the 0.05 prediction bound of the time remaining in a case (equation 2) can be used for family members wanting to know the earliest time a case is likely to end so that they can take a walk or perform other tasks. Third, shortening the preoperative fasting period to a few hours[20,21] can be difficult to manage in practice for patients who are not the first cases of the day because of uncertainty in knowing the earliest time at which their cases will start.

We reviewed the theory for determining when a patient should be ready for surgery. We showed that the 0.05 prediction bound for a case can be estimated accurately assuming that the logarithms of case durations follow a normal distribution.

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Appendix

To derive equation 2, the τth prediction bound $b = \exp(\bar{T} + s\sqrt{1 + 1/N} \cdot T^{-1}[N - 1, \tau])$, where $T^{-1}[N - 1, \tau]$ represents the τth percentile of the Student t cumulative distribution function with $(N - 1)$ degrees of freedom.[8,12] Rearranging terms, $\tau = T(N - 1, [\ln(b) - \bar{T}]/[s\sqrt{1 + 1/N}])$. Because $b > d$, the number of hours since the case started is $\tau = (T(N - 1, [\ln(b) - \bar{T}]/[s\sqrt{1 + 1/N}]) - T(N - 1, [\ln(d) - \bar{T}]/[s\sqrt{1 + 1/N}]))/(1 - T(N - 1, [\ln(d) - \bar{T}]/[s\sqrt{1 + 1/N}]))$. Solving this equation for b gives equation 2.