Tactical Decision Making for Selective Expansion of Operating Room Resources Incorporating Financial Criteria and Uncertainty in Subspecialties' Future Workloads

Franklin Dexter, MD, PhD, Johannes Ledolter, PhD, and Ruth E. Wachtel, PhD, MBA

Division of Management Consulting, Departments of Anesthesia and Health Management & Policy, Department of Management Sciences, College of Business, and Department of Anesthesia, University of Iowa

We considered the allocation of operating room (OR) time at facilities where the strategic decision had been made to increase the number of ORs. Allocation occurs in two stages: a long-term tactical stage followed by short-term operational stage. Tactical decisions, approximately 1 yr in advance, determine what specialized equipment and expertise will be needed. Tactical decisions are based on estimates of future OR workload for each subspecialty or surgeon. We show that groups of surgeons can be excluded from consideration at this tactical stage (e.g., surgeons who need intensive care beds or those with below average contribution margins per OR hour). Lower and upper limits are estimated for the future demand of OR time by the remaining surgeons. Thus, initial OR allocations can be accomplished with only partial information on future OR workload. Once the new ORs open, operational decision-making based on OR efficiency is used to fill the OR time and adjust staffing. Surgeons who were not allocated additional time at the tactical stage are provided increased OR time through operational adjustments based on their actual workload. In a case study from a tertiary hospital, future demand estimates were needed for only 15% of surgeons, illustrating the practicality of these methods for use in tactical OR allocation decisions.

(Anesth Analg 2005;100:1425–32)

Expansion of operating room (OR) capacity and plans for allocation of additional OR time are topics markedly affecting anesthesia providers. Decisions directly affect anesthesia revenue, work hours, call requirements, and job security. Decisions affect the ability of academic departments to educate residents and perform clinical research. Decisions also affect anesthesia providers indirectly through their financial impact on the hospital and its capability to make other capital improvements (e.g., purchase anesthesia information systems).

We considered hospitals at which the strategic decision had been made to increase the number of ORs because existing OR time was used fully and future demand was expected to increase. Tactical decisions regarding how the additional OR time might be allocated are made roughly 1 yr in advance. If specific subspecialties are to be targeted, the hospital must design and outfit the new ORs and recruit staff with sufficient expertise to meet the needs of those subspecialties. Alternatively, the hospital may decide to use the additional OR time as general purpose overflow for services that have filled their allocated OR time (1,2) and have more cases to perform (3,4).

We describe a practical method, using only limited information, for making tactical decisions regarding allocation of future OR resources among surgical subspecialties. Such decisions require estimates for the future demand for each subspecialty area (5,6). Assuming the hospital wishes to target subspecialties with the highest potential for financial growth (7–12), we show that OR allocation can be accomplished with demand information for only a small fraction of surgeons, wherein surgeon is considered a surrogate for subspecialty (7,8,10–12).

Furthermore, although demand estimates are approximations, their accuracy is not crucial. Once the new ORs open, operational processes fill OR time that would otherwise be unused by adjusting staffing, releasing allocated but unused OR time, and scheduling cases based on OR efficiency (1–4,13,14).

Franklin Dexter is the Director of the Division of Management Consulting within the Department of Anesthesia. He receives no funds personally other than his salary from the State of Iowa, including no travel expenses or honoraria, and has tenure with no incentive programs.

Accepted for publication October 21, 2004.

Address correspondence and reprint requests to Franklin Dexter, MD, PhD, Division of Management Consulting, Department of Anesthesia, University of Iowa, Iowa City, IA 52242. Address e-mail to Franklin-Dexter@UIowa.edu.

DOI: 10.1213/01.ANE.0000149898.45044.3D

0003-2999/05

ANESTH ANALG 2005;100:1425–32

To illustrate these methods, data were taken from a 28 OR tertiary hospital in the United States (US). The hospital had been experiencing 3% surgical growth per year for the previous 5 years. Surgical intensive care unit (ICU) beds are usually full. One third of ORs finish after 5:30 PM. The strategic decision was made to convert two storage rooms into two ORs and for two ORs to run to 9 PM each workday, increasing capacity by 10%. The planned time course for construction and recruitment of additional personnel was 1 yr.

The hospital and medical group's activity-based costing system was queried for all patients undergoing outpatient or same day admit elective surgery in 2002 (11). Total contribution margin (CM) (hospital plus professional), hours of OR time, and days of ICU care were calculated for each physician who used OR time. The analysis was limited to the 122 physicians who performed at least 20 cases in 2002. This group of physicians, including a dermatologist, is henceforth referred to as "surgeons."

Methods

Financial considerations associated with allocation of OR time have been reviewed previously (11): managerial cost accounting methods (9), rationale for selection of patients undergoing only elective surgery (7–9), use of surgeon as a surrogate for subspecialty (7–9), linear programming to include constraints such as limited regular ward or ICU beds (8,9), calculation of confidence intervals for CM per OR hour (CM/OR hour) for each surgeon (10), and quadratic programming to prevent spurious decisions from outlier patients (11). Briefly, CM/OR hour for each surgeon is determined by combining OR information systems data with hospital or professional financial data. CM is revenue (reimbursement) minus variable costs. Profit is CM minus fixed costs. To maximize profit, a hospital should do more cases with a high CM/OR hour. Fixed costs are ignored because they do not change.

Calculations were performed using Excel XP's Solver tool (Microsoft, Redmond, WA) (15).

Allocation of additional OR time occurs as a two-stage process. Tactical decisions made approximately 1 yr in advance determine initial increases in allocations for each subspecialty. OR times are not reduced for any surgeon; they are increased or (mostly) left unchanged. Once the new ORs open, operational adjustments serve to fill available OR time and to match staffing (i.e., OR allocations) to actual workload.

Our novel approach to the tactical process for increasing OR allocations is to use readily available financial and operational data first to screen out groups of surgeons who should not receive increases in OR time. The advantage of eliminating these surgeons from consideration at this point is that future demand does not have to be estimated for these surgeons.

- Linear programming techniques for determining OR allocations can be used to eliminate surgeons based on their corresponding need for other limited hospital resources that would not be available, such as regular ward, ICU, or postanesthesia care unit time (8,9,16).
- Quadratic programming considers standard errors for each surgeon's CM/OR hour, and is used to eliminate surgeons with uncertainties in CM/OR hour large enough to cause spurious tactical decisions owing to outlier patients (10,11,15,17).
- Surgeons for whom the new ORs will be inherently unsuitable are eliminated (18). For example, the new ORs at the case study hospital are located at the tertiary surgical suite, far from the recovery and holding areas. They were deemed unsuitable for large-volume short outpatient cases such as pediatric otolaryngology.
- Surgeons whose OR workload is already small will have little potential for substantive increases in workload. We required that doubling their workload would result in at least one extra case per week or two additional hours per week, whichever was larger. For these surgeons, even a large increase in relative demand would consume little additional OR time. The subspecialties represented by these surgeons are unlikely to play major roles in the tactical decisions associated with OR expansion.
- Additional OR time should not be allocated at this tactical stage to surgeons with below average CM/OR hour (7,10,11). Because the second operational stage fills OR time without regard for CM/OR hour, thereby achieving the overall average CM/OR hour, allocating OR time tactically at a below average CM/OR hour would be disadvantageous financially.

The concept that surgeons can be excluded from consideration for additional OR allocations at the tactical stage before marketing data are obtained has not been recognized previously. The concept is vital to the simplicity and practicality of our method. Because these surgeons will not have their OR allocations increased, their future OR demand functions can simply be fixed at their OR workload from the preceding year. All demand functions are thus "constrained demands," representing only that portion of potential demand that can be met.

Demand functions are estimated for the remaining surgeons only. Specifically, results of data envelopment analysis (5,6) and other marketing data are used to predict the overall need for services in the future and the extent to which nearby hospitals may compete for the same patients, modified to account for local factors such as the surgeons' desires for expansion. Demand functions do not have to be determined precisely. They can be specified simply as ranges with uniform distributions. Future OR allocations are then calculated (Appendix, Equation 16).

Although many surgeons and subspecialties are excluded from being allocated OR time at the first tactical stage, they are not precluded from receiving additional OR time during the second operational stage. Surgeons and subspecialties fully using their allocated OR time and scheduling more cases can use much additional allocated OR time by having it released (2,3). Over a period of months, their OR allocations are increased to match staffing to their actual OR workloads, thereby increasing OR efficiency (13). Surgeons excluded from increased OR allocations tactically because of their need for ICU beds can schedule additional cases when ICU beds are available on short notice.

Results

Figure 1 shows the 122 surgeons from the study hospital plotted according to CM/OR hour. CM/OR hour varied several-fold among surgeons, consistent with results from two other hospitals (7,8), The average CM/OR hour among all surgeons was $1,773 (Equation 6), between previously calculated values of $1,530 (8) and $1,864 (7), adjusted for the US Bureau of Labor Statistics' national medical inflation rate.

As the tactical goal is to maximize financial gains, allocations exceed current OR usage only for those surgeons (Equation 8) whose CM/OR hour is above the weighted average for all surgeons (Equation 3). Sixty-eight surgeons were excluded at the tactical stage from receiving additional OR time because they did not satisfy this criterion.

At the tactical stage, 36 more surgeons were excluded from receiving additional OR time for miscellaneous reasons: 15 surgeons because ICU capacity would not be increased sufficiently, five surgeons because of high uncertainties in CM/OR hour, seven surgeons based on the unsuitability of the ORs for their particular specialties, and nine surgeons who contribute negligibly to overall OR workload.

Only 18 surgeons remained, representing just 15% of the original 122 surgeons. Achievable increases in demand for these surgeons were considered uniformly distributed within specified ranges (Equation 10). The OR allocations at the tactical stage were determined (Equation 16) by imposing the constraint that total additional allocations cannot exceed the total additional OR time available. This constraint was introduced through the Lagrange coefficient (Appendix), representing the smallest value of CM/OR hour

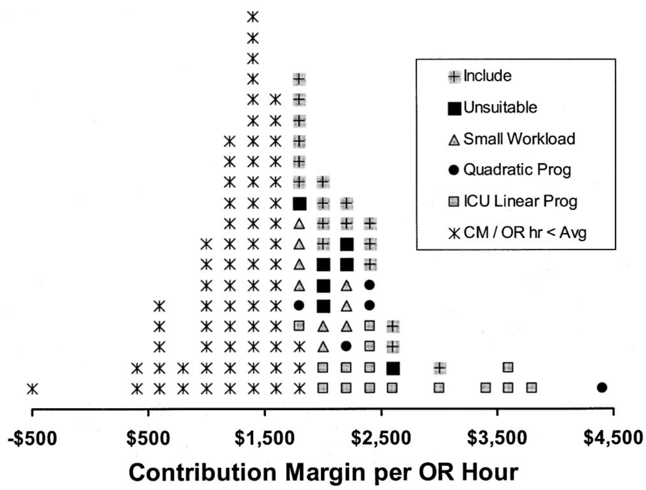

Figure 1. Contribution margins per operating room (OR) hour sorted. Each symbol represents one surgeon (n = 122). Surgeon is used as a surrogate for subspecialty. Surgeons plotted with stars are those who were excluded from consideration for expanded OR resources because their contribution margins per OR hour were less than the weighted average. Surgeons plotted with black squares were excluded by linear programming based on extensive intensive care unit usage. The surgeons plotted with circles were excluded by quadratic programming based on large uncertainty in estimated contribution margins per OR hour. Potential doubling of the surgeon's workload was considered equivalent to hiring another surgeon (8,11). Surgeons plotted with black triangles were excluded because their maximum potential increases in OR workload were <2 h per week, even with doubling OR workload. The 18 surgeons included in the analysis were those marked with + marks.

above which surgeons were eligible to receive increases in OR allocations tactically.

For the case study hospital, these calculations based on the Lagrange coefficient and CM/OR hour proved unnecessary. Data envelopment analysis (5,6) results were available for 11 surgeons in five specialties. The hospital was already performing as much surgery as expected in these fields based on the relationships between specialty workloads, hospital characteristics, and demographics throughout the region (5,6). There was no reason to expect OR workload in these specialties to increase at a rate exceeding the 1.8% annual growth from population aging (19). Other marketing data for these 11 surgeons and specialties and seven additional surgeons in two additional specialties were provided to local experts and administrators and discussed with the surgeons themselves. None of these surgeons and subspecialties appeared to have the potential for market expansion exceeding one extra case per week. Consequently, the decision was made not to target any subspecialty but to use the expanded OR resources for overflow time to be filled operationally.

Because these specific tactical results may not apply to other hospitals, we illustrate the calculation of initial (tactical) OR allocations. We created the sample data of Figure 2 by assuming that the maximum future demand equals a simple 100% proportional increase

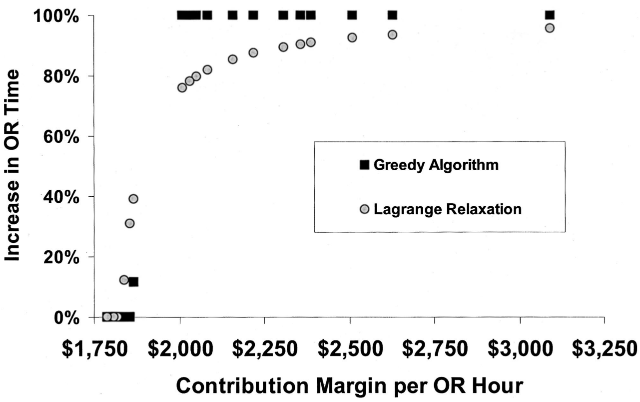

Figure 2. Differences in percentage increases in operating room (OR) resources (time) between the greedy algorithm and the Lagrange relaxation. Each point represents a single surgeon. To permit visual comparison, all surgeons are considered to have maximum percentage increases of 100%. The 18 surgeons included are those marked with + marks in Figure 1. The other 104 surgeons with zero increases are not plotted to prevent clutter. The greedy algorithm provides increased OR allocations to as few surgeons as possible because it assumes that future demand and the percentage increase are maximal for each surgeon. The Lagrange relaxation assumes that demand is a random variable ranging between the minimum increase of 0% and the maximum increase of 100%. The data are provided in Table 1.

based on previous usage (Equation 9) (i.e., hiring another surgeon), just as we do to identify surgeons with small workloads. Table 1 shows the above 18 surgeons who were not disqualified. Two sets of OR allocation results are presented in Table 1 and Figure 2: a greedy algorithm in which as many surgeons as possible are assigned the maximum 100% increase (7) and our Lagrange relaxation in which the increase in demand for each surgeon is considered a random variable between 0% and 100% (Equation 16). These two methods are not equivalent (16) because the Lagrange relaxation considers uncertainties in knowledge of future demand.

Discussion

Estimating future demand for surgical subspecialties and surgeons is an expensive, time-consuming, and politically charged process. Because OR allocations should only be increased tactically for those surgeons with above average CM/OR hour who also meet other criteria, demand functions need be estimated for only a small percentage of surgeons. Marketing research can be limited to a few subspecialties. Fewer surgeons must be consulted to solicit their expert opinions about future expansion. In addition, demand need not be predicted exactly, just estimated as a range. Thus, using demand information to make tactical decisions about OR design, equipment, and staffing becomes practical and straightforward. Conclusions are sometimes so obvious once surgeons have been excluded that the calculations in the Appendix are not needed, as shown for the case study hospital.

Whereas the usefulness of our method is a consequence of the ability to exclude most surgeons before estimating future OR workload a year in advance, the fundamental scientific advance is the consideration of OR allocation in two stages: tactical followed by operational. If the tactical decision is considered alone, surgeons with below average CM/OR hour cannot be excluded (8). Their exclusion is possible only because the two stages of OR allocation are considered together, and the surgeons have access to OR time during the second operational stage without regard to financial criteria. The end result is that the second operational stage can be far more important than the initial tactical stage in determining actual OR allocations. In fact, at the case study hospital, the appropriate tactical decision was to rely solely on the second operational stage for OR allocation to specific surgeons and subspecialties.

The Appendix includes methods for calculating initial (tactical) values for OR allocations using a Lagrange relaxation. The greedy algorithm, linear programming, and quadratic programming have been used previously for tactical OR allocation (7–12). In this paper, we considered OR allocation as a two-stage process of tactical decisions followed by operational decisions, permitting a large reduction in the number of surgeons for whom demand must be determined. We also incorporated the additional information that future demand for each surgeon is not truly a fixed value but a random variable. Whereas linear and quadratic programming are useful for excluding surgeons based on their maximal potential increases in OR workload, they are not suitable for optimizing tactical OR allocations while simultaneously considering the following operational decision. The Lagrange relaxation is an appropriate method because it considers uncertainties in demand (16).

We recommend that implementation at facilities be performed by following the same ordered process that we used. Obtain data as described in the second paragraph of the "Case Study" section and then follow the steps through the last bullet point in Methods. The references provide the details. The relevant equations are given in the Appendix.

Limitations

CM/OR hour may not be readily available for all surgeons. The case study hospital and professional group had a costing database that provided detailed financial information. Payer mix was incorporated automatically into the calculations through its effect on hospital or professional revenue. Even at institutions that lack such detailed accounting data, variable costs

Table 1. Data Used to Create Figure 2

Surgeon classified according to specialty	Ratio of total contribution margin to total hours of OR time used	Current average weekly use of OR time (h)	Greedy Algorithm	Lagrange Relaxation
General	$3,089	2.35	100%	96%
Neurosurgery	$2,628	7.00	100%	93%
General	$2,510	6.53	100%	92%
Gynecology	$2,388	3.05	100%	91%
Gynecology	$2,358	2.87	100%	90%
Gynecology	$2,307	7.49	100%	89%
Orthopedics	$2,219	5.17	100%	87%
General	$2,160	3.70	100%	85%
Orthopedics	$2,084	12.62	100%	82%
Otolaryngology	$2,052	10.86	100%	80%
General	$2,033	4.90	100%	78%
Urology	$2,009	5.02	100%	76%
Otolaryngology	$1,866	11.99	12%	39%
Otolaryngology	$1,855	18.67	0%	31%
Otolaryngology	$1,838	10.50	0%	12%
Plastics	$1,818	5.75	0%	0%
Orthopedics	$1,809	13.22	0%	0%
General	$1,789	4.07	0%	0%

OR = operating room.

Another 104 surgeons were excluded and have 0% increases. For the 2 columns at the right, $\alpha_{more}^{OR} = 10\%$, $\alpha_{surg}^{more} = 1.0$ (i.e., $d_s^{max} = 2\ Q_s^p$). For the Lagrange calculations, $R = \$1{,}773$ and $\lambda = \$1829.76$. Readers can use the data to ensure they are using equation (16) correctly before applying it to their own data.

For the greedy algorithm, each surgeon's maximum increase in demand could be set at 50%, equal to the average of a uniform distribution between 0 and 1. Then, the total increases in OR allocations would equal 50% for all 18 surgeons, because the sum of the increases in OR allocations would be less than the available increase in OR time.

can be estimated sufficiently accurately for the purposes of tactical decision-making using the patients' OR times, hospital lengths of stay, ICU lengths of stay, and implant costs (9). Emphasizing the latter, implant cost accounting is essential (9).

Although the Lagrange relaxations take into account uncertainties in demand estimations, a limitation is that the sampling error of CM/OR (10) is not considered. Nevertheless, once quadratic programming has been used to eliminate outlier surgeons, uncertainties in the estimates for CM/OR hour contribute little to the statistical risk associated with determining overall CM because the portfolio of surgeons at a hospital is sufficiently diverse (i.e., many more than eight surgeons) (11).

For screening surgeons, future demand functions can be ranges in which the maximum possible demand is a proportional increase in current usage. More precise estimates can be obtained from hospital discharge data and demographic data using methods such as data envelopment analysis (5,6). However, these estimates must be modified and adjusted by administrators and surgeons based on specific factors unique to each hospital and region. When local experts at the study hospital were asked about demand distributions, they seemed to be speculating wildly, unable to do more than suggest possible values for maximum demand and guess the probability of reduced demand. For that reason, we assumed a uniform statistical distribution for the increase in demand for the surgeons included in the tactical analysis (Equation 10). This assumption does not affect our most important finding: When OR allocation is considered a two-stage process, demand data are needed for only a small subset of surgeons. Although the assumption affects the calculated values for initial OR allocations, subsequent operational decisions using actual workload (13,14) will correct and compensate for inaccuracies in the estimates of future demand.

This article's relevance to any particular hospital depends on how the strategic decision is made to increase OR capacity. The methods are not appropriate if future use of new ORs has been predetermined by strategic decisions (e.g., local politics, educational needs, or directed gifts). The methods do not apply unless existing OR capacity is used fully. Finally, the method assumes that OR time is allocated in a two-stage process. If a hospital does not adjust allocations operationally based on OR efficiency, then these methods for tactical decision-making are inappropriate.

Only tactical increases, not reductions, in OR allocations were considered because reductions are rarely mandated via tactical mechanisms. If a strategic decision were made to reduce or eliminate a specific program, it is unlikely that fully used OR time would suddenly be reduced for that subspecialty. Instead, the hospital would stem further investment, possibly by choosing not to replace outdated equipment, limiting the number of implants purchased, or allowing the number of subspecialty surgeons to decrease through attrition. The subspecialty would decline gradually. As its OR workload decreases, operational processes would progressively reduce its OR allocations.

Summary

The allocation of OR time is a two-stage process. For the tactical stage, financial and operational data are integrated to identify a small subset of surgeons for whom future surgical demand must be estimated. These demand functions are used to determine initial OR allocations 1 yr in advance. When the ORs open, the second operational stage adjusts the allocations based on actual OR workload based on OR efficiency.

Appendix

The true mean values for the total contribution margin and OR time of the s$^{\text{th}}$ surgeon's elective cases are $\mu(\mathrm{CM_s})$ and $\mu(\mathrm{OR_s})$, respectively, $s = 1, 2, \ldots, N$. For brevity, we denote the mean contribution margin per OR hour with

$$c_s = \frac{\mu(CM_s)}{\mu(OR_s)}. \tag{1}$$

Prior (Q_s^p) and future (Q_s^f) OR times to be planned for each surgeon are related in total by

$$\sum_{s=1}^{N} Q_s^f \leq (1 + \alpha_{more}^{OR}) \sum_{s=1}^{N} Q_s^p = \mathrm{B^{OR}}, \tag{2}$$

with α_{more}^{OR} representing the allowable proportional increase in overall OR resources.

Let T_s represent the contribution to the total contribution margin from OR time planned for the s$^{\text{th}}$ surgeon. Let $\mathrm{E}(T_s)$ be its expectation over the uncertain demand distribution. The objective is to choose

$$\max_{Q_1^f, Q_2^f, \ldots, Q_N^f} \sum_{s=1}^{N} \mathrm{E}(T_s), \tag{3}$$

subject to the constraints

$$\sum_{s=1}^{N} \mathrm{Q_s^f} \leq \mathrm{B^{OR}} \quad \text{and}$$

$$Q_s^p \leq Q_s^f, \quad s = 1, 2, \ldots, \mathrm{N}. \tag{4}$$

The latter constraint specifies that the tactical decision is used only to increase OR allocations.

Without loss of generality, we rank the surgeons in descending sequence of CM/OR hour:

$$c_1 > c_2 > \cdots > c_m > R \geq c_{m+1} > \cdots > \mathrm{c_N}, \tag{5}$$

where the weighted average contribution margin per OR hour

$$R = \frac{\sum_{s=1}^{N} \mathrm{c_s} Q_s^p}{\sum_{s=1}^{N} Q_s^p}. \tag{6}$$

At the time of tactical decision-making, future demand for a surgeon's services, d_s, is unknown. However, we assume that it is bounded

$$d_s^{\min} \leq d_s \leq d_s^{\max} \tag{7}$$

Combining Equations 4 and 7,

$$\begin{array}{ll} d_s^{\min} \leq Q_s^p \leq Q_s^f \leq d_s^{\max}, & \text{for } s = 1, 2, \ldots, m \\ Q_s^p = Q_s^f, & \text{for } s = m+1, \ldots, N. \end{array} \tag{8}$$

To maximize financial gains, future OR allocations should exceed current OR time only for the first m surgeons, for whom CM/OR hour is above average (Equation 5). Thus, future demand needs to be estimated only for the first m surgeons.

When screening the m surgeons, time-consuming demand modeling can be replaced by estimating the maximal increase in demand as a proportional increase in demand ($\alpha_{more}^{surg} > 0$). For example, $\alpha_{more}^{surg} = 1.0$ represents recruitment of another surgeon of the same subspecialty (8,11). Then, for initial screening,

$$d_s^{\max} = (1 + \alpha_{more}^{surg}) Q_s^p \geq Q_s^f \geq Q_s^p, \tag{9}$$

provided future demand is not constrained by the surgeon's lack of eligibility for increases in OR time because of a lack of ICU beds or other such resources. Then, instead, $d_s^{\max} = Q_s^p = Q_s^f$.

With no or very limited distributional information available for increases in demand, a uniform distribution is assumed for the increase in demand:

$$\begin{array}{lll} F_s(Q_s^p) = & \dfrac{Q_s^p - d_s^{\min}}{d_s^{\max} - d_s^{\min}} & \\ F_s(d_s) = & \dfrac{d_s - d_s^{\min}}{d_s^{\max} - d_s^{\min}} & \text{for } Q_s^p \leq d_s < d_s^{\max}. \\ F_s(d_s) = & 1 & \text{for } d_s = d_s^{\max} \end{array} \tag{10}$$

To make the notation less cumbersome, we subsequently drop the subscript in $\mathrm{F_s}()$.

The contribution margin from OR time planned for s$^{\text{th}}$ surgeon is given by

$$T_s = \begin{cases} c_s Q_s^f, & Q_s^f \leq d_s \leq d_s^{\max} \\ c_s d_s + R(Q_s^f - d_s), & d_s^{\min} \leq d_s \leq Q_s^f \end{cases},$$

$$\text{for } s = 1, 2, \ldots, m. \tag{11}$$

If OR time allocated tactically exceeds actual demand, operational processes will fill the OR time without regard to finances, achieving a CM/OR hour equal to the average, R. The expected value equals

$$E(T_s) = (c_s - R)\left\{\int_{d_s^{\min}}^{Q_s^f} d_s dF(d_s) + RQ_s^f \int_{d_s^{\min}}^{Q_s^f} dF(d_s)\right\} + c_s Q_s^f \int_{Q_s^f}^{d_s^{\max}} dF(d_s)$$

$$= (c_s - R)\left\{\int_{d_s^{\min}}^{Q_s^p} d_s dF(d_s) + \int_{Q_s^p}^{Q_s^f} d_s dF(d_s)\right\}$$

$$+ RQ_s^f \int_{d_s^{\min}}^{Q_s^f} dF(d_s) + c_s Q_s^f \int_{Q_s^f}^{d_s^{\max}} dF(d_s).$$

Substituting the uniform distribution from Equation (10),

$$E(T_s) = \frac{1}{2(d_s^{\max} - d_s^{\min})}\{(R - c_s)(Q_s^f)^2 + 2(c_s d_s^{\max} - R d_s^{\min})Q_s^f + a_s\}, \quad (12)$$

where

$$a_s = (R - c_s)\left\{(Q_s^p)^2 - 2(d_s^{\max} - d_s^{\min})\int_{d_s^{\min}}^{Q_s^p} d_s dF(d_s)\right\}.$$

Although Equation 12 and thus Equation 6 are maximized by setting $Q_s^f = d_s^{\max}$, $s = 1, 2, ..., m$, the constraint

$$\tilde{B}^{OR} = B^{OR} - \sum_{s=m+1}^{N} Q_s^p \quad (13)$$

may not be satisfied. The constraint is introduced through the Lagrange coefficient λ and the maximization of

$$L(Q_1^f, Q_2^f, \ldots, Q_m^f) = \sum_{s=1}^{m} E(T_s) + \lambda\left\{\tilde{B}^{OR} - \sum_{s=1}^{m} Q_s^f\right\}. \quad (14)$$

The optimal values for Q_s^f are found by solving the system of $m + 1$ equations:

$$\frac{\partial L}{\partial Q_s^f} = 0, \quad s = 1, 2, \ldots, m$$

$$\frac{\partial L}{\partial \lambda} = 0.$$

From Equation 14, the condition is satisfied by requiring that:

$$\sum_{s=1}^{m} Q_s^f(\lambda) = \tilde{B}^{OR}, \quad (15)$$

(i.e., the sum of initial OR allocations are a function of λ). Also

$$\frac{\partial L}{\partial Q_s^f} = \frac{Q_s^f(R - c_s) + c_s d_s^{\max} - R d_s^{\min}}{d_s^{\max} - d_s^{\min}} - \lambda,$$

where a_s has vanished because the constant does not depend on Q_s^f. Setting $\partial L/\partial Q_s^f = 0$ and rearranging terms twice,

$$Q_s^f = \frac{\lambda(d_s^{\max} - d_s^{\min}) + R d_s^{\min} - c_s d_s^{\max}}{(R - c_s)}$$

$$= d_s^{\min} + \frac{c_s - \lambda}{c_s - R}(d_s^{\max} - d_s^{\min}).$$

Adding the conditions of Equation 8,

$$Q_s^f(\lambda) = \begin{cases} Q_s^p & , R < c_s \le \lambda \\ \max\left\{Q_s^p; d_s^{\min} + \dfrac{c_s - \lambda}{c_s - R}(d_s^{\max} - d_s^{\min})\right\} & , R < \lambda < c_s \\ d_s^{\max} & , \tilde{B}^{OR} \ge \sum_{s=1}^{m} d_s^{\max} \end{cases}$$

$$\text{for } s = 1, 2, \ldots, m. \quad (16)$$

Because λ represents the value of CM/OR hour above which surgeons are eligible to receive increases in initial OR allocations, the smallest value is chosen satisfying Equation 15. We use the standard nonlinear GRG Solver Tool in Excel.

References

1. Dexter F, Macario A, O'Neill L. Scheduling surgical cases into overflow block time: computer simulation of the effects of scheduling strategies on operating room labor costs. Anesth Analg 2000;90:980–6.
2. Dexter F, Traub RD, Macario A. How to release allocated operating room time to increase efficiency. Predicting which surgical service will have the most under-utilized operating room time. Anesth Analg 2003;96:507–12.
3. Dexter F, Traub RD. How to schedule elective surgical cases into specific operating rooms to maximize the efficiency of use of operating room time. Anesth Analg 2002;94:933–42.
4. 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.
5. Dexter F, O'Neill L. Data envelopment analysis to determine by how much hospitals can increase elective inpatient surgical workload for each specialty. Anesth Analg 2004;99:1492–500.
6. O'Neill L, Dexter F. Market capture of inpatient perioperative services using data envelopment analysis. Health Care Manag Sci 2004;7:263–73.
7. Macario A, Dexter F, Traub RD. Hospital profitability per hour of operating room time can vary among surgeons. Anesth Analg 2001;93:669–75.
8. Dexter F, Blake JT, Penning DH, Lubarsky DA. Calculating a potential increase in hospital margin for elective surgery by changing operating room time allocations or increasing nursing staffing to permit completion of more cases: A case study. Anesth Analg 2002;94:138–42.

9. Dexter F, Blake JT, Penning DH, et al. Use of linear programming to estimate impact of changes in a hospital's operating room time allocation on perioperative variable costs. Anesthesiology 2002;96:718–24.
10. Dexter F, Lubarsky DA, Blake JT. Sampling error can significantly affect measured hospital financial performance of surgeons and resulting operating room time allocations. Anesth Analg 2002;95:184–8.
11. Dexter F, Ledolter H. Managing risk and expected financial return from selective expansion of operating room capacity: Mean-variance analysis of a hospital's portfolio of surgeons. Anesth Analg 2003;97:190–5.
12. Kuo PC, Schroeder RA, Mahaffey S, Bollinger RR. Optimization of operating room allocation using linear programming techniques. J Am Coll Surg 2003;197:889–95.
13. Strum DP, Vargas LG, May JH. Surgical subspecialty block utilization and capacity planning: A minimal cost analysis model. Anesthesiology 1999;90:1176–85.
14. Epstein RH, Dexter F. Statistical power analysis to estimate how many months of data are required to identify operating room staffing solutions to reduce labor costs and increase productivity. Anesth Analg 2002;94:640–3.
15. Ragsdale CT. Spreadsheet modeling and decision analysis, a practical introduction to management science, 2nd edition. Cincinnati, Ohio: South-Western College Publishing, 1998;45–64, 128–141, 334–41.
16. Higle JL, Wallace SW. Sensitivity analysis and uncertainty in linear programming. Interfaces 2003;33:53–60.
17. Briggs AH, Mooney CZ, Wonderling DE. Constructing confidence intervals for cost-effectiveness ratios: An evaluation of parametric and non-parametric techniques using Monte Carlo simulation. Stat Med 1999;18:3245–62.
18. Dexter F, Macario A, Penning DH, Chung P. Development of an appropriate list of surgical procedures of a specified maximum anesthetic complexity to be performed at a new ambulatory surgery facility. Anesth Analg 2002;95:78–82.
19. Etzioni DA, Liu JH, Maggard MA, et al. Workload projections for surgical oncology: Will we need more surgeons? Ann Surg Oncol 2003;10:1112–7.