Analysis of Operating Room Allocations to Optimize Scheduling of Specialty Rotations for Anesthesia Trainees

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INTRODUCTION: Because specialty workloads and corresponding operating room (OR) allocations vary among days of the week, anesthesia residents and student nurse anesthetists are sometimes assigned to cases off rotation (e.g., scheduled for cardiac surgery but assigned to urology for the day). We describe a method to create hybrid rotations of two specialties (e.g., cardiac and vascular surgery), thereby reducing the numbers of days that trainees are "pulled" from their scheduled rotations.

METHODS: Raw data were the number of hours of OR time used by each surgical specialty on each workday for the preceding 9 months. These OR workloads were converted to the number of ORs to be allocated to each specialty for each day of the week on the basis of maximization of the efficiency of use of OR time. We considered all potential hybrid rotations of pairwise combinations of specialties to which trainees could be assigned. Integer linear programming was used to calculate the maximum number of trainees who could be scheduled to hybrid rotations and receive daily assignments matching those rotations.

RESULTS: Validity of the results was shown by using data from a small facility for which the optimal solution could be discerned by inspection. Validity (appropriateness) of the constraints was demonstrated by the exclusion of each constraint, resulting in answers that are obviously incorrect. Novelty and usefulness of the method was evidenced by its choosing from among hundreds of thousands of potential combinations of specialties and its identifying appropriate assignments that were substantively different from current rotations.

CONCLUSIONS: We developed a methodology to determine rotations consisting of combinations of specialties to be paired for purposes of trainee scheduling to reduce the incidence of daily assignments off rotation. Practically, with this method, anesthesia residents and student nurse anesthetists can be assigned cases within their scheduled rotations as often as possible. (Anesth Analg 2010;111:520–4)

Anesthesia trainees (e.g., residents and student nurse anesthetists) are often scheduled to rotations (e.g., cardiac, vascular, and pediatrics) for several weeks (e.g., 2 or 4 weeks) at a time. Rotations are usually scheduled many months in advance (e.g., to coordinate with different facilities), far earlier than information is available about individual surgical cases and surgeon schedules. The result is that mismatches sometime occur between the activities of surgical specialties and trainee schedules, causing some trainees to be assigned to cases of a different specialty. Qualitatively, assignment of cases off rotation is a source of dissatisfaction among trainees and results in complaints to program reviewers and to program applicants during interviews.

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As with trainee rotation schedules, operating room (OR) allocations for different days of the week are calculated months in advance by using historical workload data.[1,2] These forecasts of OR workload can be used to reduce the frequency at which trainees are assigned to cases off rotation.

In this article, we show how to calculate (a) the maximum number of trainees who can be scheduled to single specialties each day and be assigned those cases. When these maxima are summed among specialties, the total can be less than the number of trainees to be scheduled. We also show (b) how to create hybrid rotations of two specialties, thereby increasing the total number of trainees over (a) who can be assigned to cases matching their scheduled rotations.

As a trivial example, suppose that otolaryngology has 2 first-case-of-the-day starts (2 ORs allocated) on Mondays through Wednesdays and 1 start on Thursdays and Fridays. Oral surgery has no ORs on Mondays through Wednesdays and 1 OR on Thursdays and Fridays. Then (a) at most 1 anesthesia resident can be scheduled to otolaryngology with the assurance that the resident can be assigned to otolaryngology cases 5 days per week. However, (b) if a hybrid otolaryngology–oral surgery rotation were created, then 2 residents could be scheduled without either needing to be assigned off rotation.

Our work is novel scientifically in that it considers trainee scheduling to solve an anesthesia staffing problem (i.e., how many providers of each type for different specialties on each day of the week). A previous study examined

Table 1. Operating Room Allocations of Outpatient Surgery Center Used for Table 2

	Monday	Tuesday	Wednesday	Thursday	Friday	
EYE	1	2	2	2	1	Ophthalmology
GSG	0	0	1	0	0	General surgery
GYN	1	0	0	0	1	Gynecology
ORT	2	2	2	4	2	Orthopedics
OTO	0	2	0	0	2	Otolaryngology
TOTAL	4	6	5	6	6	Total number of ORs

ORs, operating rooms.

internal medicine resident rotations to guide staffing decisions, but the rotations were very different than were those for anesthesia trainees (e.g., number residents scheduled on night float or to be on call every fourth night).[3] Our work also differs from studies of radiology and surgical resident scheduling that assumed the staffing numbers for each rotation were already decided.[4,5]

The **RESULTS** and **DISCUSSION** sections below were written to be self-contained for readers less interested in the equations and the method of numerical solution.

METHODS

Let there be N surgical specialties (e.g., otolaryngology, orthopedics, and neurosurgery).

Let X_{ij} equal the number of trainees scheduled to the pairwise (ij) combination of the ith and jth specialties. These are their rotations for the week. The X_{ij} are nonnegative integers. When the rotation consists of a single specialty, $i = j$. Otherwise, $i = 1, 2, \ldots, \mathrm{N}$ and $j = i + 1, \ldots, \mathrm{N}$. There are N (N + 1)/2 different X_{ij}.

Let there be m workdays each week, represented by $k = 1, 2, \ldots, \mathrm{m}$. Although typically m = 5, it can be less. For example, if residents or student nurse anesthetists have classroom sessions or reading days once a week, then m = 4. Calculations would then need to be performed separately for residents and student nurse anesthetists.

Let OR_{ijk} be the observed number of ORs of cases for the ith and jth specialties combined on the kth day of the week. These can be (but do not have to be) the number of surgical blocks for the day, depending on whether the blocks reflect actual workload.[6] There are m N (N + 1)/2 different OR_{ijk}.

Let $\mathrm{OR}_{i\cdot k}$ be the observed number of ORs of cases for the ith specialty on the kth day of the week (e.g., as is shown in Table 1). Thus,

$$\mathrm{OR}_{ijk} = \begin{cases} \mathrm{OR}_{i\cdot k} + \mathrm{OR}_{j\cdot k}, & i \neq j \\ \mathrm{OR}_{i\cdot k}, & i = j \end{cases}.$$

Calculation of $\mathrm{OR}_{i\cdot k}$ was reviewed recently[2,7] and thus is simply summarized in the Appendix. The $\mathrm{OR}_{i\cdot k}$ are the OR allocations for each specialty on each day of the week calculated from the OR workload (i.e., total hours of cases including turnovers).

Let Y_{ijkl} be the contribution of ORs of cases from the lth specialty on the kth day of the week to the trainees' rotations of the pairwise combination of the ith and jth specialties. By definition, $l = i$ or $l = j$. The Y_{ijkl} are nonnegative integers. There are mN^2 different variables Y_{ijkl}. For Table 1 with N = 5 specialties, there are 125 different variables.

Then, the optimization problem is the selection of Y_{ijkl} for all i, j, k, and l to maximize the number of anesthesia residents or student nurse anesthetists who can be scheduled to rotations,

$$\sum_{i,j} X_{ij}, \tag{1}$$

while satisfying the following three constraints.

First, no more than p trainees are scheduled to rotations of nonidentical specialties:

$$\sum_{i \neq j} X_{ij} \leq \mathrm{p}. \tag{2}$$

For example, if p = 0, then $X_{ij} = 0$ for all $i \neq j$ (i.e., there are no hybrid rotations).

Second, each scheduled trainee is assigned daily

$$X_{ij} = \sum_{l \in (i,j)} Y_{ij1l} = \sum_{l \in (i,j)} Y_{ij2l} = \cdots = \sum_{l \in (i,j)} Y_{ijml}, \tag{3}$$

for all $i = 1, 2, \ldots, \mathrm{N}$ and $j = i, i + 1, \ldots, \mathrm{N}$.

Third, the contribution of ORs from the lth specialty on the kth day of the week to rotations cannot exceed the specialty's available number of ORs:

$$\sum_{i} Y_{ilkl} + \sum_{j \neq l} Y_{ljkl} \leq \mathrm{OR}_{l\cdot k}. \tag{4}$$

A consequence of this constraint is a resulting upper-bound on equation (1):

$$\sum_{i,j} X_{ij} \leq \min_{k} \sum_{i,j} \mathrm{OR}_{ijk}. \tag{5}$$

Equations (1) to (5) describe a linear integer optimization problem. The equations are "linear" in that each function involves only sums of the unknown variables Y_{ijkl}. They are "integer" in that the solutions for Y_{ijkl} are restricted to integer values (0, 1, 2, etc.). The system of equations was solved in Excel 2003 (Microsoft, Redmond, Washington) using Frontline System's Standard Solver (Incline Village, Nevada). The Standard Solver is an add-in program that comes complimentary with Excel, but is limited to 200 variables. Excel and this Standard Solver work for N ≤ 6 educational specialties, because $5 \times 6^2 < 200$, whereas $5 \times (1 + 6)^2 > 200$. Although sufficient for the outpatient surgery center of Table 1, Standard Solver was not adequate for our real example from an academic program with N = 12 educational specialties, resulting in 720 variables to be optimized (i.e., 5×12^2). Therefore, for the larger linear optimization problem, we used Frontline System's Premium Solver version 9.5.

Table 2. Example of Number of Trainees (X_{ij}) Scheduled to Different Rotations for 6–Operating Room Outpatient Surgery Center

Rotation		p (maximum no. of trainees scheduled on rotations that arepairs of specialties)			
Specialty *i*	Specialty *j*	0	1	6	10
EYE	—	1	1	1	1
ORT	—	2	2	2	2
EYE	GYN	0	1	1	1
Total no. of trainees that can be scheduled to rotations and be assigned those rotations		3	4	4	4

The first column of numbers in Table 2 shows that the integer programming gives the same answer. Subsequent columns in Table 2 correspond to increasing values of p (i.e., some trainees scheduled to hybrid rotations of pairwise combinations of specialties). EYE, ophthalmology; ORT, orthopedics; GYN, gynecology. The dashes in the second column indicate rotations that are single specialty. Among the 5 specialties plus 10 pairwise combinations of the specialties, 12 had 0 trainees scheduled for all values of p and so are not shown in the table.

RESULTS

Tables 2 and 3 show examples, the former of a 6-OR outpatient surgery center with the OR allocations of Table 1, and the latter of an academic program with N = 12 specialties. The bottom row of numbers in each table gives the total number of trainees who can be assigned to individual specialties or to hybrid rotations of pairs of specialties. The first column of numbers is calculated using p = 0 (i.e., on all workdays, all trainees can be assigned to their scheduled specialty, none to a hybrid rotation). For example, for Table 2, if more than 3 trainees were scheduled, then some trainees would receive daily assignments that are not their scheduled rotations. Subsequent columns in Table 2 show that the addition of 1 hybrid rotation results in 1 more trainee who can be scheduled while being assigned daily to his or her rotation.

Assessment of Validity of the Integer Programming

The results have validity based on the matching of results to findings that are self-evident using data from a small facility. Reviewing Table 1, one sees that ophthalmology (EYE) has at least 1 OR on all days of the week. Orthopedics (ORT) has at least 2 ORs on all workdays. The other three specialties each have at least 1 day of the week with no allocated OR. Thus, for p = 0 (i.e., all trainees scheduled to single specialties), 3 trainees should be scheduled, 1 to ophthalmology and 2 to orthopedics. The first column of numbers in Table 2 shows that the integer programming gives the same answer of 3. Subsequent columns in Table 2 correspond to increasing values of p (i.e., some trainees scheduled to hybrid rotations of pairwise combinations of specialties). At most, 4 trainees can be scheduled daily and still be assigned to their scheduled rotations. Table 1 confirms that the value of 4 is the maximum possible, because that is the numbers of ORs on the day of the week (Monday) with the smallest number of ORs running (see equation (5)). EYE and GYN (gynecology) are combined in Table 2. From the first row of Table 1, EYE contributes 1 OR on Tuesdays, Wednesdays, and Thursdays. GYN contributes 1 OR on Mondays and Fridays. From Table 1, no

Table 3. Example of Number of Trainees (X_{ij}) Scheduled to Different Rotations for 32–Operating Room Academic Facility

Rotation		p (maximum no. on trainees scheduled on rotations that are pairs of specialties)							
Specialty *i*	Specialty *j*	0	1	2	3	4	5	6	32
SPINE	—	2	2	2	2	2	2	2	2
EYE	—	2	2	2	2	2	2	2	2
GSG	—	5	5	5	5	5	5	5	5
GYN	—	1	1	1	1	1	1	1	1
HEART	—	2	2	2	2	2	2	2	2
NSG	—	2	2	2	2	2	2	2	2
ORT	—	4	4	4	4	4	4	4	4
OTO	—	1	1	1	1	1	1	1	1
PEDS	—	3	3	3	3	3	3	3	3
URO	—	1	1	1	1	1	1	1	1
VASC	—	1	1	1	1	1	1	1	1
SPINE	THOR	0	1	1	1	1	1	1	1
GSG	GYN	0	0	0	0	1	1	1	1
GYN	ORT	0	0	0	0	0	0	1	1
ORT	PEDS	0	0	1	2	2	2	2	2
OTO	PEDS	0	0	0	0	0	1	1	1
Total no. of trainees that can be scheduled to rotations and be assigned those rotations		24	25	26	27	28	29	30	30

There are 12 specialties and 66 pairwise combinations of specialties. Among these 78 possibilities, the 62 not shown have 0 scheduled trainees at all values of p. The dashes in the second column indicate rotations that are single specialty. Abbreviations are as follows: SPINE, spine surgery; EYE, ophthalmology; GSG, general surgery; GYN, gynecology; HEART, adult and pediatric cardiac surgery; NSG, neurosurgery; ORT, orthopedics; OTO, otolaryngology; PEDS, all pediatric surgery except cardiac and thoracic; URO, urology; VASC, vascular surgery; and THOR, adult and pediatric general thoracic surgery. Specialties were created from the cases performed, not hypothetical blocks. Each case's primary surgical Current Procedural Terminology code was classified into a specialty on the basis of its Clinical Classifications Software (CCS) code (www.HCUP-US.AHRQ.gov/toolssoftware/ccs_svcsproc/ccssvcproc.jsp, accessed February 24, 2010). Specialties corresponding to each CCS were unambiguous (e.g., CCS 1 "Incision and excision of CNS" was classified as NSG). "PEDS" is all cases performed on patients 17 years and younger, excluding HEART.

pairwise combination other than EYE and GYN can provide for a trainee to have an assignment for each day of the week matching the scheduled hybrid rotation.

The constraints are each valid on the basis of the impact of their exclusion:

If the first constraint, from equation (2), were excluded, then different choices of p would not be possible. The answers in the different columns of Tables 2 and 3 would all be the same.

If the second constraint, from equation (3), were excluded, and the data used were those from Table 1, a solution for $p = 0$ would be Table 1 itself. Assignments would no longer be based on scheduled rotations, because they would vary among days of the week.

If the third constraint, from equation (4), were excluded, and $p = 0$, then 1000 trainees could be scheduled to each single specialty rotation, which is obviously incorrect.

Assessment of Usefulness of the Integer Programming

The results are not obvious for increasingly larger choices of the number of trainees (p) scheduled to hybrid rotations. To create Table 3, we evaluated the 12 specialties (N) and 66 pairwise combinations of specialties (i.e., $N[N - 1]/2$). All 78 have at least 1 OR of cases on all days of the week, meaning that the specialty or combination could be selected. Table 3 shows that each pairwise combination of specialties typically would be assigned 0, 1, or 2 trainees. There are 287,496 permutations of pairwise combinations of specialties to evaluate (i.e., 66^3). This number in fact underestimates the true number of possibilities, because the academic anesthesia department whose data are in Table 3 used combinations of as many as 4 specialties in an effort to reduce assignments of trainees off rotation.

Application of this method to data from the academic anesthesia department yielded new insight into resident scheduling. Anesthesia trainees from the department of Table 3 were previously scheduled to each rotation to match the median number of ORs among workdays, not the minimum among workdays. In retrospect, it was predictable that scheduling based on the median workload would be suboptimal. To understand why the academic department had not recognized its root cause for trainees being assigned to cases off rotation, we searched the scientific literature for a previous description of the strategy they could have been using. Among the 6 relevant articles that we knew of,[8–13] none addressed the maximum number of staff to schedule for each rotation or the impact of scheduling on trainees. Search of PubMed (February 24, 2010) for (anesth* OR anaesth*) in titles or abstracts AND (assignment OR scheduling) in the titles of articles, and search of Web of Knowledge and Google, plus citations of the articles, found no additional publications.

DISCUSSION

We developed a method to determine rotations consisting of combinations of specialties to be paired for purposes of trainee scheduling to reduce the incidence of daily assignments off rotation. Practically, by using this method, anesthesia residents and student nurse anesthetists can more often be assigned cases within their (albeit expanded) rotations.

The process of implementing our method depends on whether the number of ORs ("blocks") for each specialty are calculated on the basis of maximizing the efficiency of use of OR time.[2,14,15] If done this way, as we did, our method runs automatically, as is described in the Appendix. If not, the OR_{ijk} need to be selected manually on the basis of the master surgical (block) schedule and expert judgment of how blocks differ from actual OR case scheduling. Whereas manual selection can be based on the specialty of the first-case-of-the-day starts, the automatic analysis in the Appendix also considers the OR hours used by each specialty.

An alternative approach to our method is for an OR management committee to tell surgeons which days they can operate (i.e., plan block time) to achieve homogeneous numbers of ORs among workdays for each specialty. Our approach does not require this type of planning and is preferable for two reasons. First, important clinical factors contribute to choices of days of the week of blocks.[6,16–21] These factors should not be overridden by committees. Second, at some facilities, some specialties have insufficient workloads to fill the same number of ORs on each weekday.[2,15,22–24]

Another approach is to develop custom mathematical software for case assignments to find the best possible daily assignment plans.[25] However, when creating anesthesia assignments, anesthesia coordinators often use multiple pieces of paper to link staff schedules, staff assignments, and case schedules. They communicate decisions asynchronously to multiple stakeholders.[26] Reproduction of this process electronically is expensive because it differs among facilities and anesthesia groups. Our approach intervenes at a preceding automatable stage, making the method suitable for many hospitals.

A program director, anesthesia vice chair, etc., may conclude that the two preceding alternative approaches are implausible to implement, yet may also not want to use our hybrid rotations. For example, suppose that the program director at the department whose results are shown in Table 3 thought that a combination of spine and thoracic surgery would not mitigate residents' dissatisfaction with being "pulled" or "bounced" from their scheduled rotations. Then our method—essentially the Appendix and equation (5)—provides a useful bottom line reality for how many trainees can be scheduled to each specialty simultaneously. The first column of Table 3 shows that no more than 24 trainees can be scheduled to ORs without dissatisfaction. The limiting factor is the minimum number of ORs for each specialty among weekdays. That is the reality of the department's situation, regardless of the program director's opinion of hybrid rotations.

DISCLOSURE

The University of Iowa performs statistical analyses for hospitals and anesthesia groups, including those in this article. Drs. Dexter and Wachtel receive no funds personally other than their salaries from the University of Iowa, including no travel expenses or honoraria, and have tenure with no incentive programs. Richard H. Epstein is President of Medical Data Applications, Ltd., whose CalculatOR™ software includes analyses used in this article.

APPENDIX

Numbers of Operating Rooms for Each Specialty

Each specialty's number of ORs of cases is calculated from its performed OR cases by maximizing the expected efficiency of use of OR time.[2] The following steps were taken from the review by McIntosh et al. and the Appendix of Dexter and Epstein.[2,7]

1. Calculate turnover times between each pair of sequential cases in the same OR on the same day.

"*Turnover time*" refers to the time from when a patient exited the OR until the next patient entered the same OR on the same day.[27] Set turnovers longer than 90 minutes equal 90 minutes, because these likely represent the effect of case cancellations or scheduled delays between cases.

2. Calculate the OR workload for each specialty on each day by using the most recent 9 four-week periods of data.[2,28]

OR workload for a specialty on a day refers to its total hours of OR and turnover times on the day,[2] with urgent cases excluded.

3. Assign each combination of specialty and day of the week with a mean OR workload <5.60 hours to the pseudospecialty representing open, unblocked, first-scheduled, first-served "OTHER" time for low-workload specialties (i.e., the specialty does not get its own OR).[2] The 5.60 hours is the break-even point. The inefficiency of use of OR time would be the same whether 2 specialties, each with 5.60 hours of cases, have their cases scheduled into the same shared OR time or whether each is scheduled into its own 8 hours of allocated OR time, on the basis of overutilized OR time costing 1.5 times as much as underutilized OR time[29]: $1.50 \times (2 \times 5.60 - 8.0 \text{ hours}) = 2 \times (8.0 \text{ hours} - 5.60)$.
4. For each combination of specialty and day of the week, the total inefficiency of use of OR time among days was calculated for choices of 0 ORs, 1 OR, 2 ORs, etc., and the choice with the smallest inefficiency was used as the allocation.

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