

High-throughput Operating Room System for Joint Arthroplasties Durably Outperforms Routine Processes

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Background: Recent publications have focused on increased operating room (OR) throughput without increasing total OR time. The authors hypothesized that a system of parallel processing for lower extremity joint arthroplasties sustainably reduces nonoperative time and increases throughput.

Methods: The high-throughput parallel processing strategy included neuraxial anesthesia performed in an “induction room” adjacent to the OR, patient selection, an additional circulating nurse, and end-of-case transfer of care to a recovery room nurse who transported the patient from the OR to recovery. Instruments and supplies were prepared in a dedicated sterile setup area. Data were extracted from administrative databases. Group comparisons used standard statistical methods; statistical process control was used to evaluate performance over time.

Results: There were 688 historic control cases from 299 days over 16 months, and 905 high-throughput cases from 304 days spanning 24 consecutive months starting September 1, 2004. Throughput increased from 2.6 ± 0.7 (mean ± SD) to 3.4 ± 0.8 arthroplasties per day per room. Nonoperative time decreased by 36 min (or 50%) per case. Operative time also decreased by 14 min (12%) per case. The end time for the high-throughput OR day was only 16 min later than control. Nonoperative time, operative time, and throughput remained significantly improved after 2 yr of operation. Contribution margin increased 19.6%.

Conclusion: Reorganizing the perioperative work process for total joint replacements sustainably increased OR throughput. Because joint arthroplasties generated a positive margin greater than the incremental cost, the high-throughput system improved financial performance.

HISTORICALLY, the evaluation of operating room (OR) efficiency has been based on block time utilization and turnover time. A number of authors have proposed methods to optimize utilization through the use of computer modeling and through different means of predicting case duration time. These strategies have met with varying results and frequently have limited clinical applicability.

Separate from the goal of optimizing efficiency, but intrinsically linked to it, is the pursuit of enhanced OR throughput. Improvements in efficiency match resources and demand, whereas enhanced throughput might require application of extra resources to accommodate demand. Several groups have recently reported the results of Perioperative Systems Design exercises aiming to improve OR throughput.¹⁻⁸ Perioperative Systems Design is a rational approach to managing the convergent flow of patients having procedures from disparate physical and temporal starting points, through the OR and then to such a place and time (e.g., home or hospital bed) where future events pertaining to the patient have no further impact on OR operations.⁹ Perioperative Systems Design attends to both efficiency and throughput. Optimizing throughput is not necessarily the same as optimizing efficiency, but effective Perioperative Systems Design should improve the ability of hospitals to accommodate their patients’ needs while protecting hospital finances.

One strategy to improve OR throughput is to develop perioperative patient flow systems that may or may not require additional elements including personnel, physical plant modifications, and special equipment. The goal of these novel systems is to reduce nonoperative time (i.e., all of the time not spent prepping, draping, or operating) sufficiently that additional cases can be performed without extending staffed OR time. Krupka and Sandberg¹⁰ authored a comparison and review of different perioperative process flow strategies that aimed to increase throughput. Many such strategies included increased personnel cost with the stated or unstated goal of developing a means to offset increased costs through improvements in throughput and, subsequently, productivity. It is also notable that many strategies utilized parallel processing methods with the overlapping induction of anesthesia to reduce nonoperative time. Although induction rooms for general anesthesia are common in Europe, these systems are relatively rare in the United States.

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Another approach to reducing nonoperative time when regional anesthesia is involved is to use a block room separate from the OR. For example, Williams *et al.*¹¹ report on a 3-yr retrospective study of one surgeon, working with surgical teams in two ORs and using regional *versus* general anesthesia. One anesthesiologist directed two nurse anesthetists, one in each of the ORs. After the anesthesiologist administered regional anesthesia in the preoperative holding area, a holding area nurse monitored the patient until the OR was ready. General anesthesia was performed in the OR. Not surprisingly, regional anesthesia using the block room yielded the lowest average anesthesia controlled time (11.4 ± 1.4 min; mean \pm 2 SEM), roughly 9 min less than general anesthesia cases.

Our goal was to demonstrate a different outcome from the results achieved to date in our institution. Specifically, we aimed to increase throughput in a single OR by using an induction room for administration of regional anesthesia, along with additional perioperative system changes.

Our main hypothesis was that a modified parallel processing throughput strategy would reliably reduce nonoperative time such that an additional case could be scheduled and completed each day. This was accompanied by an institutional commitment to schedule and perform these additional cases. We developed the following hypotheses for testing with outcomes from the project: (1) The redesigned work flow process would reduce nonoperative time sufficiently to increase throughput in the project OR without extending staffed OR hours. (2) The incremental revenue from additional throughput would offset both the increased costs of the new system and the additional costs associated with caring for more patients. (3) The results would be durable, meaning that the improvements in nonoperative time and throughput last for more than 1 yr.

This study aims to describe the implementation of an innovative perioperative process flow strategy and test the hypotheses enumerated in the previous paragraph by analysis of data obtained during routine patient care. We also report the impact of the project on process time intervals, both operative and nonoperative, in the high-throughput project ORs, as well as in both historic and concurrent control ORs performing similar cases.

Materials and Methods

We conducted a process improvement exercise beginning on September 1, 2004, to reorganize the flow of work in orthopedic ORs performing lower extremity arthroplasties. The stated goal of the strategy was to develop a process to assist surgeons seeking to perform additional joint arthroplasties in the same-staffed interval. The target throughput was four total joint arthro-

Table 1. Summary of Milestones and Intervals Used

Name	Definition
Milestones	
Patient in room	Patient crosses door threshold entering operating room
Ready for Surgical Prep	Time at which a sufficient level of anesthesia is established to begin surgical preparation (sometimes called Anesthesia Ready)
Surgery Start Time	Surgical incision is initiated
Surgery Finish Time	Dressing is applied
Patient Out of Room	Patient crosses door threshold exiting operating room
Intervals	
Nonoperative Time	Surgery Finish Time until next scheduled patient Ready for Surgical Prep
Turnover Time	Time from previous Patient Out of Room to succeeding Patient In Room
Operative Time	Ready for Surgical Prep to Surgery Finish Time
Prep Time	Ready for Surgical Prep to Surgery Start Time

Where standard terms are available in the American Association of Clinical Directors Procedural Times Glossary,* they are generally used in this report. Turnover Time is a subinterval of Nonoperative Time, and Prep Time is a subinterval of Operative Time.

* Available at: <http://aacdq.org/members/glossary.asp>. Accessed June 21, 2007.

plasties in one OR during 1 day's routine working hours (from 7:30 AM to 5:30 PM). We performed a retrospective review of administrative data to determine the effectiveness of our intervention.

Definition of Times and Time Intervals

The definition of times and time intervals were from definitions as listed in the American Association of Clinical Directors Procedural Times Glossary whenever possible. In certain circumstances, we developed additional time intervals and defined them (table 1). Because of the process flow methodology and the overall focus of the entire team on patient care, we de-emphasized traditional intervals such as anesthesia controlled time or turnover time. Instead, we focused on nonoperative time, which subsumes anesthesia controlled time and turnover time, and reflects the efforts of the entire team working together.

Patient Demographics and Surgical Procedures

All patients had elective lower extremity total joint arthroplasty including both primary joint replacements and revisions under neuraxial anesthesia. Patients known to have severe medical comorbidity, high surgical complexity, body mass index greater than 40 kg/m², history of spinal instrumentation or difficult previous neuraxial anesthesia, or refusal of neuraxial anesthesia were intended to be excluded. Patient demographics and anesthetic procedures are detailed in table 2.

Table 2. Patient Characteristics

	Historic Controls	Concurrent Controls	High-throughput System	P Value
Number of patients	644	259	893	
Age, mean \pm SD, y	66.8 \pm 13.4	65.5 \pm 12.6	65.7 \pm 12.4	0.23, 1
ASA PS distribution				0.015, 0.013
I	13 (2)	8 (3)	32 (4)	
II	164 (25)	91 (35)	281 (31)	
III	453 (70)	147 (57)	568 (64)	
IV	14 (2)	13 (5)	12 (1)	
Women	405 (63)	150 (58)	502 (56)	0.017, 1
Anesthesia method				0.13, 0.06
Epidural	13 (2)	2 (1)	13 (2)	
General	170 (26)	52 (20)	69 (8)	
Spinal	451 (70)	203 (78)	809 (91)	
Other	10 (2)	2 (1)	2 (0)	

Numbers in parentheses are percentages. Categorical data were compared by chi-square analysis; continuous data were compared by *t* tests. The order of comparisons (*P* value column) is historic controls vs high-throughput system, then concurrent controls vs high-throughput system. Two comparisons were made for each variable, with appropriate adjustments to significance criteria. The term *other* under the anesthesia method row subsumes the few cases in which monitored anesthesia care or nerve block was listed as the primary anesthetic.

ASA PS = American Society of Anesthesiologists physical status.

Institution and Surgeons

Cleveland Clinic Hospital (Cleveland, Ohio) is a tertiary care teaching facility with 956 beds where approximately 42,000 anesthetics are performed annually. Joint arthroplasties occupy three to five ORs each workday and include a mix of upper and lower extremity procedures. Six surgeons (the members of the Section of Adult Reconstructive Surgery, Department of Orthopedics) participated in the innovative process flow strategy. These surgeons all had stable practices leading up to and through the implementation of the high-throughput parallel processing system; each surgeon's patients were also included in the historic and concurrent control groups. Scheduling for high-throughput OR days was

done several weeks in advance; schedules required a single surgeon to have a case load sufficient to perform four major joint procedures in one room on 1 day.

Process Flow Improvement Strategy

From July to September 2004, the total joint arthroplasty patient flow process was studied and evaluated for throughput modification opportunities. During the formation of the process, all care providers involved were volunteers.

Several changes to the usual perioperative flow of patients, equipment, and personnel were implemented. Hip and knee arthroplasties were scheduled into one high-throughput OR with the goal of scheduling four

Table 3. Additional Personnel and Resources Used in the High-throughput Environment versus Historic Control Cases

Personnel/Resource	Function	Use in Historic ORs	Use in High-throughput System	Incremental Cost per Day
Additional circulating nurse*	Provides nursing care for the additional patient in the induction room	Never	Always	1 OR RN FTE†
Radios for transport personnel	Facilitates communication and timing of patient transport and OR cleaning	NA	Always	Assumed depreciated
Automated medication dispensing machine in OR	Avoids a trip to the medication dispensing area when transitioning between cases	NA	Always	Assumed depreciated
Instrument table setup area/dedicated setup technician	Room with controlled access and air handling capability suitable for sterile setups; predates this project	Sometimes	Always	1 OR scrub tech FTE†
Induction room with physiologic monitor	Located near the OR—could be a nearby underutilized OR or a shared induction area bed space	Never	Always	Assumed depreciated
PACU nurse collects postoperative patient from OR*	Allows anesthesia team to initiate care of the next patient and induce anesthesia during room turnover	Never	Always	1 PACU RN FTE†

* These resources were utilized on an as-needed basis, which allows them to revert back in to their usual personnel pool when the modified overlapping induction method is not being used. † Although the regularly staffed interval in our operating rooms (ORs) is approximately 10 h, a 6.4-h day was assumed because on average cases ended around 3:30 PM and the added personnel resources were not needed beyond the start of the last case. The value of 1 full-time equivalent (FTE) results because the cost of paid time off needs to be accounted for.

NA = not applicable; PACU = postanesthesia care unit; RN = registered nurse.

arthroplasties into a 10-h staffed interval. Surgeons were advised to exclude patients with exceedingly complex or surgical medical situations. We added a dedicated recovery room nurse to the team to transport the patient from the OR to the postanesthesia care unit (table 3). Another addition to the nursing team was a second circulating nurse (CN2). The two circulating nurses (CN1 and CN2) assumed primary responsibility for alternating patients in the new system. To facilitate rapid turnover between cases, we took advantage of a preexisting but inconsistently utilized process by which the surgical tables are set up in a special sterile handling room and transported to the adjacent OR covered with sterile drapes. An OR technician was dedicated to the high-throughput OR to accomplish this. Further, we used handheld radios to facilitate communication about patient transport and OR cleaning and equipment setup. We also provided a medication dispensing machine in the induction area, thus eliminating the between-case walk to the medication dispensing area. Likewise, use of our automated anesthesia information system ARKS (GE Medical Systems, Milwaukee, WI) eliminated the need to walk paper records from ORs to a central collection station. The new, high-throughput process was fully implemented on September 1, 2004.

Patient Flow in the New High-throughput Parallel Process

The flow of patients, starting from the beginning of the day, is shown in figure 1. The first patient of the day (patient A) enters the high-throughput OR at the usual time of 7:30 AM, and a spinal anesthetic is administered. CN1 assumes care of the patient. The anesthesiologist in the OR continues to care for the patient until bandages are applied. At that time, the dedicated recovery room nurse enters the OR and assumes care of patient A (when clinically stable). At this point, the anesthetic record for patient A is ended and postanesthesia care unit care is initiated, which includes transport to the recovery room by the recovery room nurse. Before the completion of surgery on patient A, the second patient (patient B) is transported to the "induction room," where preoperative care is provided by CN2. After patient A's care has been transitioned to the recovery room nurse, the anesthesia care provider exits the OR and enters the nearby induction room. With the assistance of CN2, the anesthesia care provider interviews the patient, explains the anesthetic plan, and applies monitors. After obtaining informed consent, intravenous sedation is administered as needed, and the spinal anesthetic is induced by the nurse anesthetist-attending anesthesiologist team. This process takes approximately 15 min, which is slightly less than the time required for transport of patient A and OR cleaning/setup. In the induction room, urinary catheters and tourniquets are placed as appropriate. Patient B is then transported by the anesthetist and CN2 across

the corridor into the clean high-throughput OR, and moved onto the OR table. Patient B is then prepped and draped for surgery, with the incision following soon thereafter. As with the first turnover, the assigned recovery room nurse enters the OR for appropriate handoff and transports patient B to the postanesthesia care unit. CN1 has now transitioned to the induction room to assume care for patient C. After the anesthetic is administered to patient C and the OR is cleaned from patient B, CN1 will go with patient C into the high-throughput OR. Keeping up this "leapfrog" pattern, CN2 will subsequently care for patient D in the induction room and then the OR (fig. 1).

Cost Data

In addition to analyzing throughput, we also sought to evaluate the financial impact of running the new system. In this analysis, we assumed that the revenue to the hospital for a given surgeon performing the same arthroplasty procedure in the high-throughput OR *versus* a historic or concurrent control OR would be the same. We also assumed that the cost of supplies would not be different. Finally, we considered the high-throughput system as utilizing an established physical plant with any capital costs fully depreciated.

Given these assumptions, our analysis was simplified to a comparison of differences in contribution margin (the difference between direct cost and revenue) between the high-throughput and control environments. Because we could not perform a blinded analysis of the financial impact of the high-throughput system, we instead ascertained which added resources the new system would consume relative to historic controls in every opportunity for comparison. To accomplish this adjustment for resource intensity in the high-throughput OR, all staff positions that support the ORs were reviewed to determine the magnitude of their involvement with the project. The contributions of all personnel involved in the new perioperative process were quantified relative to their contributions to the control processes. These are summarized as fractional full-time equivalents in table 3. The average per-case contribution margin was determined using Transition Systems, Inc. software (Eclipsys Corporate Headquarters, Atlanta, GA). Because the high-throughput strategy allowed an additional case to be performed on 7 of 10 scheduled days (*i.e.*, an average increase of 0.7 cases per day), we were able to increase our daily contribution margin by 0.7 times the average contribution margin per case, offset by the additional staffing costs. To calculate the final contribution margin, we reduced the daily contribution margin per case by the estimated daily salary for the additional full-time equivalents listed in table 3 (for the Cleveland market), plus 25% for fringe benefits, plus the cost of paid time off.

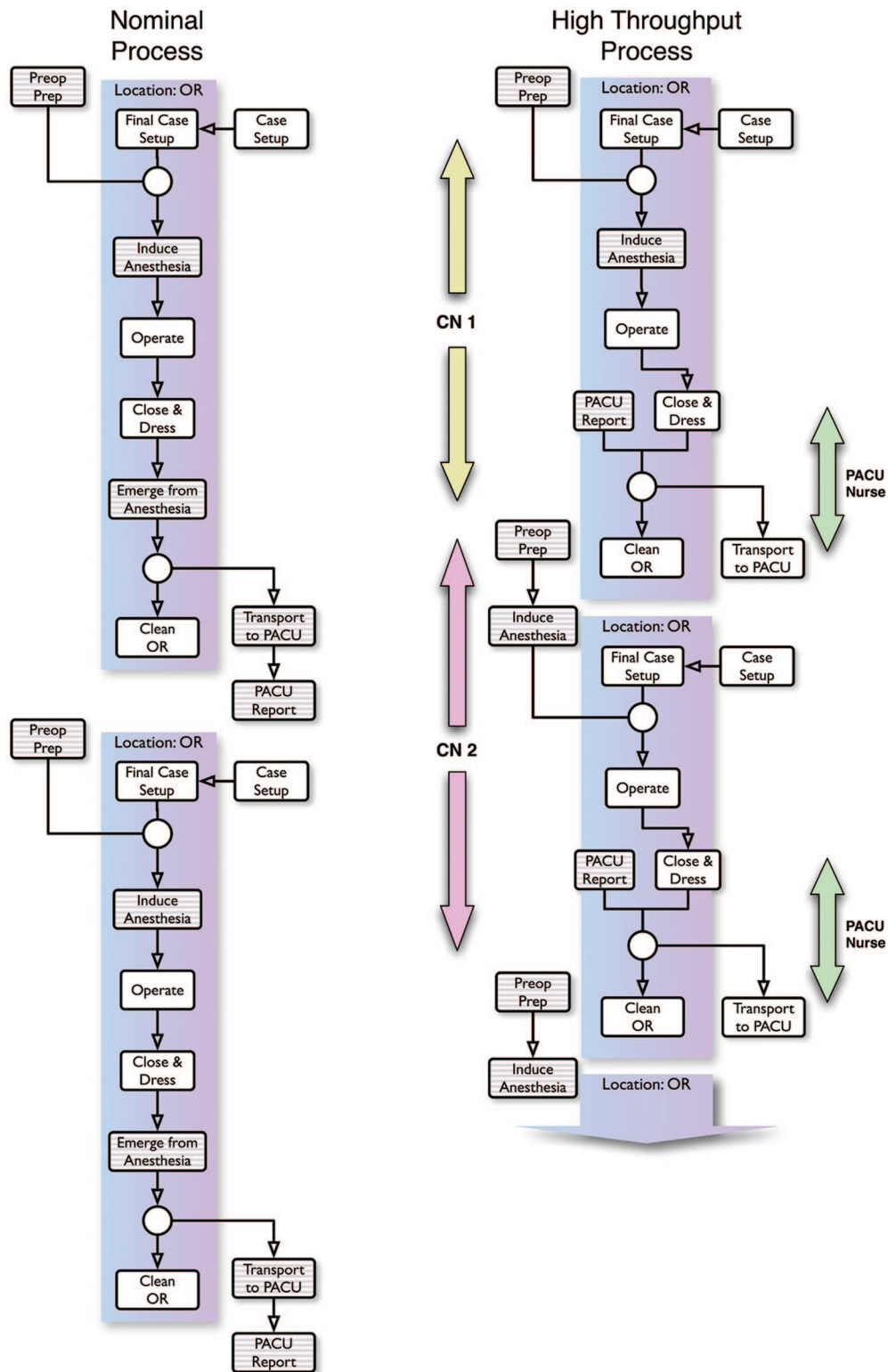


Fig. 1. Process flow diagrams of typical and high-throughput operating room (OR) flow, starting with the first case of the day. CN1 = circulating nurse 1; CN2 = circulating nurse 2; PACU = postanesthesia care unit.

Statistical Analyses

Operating room time and throughput data were extracted from administrative (scheduling and billing) databases for the period of the high-throughput project, from September 1, 2004, to August 31, 2006. We also

gathered both historic and concurrent case data for the same surgeons performing total joint arthroplasties in “standard process” ORs as control data sets utilizing the same databases. The historic control data were from the immediate 16 months preceding the initiation of the

high-throughput process. Concurrent controls were arthroplasties performed in the usual manner without the benefit of the high-throughput system. Group means of continuous variables were compared by Student *t* test after transformation as described in the next section. Categorical variables were compared by chi-square analysis. Because we have both historic and concurrent control data, statistical tests were adjusted for multiple comparisons. A family-wise type I error rate of 0.05 was maintained for each between-group hypothesis by adjusting the significance criterion for multiple comparisons using a Bonferroni correction. Analyses of performance over time were done using statistical process control, as described in the next section.

Group Comparisons of Time Data. Process time data in healthcare settings frequently have rightward skewed distributions, arising from the fact that no procedure can be done in zero or negative time, whereas a few procedures take very long. Logarithmic transformation of time data before comparisons creates a data set that more closely approximates a normal distribution.^{12**} Group means of logarithmically transformed continuous variables were compared using a two-tailed Student *t* test. For tests of significance on logarithmically transformed time data, the value of *p* reported is for the transformed data. Results were transformed back to units of time and reported as the geometric mean and 95% confidence interval.

Performance as a Function of Time. We used statistical process control (SPC) methodology (X-bar charts, a commonly used form of charts for variables) to test for systematic performance changes as the project was implemented and then over time after implementation. The general approach to SPC and the creation of X-bar charts can be found in textbooks, as well as in our previous work and the work of others.¹³⁻¹⁸ In our analysis, we plotted nonoperative time, operative time, cases per day, and end time for the last case, all as a function of calendar date. SPC methods were developed for use with sampling techniques, where only a fraction of the work output (in this case, OR process performance) is tested. However, we have a complete data set, with results for all cases involving a turnover, and SPC can be readily applied to complete data sets. In either scenario, the data are grouped sequentially into samples of a reasonable size to conduct the analysis. The appropriate sample size is found empirically, chosen to balance between the required sensitivity and acceptable noise in the data. For the following analyses, we created uniform samples of 10 sequential cases or days depending on the quantity of interest. The sample size of 10 provides excellent sensitivity to detect small changes, but sacrifices the ability to

detect performance changes rapidly. We had ample data and were interested in performance changes over months to years, so the choice of a larger sample size was appropriate.

The SPC charts contain a horizontal centerline representing the average values for the process being studied. The process is stable if accumulating data points are randomly distributed around the centerline. Points in the SPC chart are connected by straight lines to highlight the development of trends over time. The SPC charts also contain additional horizontal lines to assist in determining whether data points are sufficiently close to the centerline to be considered stable. These lines are called the upper and lower control limits (UCL and LCL).

The centerline, UCL, and LCL are constructed from stable baseline data. In this work, the UCL and the LCL are constructed to be +3 and -3 SDs above and below the centerline, respectively. Therefore, 99.7%, or nearly all points of the baseline process being studied fall between the UCL and the LCL. If a point falls outside the control limits, this indicates that the process has experienced a significant shift from the baseline condition. Even when all of the points on an SPC chart are within the control limits, they might still form systematic patterns that indicate the process has experienced a significant shift from the baseline.

To aid the visual identification of systematic performance changes in SPC charts, formal rules have been developed. We used the Western Electric rules¹³ for analyzing the SPC charts, seeking to separate distinct performance changes from random variation. The Western Electric rules are a series of tests that can be visually applied to an SPC chart without requirements for calculations or performing statistical tests. However, the rules are based on sound statistical reasoning. Therefore, they provide a known probability (typically $P < 0.005$) that processes are experiencing systematic performance changes rather than random variation.^{13,19}

Results

There were 688 cases in the historic control group from 299 OR days during the 16 months preceding the 24-month study period, during which we analyzed 262 concurrent control cases from 109 OR days and 905 cases from 304 scheduled high-throughput OR days. The characteristics of the patients in each group are summarized in table 2. Demographic data were incomplete for 44 historic controls, 3 concurrent controls, and 8 high-throughput patients. The groups were similar except for American Society of Anesthesiologists (ASA) physical status (PS). There were a higher number of ASA PS III patients in the historic control group than in either the concurrent controls or the high-throughput patients. The concurrent control group contained fewer ASA PS

** Although we present transformed data here, the mean differences and their significances were similar for comparisons of nontransformed time data, despite the fact that the distributions were skewed.

Table 4. Distributions of Surgical Procedures

	Historic Controls	Concurrent Controls	High-throughput System	P Value
Number of patients	688	262	905	
Total hip arthroplasty	367 (53)	119 (45)	436 (48)	0.48, 1
Total knee arthroplasty	224 (33)	121 (46)	347 (38)	0.20, 0.28
Bilateral knee arthroplasty	97 (14)	22 (8)	122 (14)	1, 0.10
Revision arthroplasty	151 (22)	84 (32)	146 (16)	0.03, < 0.0001

Numbers in parentheses are percentages. Categorical data were compared by chi-square analysis of frequencies relative to the total number of patients in the historic and concurrent control groups and in the high-throughput system. The order of comparisons (*P* value column) is historic controls vs high-throughput system, then concurrent controls vs high-throughput system. Two comparisons were made for each variable, with appropriate adjustments to significance criteria. The column totals exceed the number of patients because revisions are an additional category distributed over knee and hip arthroplasties.

III patients but more ASA PS IV patients than the high-throughput OR group. These differences were expected from the high-throughput OR patient scheduling process, which was designed to reduce patients whose comorbidities might unreasonably slow throughput. Only 7.7% of patients in the high-throughput group received general anesthesia, compared with 26.4% of historic controls and 20.1% of concurrent controls (all groups significantly different from the others). For patients in the high-throughput OR, use of general anesthesia extended nonoperative time by 23 (14–32) min [mean (95% confidence interval)] *versus* spinal anesthesia (*P* < 0.0001) because general anesthesia required use of the OR for induction.

The distribution of cases performed and complexity of cases (as captured by the proportion of cases that were bilateral arthroplasties or revision procedures) are summarized in table 4. The distribution of hip arthroplasties was similar across these groups. Consistent with the process design goals, the high-throughput OR performed fewer revision arthroplasties than historic or concurrent control ORs. However, the high-throughput system performed similar numbers of bilateral arthroplasties as the historic control ORs (table 4).

The results of the project with respect to OR process variables and throughput are shown in table 5. Each surgeon's throughput increased, whereas both nonop-

erative times and, to a lesser extent, operative times decreased. The end time for the OR day for the high-throughput OR was approximately 15 min later than historic controls but 20 min earlier than concurrent controls.

Figures 2 and 3 graphically assess the onset time and durability of the changes in nonoperative time and operative time (fig. 2), cases per day, and end time (fig. 3). Each panel is an SPC chart beginning with the historic control data and carrying through to 2 full years of the high-throughput process. The purpose of the figures is to compare the performance of the new process with that of the baseline (*i.e.*, historic) process. Therefore, the figures plot historic performance and high-throughput system performance over time, but the concurrent control data are omitted. In each figure, the centerline, UCL, and LCL were constructed using the complete historic control data sets, up until the high-throughput process was fully implemented on September 1, 2004. The Western Electric rules—by which the subsequent data were to be tested for systematic differences from the historic baseline data—are given in table 6.

Examination of figures 2 and 3 indicates that the project achieved its short-term goals: Throughput was increased without substantially extending staffed OR hours. Figure 2 shows a distinct reduction in nonoperative time, and a smaller but identifiable reduction in

Table 5. Process Outcomes for High-throughput Arthroplasty Perioperative System *versus* Historic and Concurrent Controls

	Historic Controls	Concurrent Controls	High-throughput System	P Value
OR days	299	109	304	
Cases	688	262	905	
Cases with a turnover	386	150	601	
Nonoperative Time, min	71.8 (69.2–74.4)	76.9 (72.0–82.1)	36.2 (34.6–37.8)	< 0.0001*
Turnover Time, min	31.9 (30.2–36.7)	35.6 (32.2–39.8)	15.7 (14.7–16.8)	< 0.0001*
Operative Time, min	120.0 (117.0–123.1)	122.5 (117.6–127.5)	106.1 (103.8–108.4)	< 0.0001*
Prep Time, min	19.5 (18.8–20.1)	18.9 (17.8–20.0)	17.2 (16.7–17.7)	< 0.0001*
Cases per day	2.3 ± 0.5	2.4 ± 0.5	3.0 ± 0.7	< 0.0001*
Arthroplasties per day	2.6 ± 0.7	2.4 ± 0.5	3.4 ± 0.8	< 0.0001*
End Time, military notation	15:05 (14:52–15:17)	15:43 (15:19–16:08)	15:21 (15:09–15:34)	0.14, 0.16†

Data are reported as mean (95% confidence interval) or mean ± SD. Nonoperative Time can only be calculated for cases with a turnover. Turnover Time is a subinterval of Nonoperative Time, whereas Prep Time is a subinterval of Operative Time. Means were compared by Student *t* test, with Bonferroni correction for multiple comparisons.

* High throughput vs historic and concurrent controls; two comparisons, both with *P* < 0.0001 after correction. † High throughput vs historic controls and concurrent controls; two comparisons.

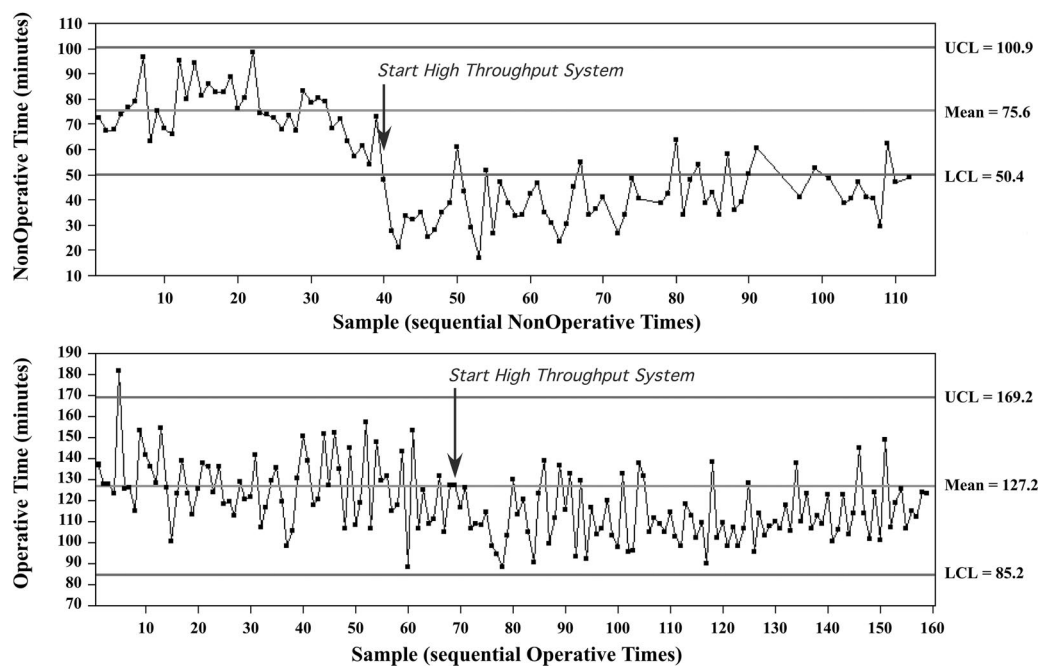


Fig. 2. Control charts showing process time (nonoperative and operative times) for 16 months before initiating the high-throughput perioperative system and then for the subsequent 2 yr. Time advances from left to right across the figure. Each data point is the average for a bin of 10 consecutive times. Note that there are more data points for operative time than for nonoperative time because the latter includes turnover time, and the first case of the day does not have a turnover. The upper control limit (UCL) and lower control limit (LCL) are 3 SDs above and below the mean denoted by the centerline. The UCL, LCL, and centerline are all derived from the complete historic control data set before implementation of the high-throughput process. The purpose of this figure is to compare the performance of the new process to that of the baseline (*i.e.*, historic) process. Therefore, it plots historic performance and high-throughput system performance over time, but the concurrent control data are omitted.

operative time, both concomitant with the initiation of the high-throughput process on September 1, 2004. Figure 3 demonstrates that this reduction in process times was matched by a clear increase in throughput but only a small increase in the end time of the OR day. Closer examination of figures 2 and 3 just before implementation of the high-throughput system reveals that nonoperative time was reduced (fig. 2, rules 2 and 3) and cases per day increased (fig. 3, rule 1) in advance of full implementation (see table 6 for definition of rules). We attribute this change in performance to improvements made during the process improvement exercise before full implementation.

The figures also indicate that the process improvements are durable. Both figures indicate some relaxation back toward historic performance in the second year of the analysis, but process times are still reduced, and throughput is still increased, 2 yr after beginning the project.

The additional costs associated with the high-throughput OR are summarized in table 3. While the regularly staffed interval for our ORs is approximately 10 h, cases ended around 3:30 PM and added personnel were not required beyond the start of the last case of the day, resulting in a 6.4-h cost allocation for the added personnel. Only 6.4 h was allocated because personnel were utilized in other OR areas to complete their shifts. The costs are presented as full-time equivalents, so that read-

ers may substitute their own institutional costs. However, in the contribution margin determination, we used daily staffing costs based on the Cleveland market. Unlike many previous reports, the current project is neutral with respect to utilization of anesthesia personnel. The total process time for a case in our high-throughput OR is roughly 1.75 h; our high-throughput system accommodated an average of 0.7 additional cases per day in the staffed interval. Although institutional regulations prohibit us from publishing the detailed financial data, we observed that a 19.6% increase in the final daily contribution margin may be achievable from our process (calculated as 0.7 times the average contribution margin per case during the period under study, minus increased daily staffing expenses, 25% fringe benefits, and the cost of paid time off). It is important to note that per-case revenue to the anesthesia department will be reduced somewhat due to the decreased total process time leading to less billable time per case. However, the added revenue from additional cases offsets this decrease in revenue per case, as observed previously.⁵

Discussion

Our observation in a large teaching hospital supports the notion that OR throughput can be substantially im-

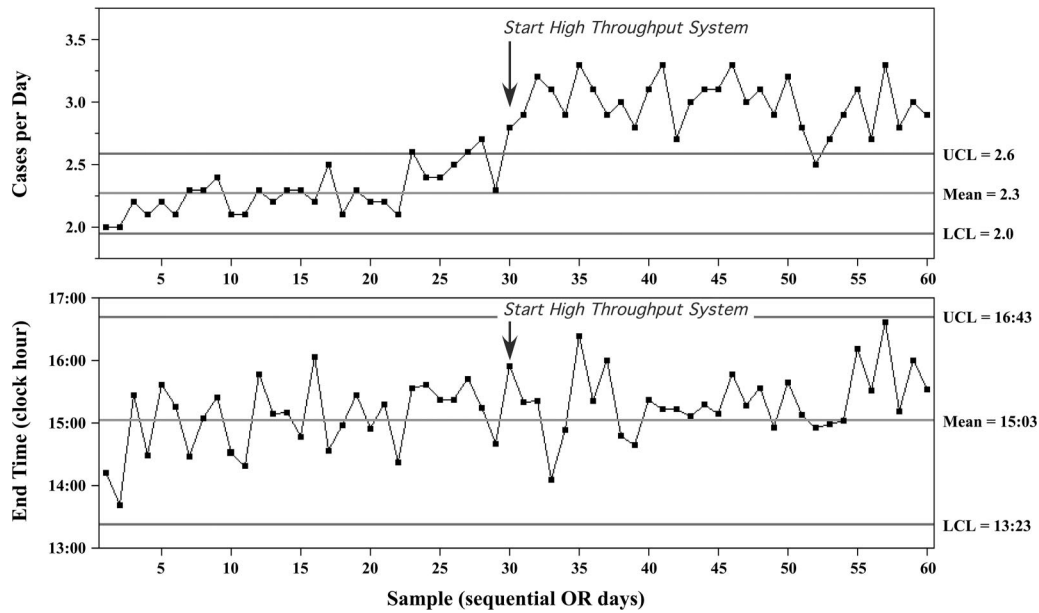


Fig. 3. Control charts showing throughput (*upper panel*) and the average end time (*lower panel*) for 16 months before initiating the high-throughput perioperative system and then for the subsequent 2 yr. Time advances from left to right across the figure. Each data point is the average for a bin of 10 consecutive days in the data set. The upper control limit (UCL) and lower control limit (LCL) are 3 SDs above and below the mean denoted by the centerline. The UCL, LCL, and centerline are all derived from the complete historic control data set. The purpose of this figure is to compare the performance of the new process to that of the baseline (*i.e.*, historic) process. Therefore, it plots historic performance and high-throughput system performance over time, but the concurrent control data are omitted. OR = operating room.

proved by process redesign. We show that a parallel processing system applied to appropriate surgical cases can result in approximately 50% reduction in nonoperative time and a concomitant 12% reduction in operative time, allowing the completion of additional procedures in the same-staffed interval. We showed that this is possible without extensive physical space redesign and capital investment.

Comparison with Previously Reported Work

Dexter *et al.*²⁰ have shown that on the day of surgery, efficiency of use of OR time condenses to making decisions that minimize overutilized time. However, as pointed out above, efficiency is not synonymous with throughput. Increasing throughput either to accommodate additional patients without increasing OR hours or

to reduce surgeon waiting time between cases is a strategic goal that several hospitals have pursued.^{1-8,11} Each of these exercises achieved reductions on nonoperative time or one of its constituent intervals. Most demonstrated increases in throughput as a consequence of reduced between-case time.^{2,3,5-8} Only two groups, both from the same institution, have demonstrated significant throughput improvements from a single OR.^{5,6,8,14,21} These previous projects either used general anesthesia or local anesthesia administered without an anesthesia team; none had consistently used neuraxial regional anesthesia as the preferred method. Before our report, no investigators had attempted to increase throughput by reducing nonoperative time in cases with the equipment complexity entailed by total joint arthroplasty. Our report adds to knowledge in this field by demonstrating that parallel processing of nonoperative activities, using neuraxial regional anesthesia and by using selected additional personnel and facilities, reduces nonoperative time and increases OR throughput, even for cases with high technical complexity such as total joint arthroplasties.

Nonoperative Time

Focusing on isolated time intervals during the preoperative throughput process, such as turnover time and anesthesia controlled time, fails to emphasize that the rest of the entire perioperative team should play an active role even after the patient has been turned over to the surgeon. Our modified overlapping induction strat-

Table 6. The Western Electric Rules

Rule Number	Rule Description
1	One or more points outside of the control limits
2	Two of three consecutive points on the same side of the centerline, outside the 2-SD warning limits but still inside the control limits
3	Four of five consecutive points on the same side of the centerline, beyond the 1-SD limits
4	A run of eight consecutive points on one side of the centerline

Descriptions of the statistical process control rules used to identify performance changes associated with implementation of text page alerts and to monitor performance over time.

egy was designed so that all team members continually contribute to case throughput and so that surgeons can spend their time operating instead of waiting for the next case. That is also why we have focused on the nonoperative time. For example, because we were dealing with highly technically intensive surgical procedures, we included an additional surgical technician for setup and breakdown of the back table not in the OR.

Process Durability over Time

Many of the strategies reported to improve throughput are based on short trials of 6 months or less,^{1-4,7,8} which begs the question of the durability and resilience of these process designs. ORs across the country are familiar with projects that were successful at first and then lost momentum in the following months. Only one group has demonstrated sustained results (*i.e.*, improved throughput performance lasting longer than the period of the initial pilot).^{5,6,14,21} Our goal was to develop an enduring strategy, a goal mostly accomplished as seen from the 2-yr results presented in figures 2 and 3.

Added Costs

The process was designed to modify work flow, but also added low cost personnel to improve throughput. There were no physical plant modifications or modifications in surgical technique or equipment, although it did rely on the availability of an "induction room" near the high-throughput OR. Although there was increased salary cost, this was more than offset by increased productivity from the positive contribution of additional cases accommodated in the staffed interval, as indicated by the 19.6% improvement in contribution margin. Our surgeons frequently utilized a second OR during the control periods to handle the same case load. For example, during the historic control period, the same surgeons utilized *two* standard ORs to complete 2.9 ± 0.7 arthroplasty cases on 153 different days, compared with 3.0 ± 0.7 cases in *one* high-throughput OR. Our analysis ignores the benefit which accrues from saving the personnel required to staff this second OR and therefore represents a worst-case financial scenario.

Limitations of Our Report

This is a retrospective review of OR database systems; results should be interpreted with this in mind. It is possible that selection bias might have affected our results favorably. However, the patients and controls were selected based on previously identified time periods, and no patients were excluded from the analysis. It is also possible that the environment changed at the same time our high-efficiency project was begun. Our concurrent control group attempts to address this concern. As seen from table 5, the process outcomes from the concurrent controls did not differ substantively from the historic controls. We take this as a strong indication that opera-

tions outside the high-throughput system were not affected by major change.

Our observations are not fully applicable in an environment where parallel processing is maximally achieved even without the use of an induction area. Specifically, the anesthesiologist may bring the patient into the OR and administer anesthesia at any time once universal protocol for patient identification and procedure verification has been performed. Therefore, induction of anesthesia could be run in parallel with OR setup. This might be the case for both spinal anesthetics as well as other types of regional anesthetic blocks. It is our observation, however, that this rarely or inconsistently happens in either of our hospitals. Even if it did occur reliably, induction cannot take place until the OR is cleaned, which limits nonoperative time reduction.

Generalizability

Our observations were made in a large tertiary care center. Although they may not be applicable to "boutique" hospitals or ambulatory surgery centers, we believe they are reasonably representative of conditions in similar institutions. For example, only 6.4 h per day in added personnel cost was allocated to the high-efficiency OR because cases ended around 3:30 PM and the added personnel were not needed beyond the start of the last case. When not needed for the high-efficiency operation, these personnel resources, and their cost allocation, reverted to the general OR personnel pool. In smaller hospitals, work may not be available for these personnel, and therefore their entire 8-h per day cost would need to be allocated to the high-efficiency OR. If this is done and the cost of paid time off is included, the improvement in contribution margin decreases from 19.6% to 18.6%.

It is unlikely that our results can be readily transposed into other surgical populations. We did not use non-orthopedic controls, which limits the applicability of our observations to lower extremity joint arthroplasties or, at the most, to surgical procedures of 90–120 min in duration that can be performed with regional anesthesia. The imbalance in ASA PS points to the case selection process that may be necessary to achieve our results. Nevertheless, it is remarkable that fully 65% of the high-throughput patients were ASA PS III or IV. The capability of the redesigned parallel processing system to deal with such a substantial fraction of medically complex patients gives testimony of its resilience and flexibility for a wide spectrum of patients. It is likely that this characteristic of the system was imparted by the additional nursing personnel and emphasis on care continuity.

Conclusion

Our modified parallel processing operating suite for lower extremity joint arthroplasty resulted in greater

throughput as measured by nonoperative procedure time and ability to complete an additional case within regularly staffed work hours. Nonoperative time, as well as surgical procedure time, decreased substantially compared with historic controls and concurrent controls. With relatively little additional cost, hospitals can improve OR and financial performance using a parallel processing, high-throughput approach such as the one we describe.

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