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Development of a patient and institutional-based model for estimation of operative times for robot-assisted radical cystectomy: results from the International Robotic Cystectomy Consortium

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Objectives

To design a methodology to predict operative times for robot-assisted radical cystectomy (RARC) based on variation in institutional, patient, and disease characteristics to help in operating room scheduling and quality control.

Patients and Methods

The model included preoperative variables and therefore can be used for prediction of surgical times: institutional volume, age, gender, body mass index, American Society of Anesthesiologists score, history of prior surgery and radiation, clinical stage, neoadjuvant chemotherapy, type, technique of diversion, and the extent of lymph node dissection. A conditional inference tree method was used to fit a binary decision tree predicting operative time. Permutation tests were performed to determine the variables having the strongest association with surgical time. The data were split at the value of this variable resulting in the largest difference in means for the surgical time across the split. This process was repeated recursively on the resultant data sets until the permutation tests showed no significant association with operative time.

Results

In all, 2 134 procedures were included. The variable most strongly associated with surgical time was type of diversion, with ileal conduits being 70 min shorter ($P < 0.001$). Amongst patients who received neobladders, the type of lymph node dissection was also strongly associated with surgical time. Amongst ileal conduit patients, institutional surgeon volume (>66 RARCs) was important, with those with a higher volume being 55 min shorter ($P < 0.001$). The regression tree output was in the form of box plots that show the median and ranges of surgical times according to the patient, disease, and institutional characteristics.

Conclusion

We developed a method to estimate operative times for RARC based on patient, disease, and institutional metrics that can help operating room scheduling for RARC.

Keywords

robot-assisted, cystectomy, operative time, quality control, scheduling

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Introduction

The operating room (OR) is considered to be one of the most costly functional areas within hospitals, as well as their major profit centre. It is known that managing an OR department is a challenging task, which requires the integration of many actors (e.g., patients, surgeons, nurses, technicians), who may have conflicting interests and priorities. Considering these aspects, the present study focuses on developing a methodology for scheduling ORs that reflects the complexity and variability associated with surgery.

Radical cystectomy (RC) with urinary diversion is a complex surgery associated with significant morbidity and cost [1]. RCs performed with robot-assistance has grown dramatically (<1–13%) between 2004 and 2010 [2]. Despite the benefits of robot-assisted RC (RARC), in terms of perioperative outcomes such as blood loss, hospital stay and recovery, it has been criticised for long operative times and the associated cost. Although RARC was associated with shorter hospital stay [$658 (American dollars) a day] when compared to open RC, it was also associated with significantly longer operative times ($1902 an hour). Continuous refinement of the technique and expertise may result in additional reductions of operative times and costs [3].

For RC, prolonged operative times have been associated with higher incidence of complications and perioperative mortality independent of the disease stage or associated comorbidities [4]. Additionally, longer operative times have been directly associated with increased healthcare costs, where each OR minute was found to add $15 to the overall hospital charges [5]. Not surprisingly, operative time has been identified as a quality measure for surgical performance for RARC [6,7].

Scheduling OR time for RARC is a challenging task owing to the complexity and reconstructive nature of the procedure. Patients have multiple confounding factors that contribute to variation in operative time for RARC, including patient demographics and comorbidities, disease stage, procedural complexity, technical modifications, surgeon experience, and hospital volume [8]. In this context, we sought to develop a statistical model that incorporates different preoperative data, including patient, disease, surgical and institutional variables, to estimate operative times for RARC at the individual patient level.

Patients and Methods

A retrospective review of 2 685 RARCs, performed at 27 institutions from 11 countries included in the International Robotic Cystectomy Consortium (IRCC) database (I-97906), was performed. For prediction of operative time (from incision to wound closure), we included all the relevant patient, disease, technical and institutional variables that can be assessed preoperatively and therefore can be included in a predictive model. Patient factors included: age, gender, body mass index (BMI), the American Society of Anesthesiologists (ASA) score, and prior history of abdominal surgery or irradiation. Disease factors included preoperative clinical staging. Technical factors included: the receipt of neoadjuvant chemotherapy, planned type and technique of diversion, and extent of pelvic lymph node dissection (PLND). The overall RARC surgeon and institutional volumes were also included in the model.

Descriptive statistics were used to summarise the data. A conditional inference tree method was used to fit a binary decision tree predicting the distribution of operative times. Permutation tests were performed to determine the variable having the strongest association with RARC surgical time. The data were split at the value of this variable, resulting in the largest difference in means for the surgical time across the split. This process was repeated recursively on the resultant data sets until the permutation tests showed no significant association between any of the explanatory variables and operative time. The resulting data sets are known as terminal 'Nodes' or 'Leaves'.

The output of the software package was in the form of box plots depicting the median, interquartile range (IQR), the minimum and the maximum duration of operative times within each terminal Node. Operative times are generally known to be lognormally distributed [9]. Within each terminal Node a lognormal model was also fit to the operative times of patients included in the Node. This lognormal model fit allows any quantity associated with the distribution of operative times to be estimated.

All tests were two-sided, with statistical significance defined as $P < 0.05$. All statistical analyses were performed using R software (version 3.2, R Core Team, 2016) [10,11].

Results

The final analysis comprised 2 134 RARCs (Table 1). The mean (SD) age was 67 (10) years and 74% were males. In all, 16% had clinical extravesical disease, 20% received neoadjuvant chemotherapy, with 67% receiving ileal conduits and 69% having an intracorporeal diversion. The median (IQR) operative time was 364 (300–446) min. In all, 56% had extended, 35% had standard PLND, and 39% of the patients had ≥20 lymph nodes (LNs) on the final pathology (Table 1). There was a trend towards shorter operative times for RARC, decreasing from a mean of 371 min in 2006 to 323 min in 2015 ($P = 0.052$; Fig. 1).

The variable most strongly associated with surgical time was the type of diversion and it resulted in the largest mean difference, with ileal conduit surgery being 70 min shorter than that for neobladders ($P < 0.001$). Amongst patients who received neobladders, the extent of the PLND was the most

Table 1 Perioperative outcomes of 2 135 patients who received RARC.

Variable	Value
Number of patients, *n*	2 134
Preoperative characteristics	
Age at cystectomy, years, mean (SD)	67 (10)
Sex, males, *n* (%)	1 578 (74)
BMI, kg/m^2, mean (SD)	28 (5)
ASA score, mean (SD)	2.4 (0.7)
Prior abdominal/pelvic surgery, *n* (%)	580 (46)
NAC, *n* (%)	400 (20)
Clinical T stage ≥3, *n* (%)	302 (16)
Operative outcomes	
Type of diversion, Ileal conduit, *n* (%)	1 553 (78)
Location of diversion, Intracorporeal, *n* (%)	1 006 (69)
Operative time, min, median (IQR)	364 (300–447)
EBL, mL, median (IQR)	300 (200–500)
No PLND, *n* (%)	103 (9)
Limited PLND, *n* (%)	9 (1)
Standard PLND, *n* (%)	412 (35)
Extended PLND, *n* (%)	666 (57)
Pathological outcomes	
pT3/T4, *n* (%)	776 (39)
LNY, *n*, mean (SD)	18.4 (11)
LNY ≥20, *n* (%)	726 (39)
N1, *n* (%)	499 (23)
Positive soft tissue surgical margins, *n* (%)	144 (7)
Postoperative outcomes	
Adjuvant chemotherapy, *n* (%)	262 (16)
Hospital stay, days, median (IQR)	9 (6–13)
ICU stay, days, median (IQR)	1 (0–1)
Complications within 30 days, *n* (%)	559 (26)
Complications ≥ Clavien 3 within 30 days, *n* (%)	164 (8)
Complications within 90 days, *n* (%)	653 (31)
Complications ≥ Clavien 3 within 90 days, *n* (%)	202 (10)
Readmissions within 30 days, *n* (%)	115 (5)
Readmissions within 90 days, *n* (%)	197 (9)
Mortality within 30 days, *n* (%)	14 (1)
Mortality within 90 days, *n* (%)	51 (3)
Follow up, months, median (IQR)	12.4 (5–27)

NAC, neoadjuvant chemotherapy; LNY, lymph node yield.

strongly associated with RARC time. Extended or standard PLNDs were on average 26 min longer than limited or no PLND ($P < 0.001$). Whatever the extent of PLND, having a lower BMI was significantly associated with at least 33 min shorter operative time (Fig. 2).

Amongst patients who received ileal conduits, surgeons with an overall volume of ≥66 procedures had significantly shorter operative times (55 min shorter, $P < 0.001$). Also, irrespective of the surgeon volume, a lower BMI was significantly associated with shorter operative times ($P < 0.001$). For lower volume surgeons (<66 RARCs) and patients with a BMI of ≤30 kg/m^2, the extent of PLND further affected operative time (21 min longer in extended or standard PLND, $P < 0.001$). For patients who underwent standard or extended PLND, prior abdominal surgery and surgeon volume (41 RARCs) were also significantly associated with shorter operative times ($P < 0.001$; Fig. 2).

The longest estimated operative times were seen in patients who received neobladders and underwent limited or no PLND and with a BMI of >41 kg/m^2 [Node 5; median (IQR) 461 (390–571) min]. Conversely, the shortest estimated operative times were in patients who received ileal conduits, had BMIs of ≤30 kg/m^2, underwent standard or extended PLNDs, did not have any prior surgery, and their RARC was performed by surgeons with volume of 42–66 RARCs [Node 16: median (IQR) 284 (264–340) min; Fig. 2; Table 2].

The use of the binary decision tree is best illustrated with an example. Assume a urologist who has performed 50 RARCs had a patient whose BMI is 26 kg/m^2 and no prior abdominal surgery. The patient is to be scheduled for a RARC with an ileal conduit and an extended PLND. Starting at the top of the tree (Fig. 2), we proceed to the right due to the scheduled ileal conduit. Then, at Node 9 we proceed left due to the surgeon's volume of 50 RARCs. At Node 10, we proceed left due to the patient's BMI. At Node 11, we again proceed left due to the planned extended PLND. At Node 12, we proceed to the right because the patient has no history of abdominal surgery. Finally, we proceed right, again due to the surgeon experience, ending in Node 16. From Table 2 we can now see that similar surgeries had a mean (SD) operative time of 307 (60) min. Similarly the minimum, maximum, median and IQR for similar surgeries is readily available in Table 2.

Discussion

Bladder cancer is one of the most expensive cancers to manage [1,12]. Bearing this in mind, it is vital to explore the association between patient, disease, surgeon, and institutional factors with RC operative times. Within hospitals, ORs have been identified as the key financial component, where they contribute to >40% of hospitals' revenue [13]. On the other hand, costs associated with staffing and equipment makes OR utilisation very expensive, accounting for ~30% of the total hospital expenditure [14]. Late starting or finishing times and large time gaps between surgeries can lead to suboptimal OR utilisation. Consequently, attempts are made to optimise OR availability to maximise profitability, minimise expenditure (costs associated with staffing, especially the overtime cost), and limit under-utilisation.

Scheduling operative times can be done via various methods. Common strategies include: open (assigning an OR at the convenience of surgeons), block scheduling (surgeons are assigned time blocks into which they arrange their procedures), and modified block scheduling (some time is blocked and some is left open and any unused time can be released) [15]. The key to maximising OR utilisation is to determine the appropriate block time for each kind of surgery, considering the different variables that may affect it. Accurate estimates of operative times would facilitate scheduling, service planning, and maximise the utility of the OR. Historical data, such as the average time for the last 10 cases, average surgeon's list or surgeon's estimate have been

Fig. 1 Mean operative times for RARC between 2005 and 2015 ($P = 0.052$).

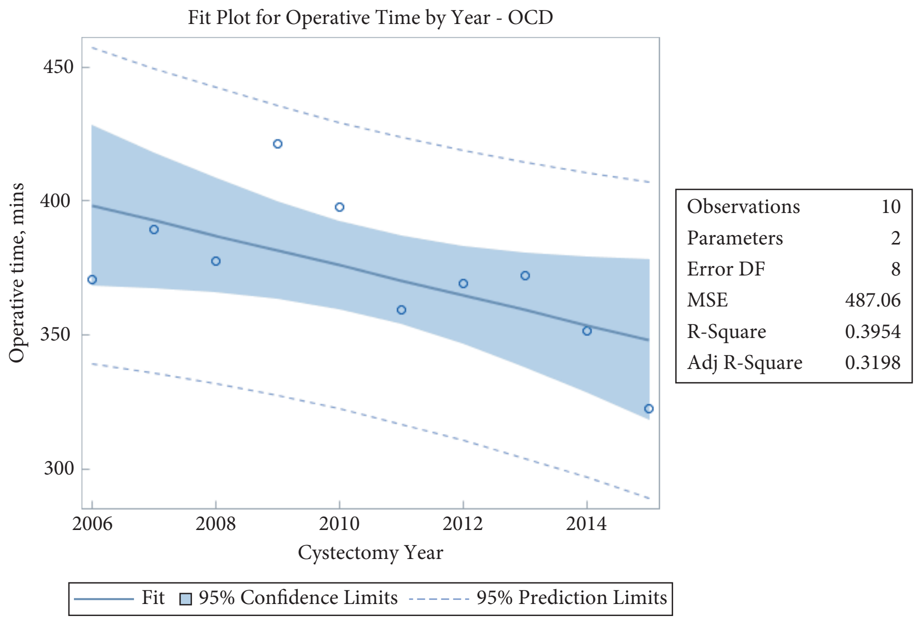
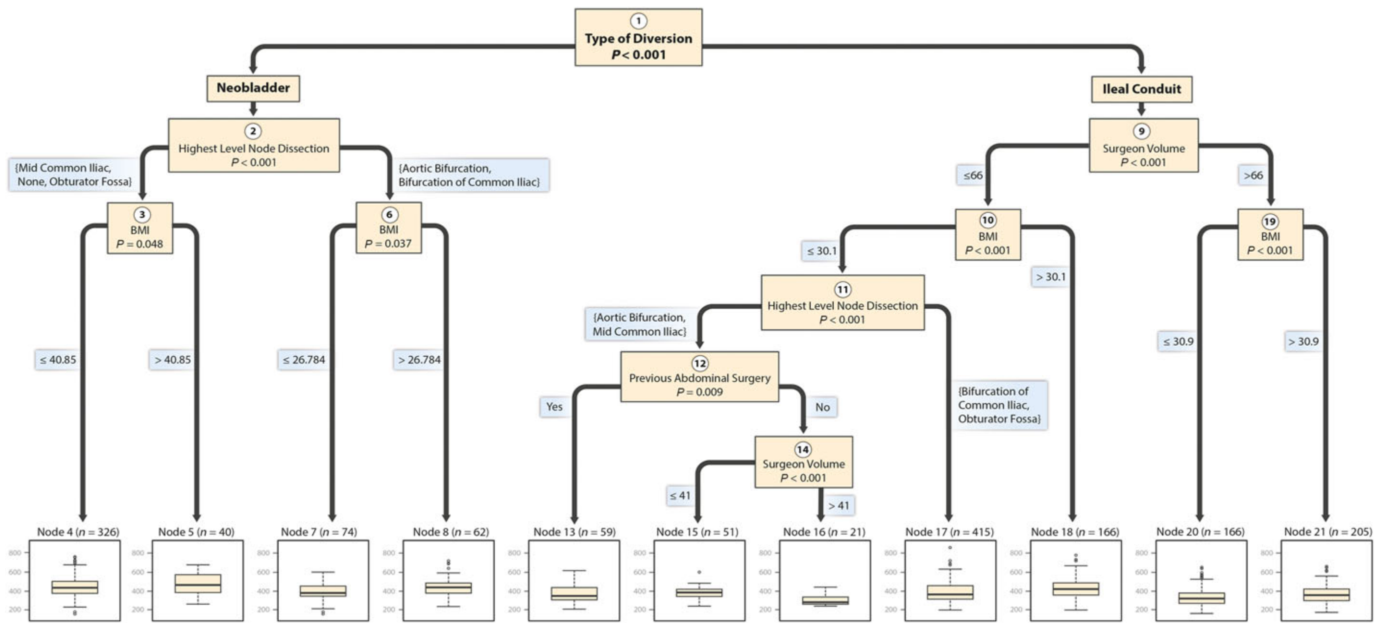


Fig. 2 Regression tree showing the outcome as box plots for each Node.



proposed as means for estimating scheduled operative times [16]. However, none of these methods have shown a reliable predictive validity [16]. Consequently, OR utilisation can be as low as 80% of the target, which has substantial financial implications [17]. Accurate prediction of OR times can be helpful in planning and anticipating issues, such as fluid load challenges and planning for intensive vs high-dependency bed requirement.

Surgery planning and scheduling offers unique challenges owing to the amount of associated uncertainty. It requires integration of multiple and variable factors, including patient, surgical team, disease, technical, surgeon, and institutional factors. Not only that, each patient is unique and therefore, even for the same procedure, the scheduled time for one patient may not be appropriate for another. Different statistical methods have been proposed, including linear

Table 2 Median, IQR, mean, SD and ranges for operative times for each Node.

Node	Patients at Node, *n*	Mean operative time, min	SD, min	Minimum operative time, min	Maximum operative time, min	Median operative time, min	25th percentile, min	75th percentile, min
4	326	438	114	157	760	434	375	501
5	40	471	114	260	680	461	390	571
7	74	390	93	159	600	375	345	448
8	62	446	100	240	720	444	375	495
13	59	379	99	210	618	350	308	435
15	51	384	63	240	600	389	342	417
16	21	307	60	239	440	284	264	340
17	415	390	108	200	862	370	313	457
18	166	430	108	200	780	420	360	490
20	715	332	89	159	827	318	270	378
21	205	371	100	172	830	360	300	420

regression, generalised linear, and intelligent-based models [9]. Selection of a model should be based on examination of the data distribution, where linear regression can be used in cases of normal distribution. Recently, there has been a trend towards incorporating intelligent-based models and data mining techniques, such as rough sets, artificial neural networks and fuzzy inference systems, to predict procedure times, despite initial unsatisfactory results [18]. We used a multi-level conditional inference tree model that can handle complex interactions between variables and determine the contribution of each variable at each level. Tree-based models have several advantageous features including: scalability to large numbers of explanatory variables and subjects, simplicity of model interpretation, and ease of use by the non-statistician. These models are also adept at fitting data that are far from normally distributed. Using this model we were able to estimate operative times at the individual patient level.

Filson et al. [8] examined the different factors that may contribute to operative times. They divided them into potentially modifiable (such as perioperative procedures, PLND, and diversion type and technique), non-modifiable patient factors (such as age and sex), and institutional and surgeon factors. Similar to our present study, they observed longer operative times with neobladders and with more extensive PLNDs. Older age and the number of comorbidities were significantly associated with shorter operative times [19]. Surgeons are usually concerned about the potential higher anaesthetic complications in older and sicker patients. Female patients were also found to have longer operative times (possibly because of performance of hysterectomy and vaginal reconstruction) [8]. This is in contrast to the present and prior studies [20]. BMI and prior abdominal surgery were significantly associated in our present study with operative times. Higher BMI and prior abdominal surgery add to the complexity of RARC, with more time spent in port placement, careful dissection, as well as PLND [19,21]. We did not find any difference between intracorporeal and extracorporeal diversion. One possible explanation is that the additional time for undocking, patient positioning and then re-docking for extracorporeal diversion may have reduced the difference between both approaches.

High-volume institutions had shorter operative times for RC. This may be attributed to the experience of the surgeon and the team at those institutions [8]. However, institutional volume was not significantly associated with operative time in our present study. This may be explained by the fact that the IRCC includes mainly high-volume institutions, which limits any conclusions drawn about the institutional volume. Other studies have shown a clear association with hospital type, where academic centres had longer operative times (~40 min longer). Academic centres involve postgraduate trainees (residents and fellows in anaesthesia and urology), and they are also more likely to perform extended PLNDs, intracorporeal diversion and neobladders [22]. In agreement with our present findings, a significant decrease in operative time was associated with higher surgeon volume [23,24]. The threshold for surgical proficiency for RARC is higher in our present study than previously reported (22 RARCs) [25]. In our present study, surgeons who had performed ≥66 RARCs saved an average of 55 min of operative time amongst patients who underwent ileal conduits [Node 10 (mean 396 min) vs Node 19 (mean 340 min), $P < 0.001$]. A surgeon volume of 44 RARCs resulted in a saving of 77 min on average for patients who underwent extended PLND [Node 15 (384 min) vs Node 16 (307 min), $P < 0.001$]. These thresholds have been objectively determined by the statistical model. This highlights the importance of fellowship training and dedicated cystectomy programmes, where surgeons can increase their RARC volume [26,27]. One interesting finding was that the longest operative time was seen for Node 5 (neobladder, with limited or no PLND and high BMI). It is the standard of care that PLND should be an integral part of cystectomy. If patients did not receive PLND, this was probably because of a lack of experience or an early learning curve for RARC, which may be reflected in the longer operative times.

Despite the uniqueness of the present study, several limitations exist. The retrospective study design has its recognised limitations. Any surgical procedure typically involves three stages: pre-surgery, surgery, and post-surgery. The actual procedural duration (time elapsed from incision to wound closure) is the amount of time during which surgery occurs and corresponds to the defined Current Procedure Terminology (CPT) codes. Most databases do not account for non-operative times that include delays in patient arrival, times related to anaesthesia induction, patient discharge, and turnover times (cleaning and preparing the OR for the next patient). Although the actual operative time would probably be shorter than the overall OR time, a reliable OR schedule can only be achieved when accurate estimates about the time needed to perform the surgery are available [28]. Otherwise, operations that take significantly longer or shorter than predicted will increase the chance of OR underutilisation. We believe that some variability between scheduled and actual procedures cannot be avoided, especially those arising due to unexpected intraoperative findings. Another limitation of our present study was the inability to account for the heterogeneity of teams and ORs due to the multi-institutional nature of the IRCC database.

Conclusion

We developed a methodology, utilising a large database, to estimate operative times for RARC based on patient, disease, and institutional metrics that can be used to facilitate OR scheduling for RARC.

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Conflicts of Interest

Jihad Kaouk, speaker for Healthtronics and device testing consultant for Intuitive Surgical. Carl J. Wijburg, Proctor for Intuitive Surgical. Alexandre Mottrie, Proctor for Intuitive Surgical. Peter Wiklund, Research grant from Intuitive Surgical.

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Abbreviations: (RA)RC, (robot-assisted) radical cystectomy; ASA, American Society of Anesthesiologists; BMI, body mass index; IQR, interquartile range; IRCC, International Robotic Cystectomy Consortium; LN, lymph node; OR, operating room; PLND, pelvic lymph node dissection.