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Simulation with Monte Carlo methods to focus quality improvement efforts on interventions with the greatest potential for reducing PACU length of stay: a cross-sectional observational study

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ABSTRACT

Background Time and money are limited resources to pursue quality improvement (QI) goals. Computer simulation using Monte Carlo methods may help focus resources towards the most efficacious interventions to pursue.

Methods This observational, cross-sectional study analysed the length of stay (LOS) for adult American Society of Anesthesiologists (ASA) 1–3 patients in the postanesthesia care unit (PACU) at a major academic medical centre. Data were collected retrospectively from 1 April 2023 to 31 March 2024. Statistical analysis with Monte Carlo methods simulated the per cent reduction in PACU LOS following the elimination of postoperative nausea and vomiting (PONV), hypothermia (initial temperature < 36°C), severe pain (pain score ≥ 7) or moderate opioid use (≥ 50 mcg fentanyl or ≥ 0.4 mg hydromorphone).

Results The PACU LOS of 7345 patients were included in this study. PONV was experienced by 10.29% of patients and was associated with a mean PACU LOS of 96.64 min (±33.98 min). Hypothermia was the least frequent complication, experienced by 8.93% of patients and was associated with a mean PACU LOS of 83.55 min (±35.99 min). Severe pain and moderate opioid use were seen in 34.05% and 40.83% of patients, respectively and were associated with PACU LOS that were shorter than those experienced by patients with PONV. Monte Carlo simulations demonstrated that the greatest impact on PACU LOS (12.5% (95% CI 12.0% to 13.0%)) would result from the elimination of moderate opioid use.

Discussion Although PONV was associated with the longest PACU LOS, statistical simulation with Monte Carlo methods demonstrated the greatest per cent reduction in PACU LOS would result from the elimination of moderate opioid use, thus indicating the most efficacious project to pursue.

Conclusion Statistical simulation with Monte Carlo methods can help guide QI teams to the most efficacious project or intervention to pursue.

BACKGROUND

Health centres are required to continuously evaluate the care they provide and identify areas for improvement.¹ The innumerable

WHAT IS ALREADY KNOWN ON THIS TOPIC

⇒ Postoperative complications such as postoperative nausea and vomiting, hypothermia, severe pain and opioid use are known to increase postanesthesia care unit (PACU) length of stay (LOS). However, it is difficult to identify which interventions would have the greatest impact on PACU LOS, if eliminated or reduced.

WHAT THIS STUDY ADDS

⇒ This study applies Monte Carlo simulation to determine which complication, when eliminated or reduced, would result in the greatest decrease in PACU LOS. This study highlights that not all factors contributing to prolonged PACU LOS have equal impact, providing a data-driven approach for resource allocation in quality improvement (QI) projects.

HOW THIS STUDY MIGHT AFFECT RESEARCH, PRACTICE OR POLICY

⇒ This study stimulates further research exploring whether Monte Carlo methods have sustained effects on QI efforts whether time or money is saved by employing these methods and if policies can be implemented more quickly in response to these simulations.



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data points that narrate a patient's care from preoperative optimisation to postoperative discharge all serve as potential quality improvement (QI) initiatives that can be formally pursued as individual projects. However, it is difficult to critically evaluate which interventions merit the investment of limited resources. For example, there are several complications that could potentially delay a patient's discharge from the postanesthesia care unit (PACU). Although each PACU complication can be characterised by an incidence and relative impact on a patient's length of stay (LOS), it is difficult to determine which intervention is most worthy to target just by reviewing these data.

Computer simulation with Monte Carlo methods may assist in identifying the most efficacious intervention to pursue.

Monte Carlo simulations are used in various fields (finance, business, medicine, etc) to assess risk or quantify the likelihood of various outcomes such as exceeding a budget or predicting the impact of labour costs. With respect to perioperative care, prior investigators have used the Monte Carlo simulation to quantify the impact of eliminating administrative delays on PACU LOS.² Dexter *et al* created data sets based on the probability that a patient would experience a prolonged PACU LOS for administrative reasons such as the ability to transfer a patient to a regular hospital room. Using the distribution parameters (mean and SD) of the data set and the incidence of the problem, Monte Carlo methods were used to simulate the impact of eliminating administrative delays. This simulation was then repeated 100 000 times to maximise confidence in the results. Because this modelling demonstrated that eliminating administrative delays would reduce PACU LOS by only 4.54% (95% CI 4.34% to 4.74%), the authors determined that this was not a problem worth pursuing.

Computer simulation using Monte Carlo methods requires two data sets describing an outcome (PACU LOS, for example) where one data set includes patients who experienced a complication (administrative delay, for example) and the other data set does not. Based on these data and the incidence of the complication, the computer simulates the outcome for each patient. Simulations are repeated at least 10 000 times to increase statistical confidence in the results. For QI projects using this method, the effect is usually described as a per cent improvement in the outcome.

Other recent studies investigating opportunities to decrease PACU LOS have proposed complex predictive algorithms.^{3,4} These algorithms are difficult to construct and may also be difficult to comprehend. Consequently, they may not serve as useful tools for physicians without substantial background knowledge in statistics or informatics. In contrast, Monte Carlo computer simulations may allow faculty leaders or residents to evaluate multiple potential interventions and focus their efforts on those likely to be the most efficacious. This study illustrates how to construct and complete Monte Carlo simulations designed to select the most efficacious intervention among multiple options to reduce PACU LOS at a major academic medical centre.

METHODS

Study design and setting

This study followed a cross-sectional, observational design. No funding was acquired.

Inclusion criteria

The study population included patients aged 18 years or older of ASA classification 1–3 who had undergone

surgical or non-surgical procedures requiring either regional or general anaesthesia and recovery in the PACU between 1 April 2023 and 31 March 2024.

Exclusion criteria

Patients were excluded if PACU LOS times were less than 15 min or greater than 180 min.

Definitions

Postoperative nausea and vomiting (PONV) were defined as the administration of ondansetron, Compazine or prochlorperazine while in the PACU. Hypothermia was defined as an initial skin temperature reading of less than 36°C on patient presentation to the PACU. Severe pain was defined as an initial pain score greater than or equal to 7 out of 10 on patient presentation to the PACU. Moderate opioid use was defined as the total opioid dose in the PACU greater than or equal to 50 mcg of fentanyl or 0.4 mg of hydromorphone.

Data collection

The incidences of the following PACU complications were collected from the electronic medical record: PONV; hypothermia; severe pain; and moderate opioid use. The mean PACU LOS (in minutes) and SD for patients with and without each PACU complication were also collected. For simplicity, each PACU complication was analysed as an independent event. The data set for each PACU complication was made up of the same total patient population because every patient either did or did not have PONV, hypothermia, severe pain or moderate opioid use.

Primary outcomes

The primary outcomes for this study were the per cent reductions in PACU LOS for each of the complications studied if the incidence of the complication was reduced to zero. Sensitivity analyses examined the impact of reducing the incidence of each complication by 50%.

Statistical analysis plan

To perform the Monte Carlo simulation, two normally distributed data sets were created using the mean and SD for patients with and without each PACU complication. For simplicity, the assumption of normality was not tested. The incidence of each complication was used to create a binomial distribution indicating the absence or presence of the complication. Each simulation considered the following elements: The probability that each patient admitted to the PACU will have the complication, the time that each patient is expected to stay in the PACU with that complication and the per cent reduction in PACU LOS if the complication was not present. Each simulation was repeated 10 000 times. We determined that a per cent reduction in PACU LOS would lead to the most interpretable results with a 10% or greater reduction in PACU LOS being clinically meaningful. The per cent reduction in PACU LOS was calculated using the following expression:

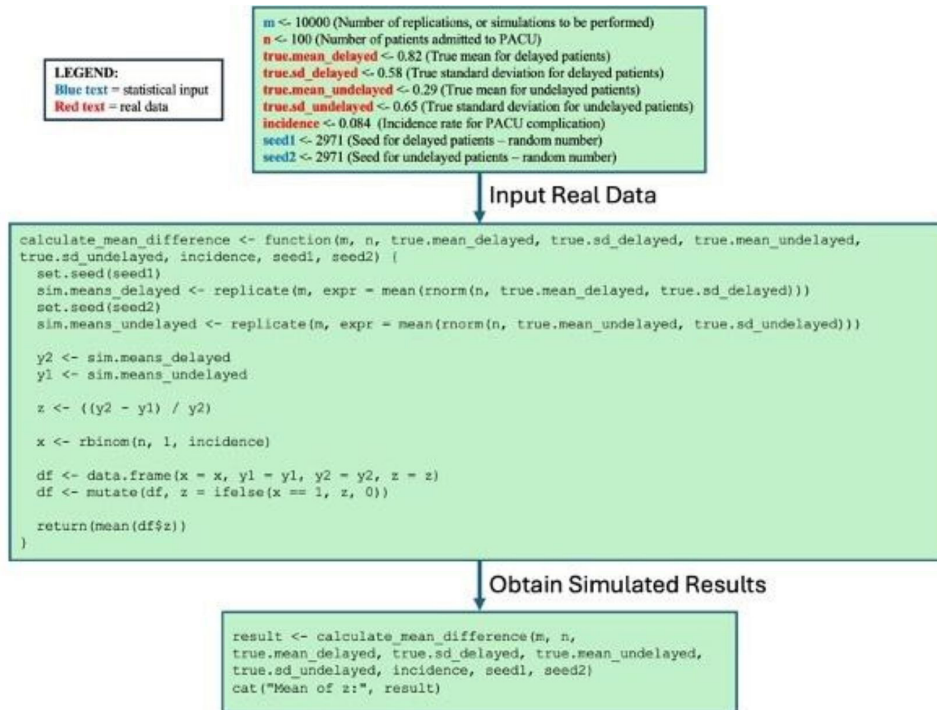


Figure 1 Statistics code for the simulated impact of eliminating a PACU complication. PACU, postanaesthesia care unit.

$$\frac{(\text{mean LOS with complication} - \text{mean LOS without complication})}{\text{mean LOS without complication}} \quad (1)$$

The 95% CI was calculated with the following expression:

$$2 * 1.96 * \text{standard deviation} / \sqrt{\text{number of replications}} \quad (2)$$

All statistical analyses were conducted with RStudio. This is free software that readers can download.⁵ (To obtain the software, one must first download the ‘R installer’ followed by ‘RStudio’ from the following website: <https://posit.co/download/rstudio-desktop/#download>.) Figure 1 displays the codes used for the Monte Carlo simulations.

RESULTS

A total of 9208 patients were screened for inclusion. Eligibility criteria was not met in 1735 cases and another 128 were excluded due to insufficient data (missing timestamps, for example). The entire data set included 7345

patients with a PACU LOS, on average, of 77.73 min (SD 34.98 min).

All PACU complications considered for this study were associated with prolonged LOS. PONV was present in 10.29% of patients and was associated with a mean PACU LOS of 96.64 min (±33.98 min). Hypothermia was the least frequent complication, experienced by 8.93% of patients but was still associated with a mean PACU LOS of 83.55 min (±35.99 min). Severe pain and moderate opioid use were seen in 34.05% and 40.83% of patients, respectively and were associated with similar PACU LOS. Table 1 presents data for the total time that patients spent in the PACU with each of the studied complications.

Moderate opioid use was associated with the greatest difference (25.11 min) in PACU LOS when comparing patients with moderate opioid use to those who did not require moderate opioid use. PONV and severe pain were associated with similar differences in PACU LOS when comparing patients with PONV or severe pain to those

Complication	Incidence	PACU LOS*	
		With	Without
PONV	10.29%	96.64 (33.98)	75.56 (34.44)
Hypothermia	8.93%	83.55 (35.99)	77.05 (34.83)
Severe pain	34.05%	92.06 (34.11)	70.93 (32.92)
Moderate opioid use	40.83%	92.59 (32.38)	67.48 (32.98)

*Data are mean (SD) for patients with or without the associated complication (PONV, hypothermia, severe pain or moderate opioid use). LOS, length of stay; PACU, postanaesthesia care unit; PONV, postoperative nausea and vomiting.



Table 2 Simulated reduction in PACU LOS with elimination of each complication

Complication	Simulated reduction in PACU LOS*
PONV	1.75% (1.52% to 1.98%)
Hypothermia	0.624% (0.541% to 0.707%)
Severe pain	8.04% (7.61% to 8.47%)
Moderate opioid use	12.5% (12.0% to 13.0%)

*Data are mean per cent decrease (95% CI).
LOS, length of stay; PACU, postanesthesia care unit; PONV, postoperative nausea and vomiting.

who did not experience PONV or severe pain at 21.08 min and 21.13 min, respectively. However, despite these similar absolute reductions in PACU LOS, there were marked differences in the simulated reductions in PACU LOS for patients with PONV compared with those with severe pain. While the elimination of severe pain yielded a simulated reduction in PACU LOS of 8.04% (95% CI 7.61% to 8.47%), the elimination of PONV yielded a simulated reduction in PACU LOS of only 1.75% (95% CI 1.52% to 1.98%). Table 2 presents simulated predicted reductions in PACU LOS for complete elimination of each complication.

A 10% reduction in PACU LOS was considered clinically meaningful and suggestive of an intervention that should be pursued. The data indicate that restricting opioid use to less than 50 mcg fentanyl or 0.4 mg hydromorphone has the greatest potential for reducing PACU LOS and should, therefore, be the focus of future QI efforts.

Sensitivity analyses

All primary analyses assumed that the planned QI project would completely eliminate each PACU complication such that the incidence of PONV, for example, would decrease from 10.29% to 0%. Because the complete elimination of a PACU complication may not be realistic, secondary analyses tested the impact of a 50% reduction in the incidence of each PACU complication. A 50% reduction in the incidence of moderate opioid use again led to the greatest predicted potential reduction in PACU LOS (4.89% with 95% CI 4.48% to 5.3%) but this was not considered to be clinically meaningful (< 10% simulated reduction in PACU LOS).

DISCUSSION

Tools are needed to help guide QI initiatives so that limited resources can be dedicated to the most efficacious interventions. Monte Carlo simulation is a statistical tool that can be used to model possible outcomes in a process that can be impacted by multiple random variables. Dexter *et al* used Monte Carlo computer simulation to answer a specific question: What impact will eliminating administrative delays have on PACU LOS? In the current study, we demonstrated how to expand on the

methods used by Dexter *et al* and identify which intervention among several potential opportunities would be the most efficacious in pursuit of decreasing PACU LOS.

Of the complications that were reviewed, moderate opioid use was the most frequent followed by severe pain, PONV and finally hypothermia. However, the incidences of these complications provide insufficient support to direct limited resources toward their solutions. Based on Monte Carlo simulations, the greatest potential impact on PACU LOS was noted to be (in descending order) in patients with the following complications: Moderate opioid use, severe pain, PONV and hypothermia. Moderate opioid use was the most common PACU complication and was associated with the greatest difference in PACU LOS. However, the relative difference in PACU LOS among patients with the complication compared with those without the complication must be simultaneously considered along with its incidence, to calculate the expected reduction in PACU LOS if that problem was eliminated. There is no simple equation that allows us to predict this. Because of the impact of multiple random variables, the relative impact of a complication can only be projected with computer simulations. With the help of Monte Carlo methods, the expected reduction in PACU LOS from eliminating moderate opioid use was predicted to be 12.5%, thus providing justification to address this problem.

Patients with PONV remained in the PACU, on average, for the greatest amount of time. A QI team may erroneously choose to target decreasing PONV to reduce PACU LOS. However, Monte Carlo simulations demonstrate that eliminating PONV would only decrease PACU LOS by 1.75% or approximately 1.36 min which is not clinically meaningful and substantially less than the expected reduction in PACU LOS from eliminating moderate opioid use (on average, 12.5% of 77.7 min or approximately 9.7 min).

As demonstrated in this study, Monte Carlo simulation can help identify projects that will have the greatest impact on QI goals. Unlike comparable QI studies investigating PACU LOS, our methods do not require complex statistical software or predictive algorithms.^{3 4} After installing free statistics software, the codes used for this study can be easily copied and pasted into RStudio and modified for any project.

The generalisability of Monte Carlo simulation is supported by its use in a variety of QI projects to study financial impacts, medication dosing and perioperative efficiency. The economic ramifications of hypotension and hypertension have been simulated with Monte Carlo methods as well as the financial savings associated with student-run health clinics.^{6 7} Moreover, Monte Carlo simulation methods have been used to identify the optimal parameters for paediatric patient-controlled analgesia delivery systems, the least amount of time necessary to perform preoperative nerve blocks and the most favourable surgical schedule for elective congenital heart surgery in paediatric patients.⁸⁻¹⁰

Monte Carlo simulation methods may assist in the sustainability of QI initiatives over the long term. Simulations can be performed at regular intervals (every 6 months, for example) to ensure that resources remain focused on the most efficacious intervention(s). For such longitudinal projects, the intervention may become dynamic (changing in response to the need at the time) to achieve the target outcome (30% decrease in PACU LOS, for example).

Limitations

Although patient characteristics such as age and comorbid conditions may affect PACU LOS and provide logical categories for additional analyses, results for patient groups were not the focus of this study and we sought, instead, to focus on PACU LOS for all adult patients. Therefore, patient-specific data were not collected. The analyses presented in this manuscript assume a normal distribution for PACU LOS and the incidence of the complications reviewed. This assumption is appropriate if the sample of patients is indeed representative of all patients admitted to the PACU. The analyses also assume that each PACU complication is independent such that treatment of pain, for example, does not lead to PONV which may be overly simplistic. Therefore, every patient was evaluated with respect to each PACU complication. Lastly, this analysis only considered the complete or partial elimination of each individual complication. Predictions of the impact of concurrent interventions on multiple complications were not considered.

Future research

Future research should focus on validating this approach for selecting the most efficacious QI projects to pursue using actual before/after comparisons. In addition, applications to other primary outcomes such as start time delays or surgical schedule overruns could be explored.

CONCLUSION

Statistical simulation with Monte Carlo methods simulated the greatest per cent reduction in PACU LOS would result from the elimination of moderate opioid use despite the fact that PONV was associated with the longest PACU LOS. This simulation methodology could similarly be applied to other QI opportunities providing guidance to the most efficacious projects to pursue.

Contributors JHJ is the guarantor. Both JHJ and NF have satisfied the following authorship criteria: Substantial contributions to the conception or design of the work; or the acquisition, analysis or interpretation of data for the work; AND Drafting the work or revising it critically for important intellectual content; AND Final

approval of the version to be published; AND Agreement to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved.

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Competing interests JHJ declares no conflicts of interest. NF has taken part in the following contracted research projects: Masimo, Edwards LifeSciences, Rostrum Medical Innovations, Tsumura Pharmaceuticals, Haisco Pharmaceuticals. NF has served as Speaker Honoraria for Edwards LifeSciences.

Patient and public involvement Patients and/or the public were not involved in the design, or conduct, or reporting, or dissemination plans of this research.

Patient consent for publication Not applicable.

Ethics approval The protocol used in this study was approved by the Institutional Review Board (IRB) at the University of North Carolina at Chapel Hill (IRB Number: 24-2250). The requirement for written informed consent was waived by the IRB.

Provenance and peer review Not commissioned; externally peer reviewed.

Data availability statement Data are available upon reasonable request.

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