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Investigation of Factors Associated with Excessive Residual Volume in Patient-Controlled Analgesia Pumps Under an Intelligent Closed-Loop Management Model

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Abstract: *Objective*: To analyze the causes of excessive residual volume (≥100 mL) upon removal of patient-controlled analgesia (PCA) pumps in patients undergoing lower abdominal surgery under an intelligent closed-loop management model, and to provide evidence for optimizing analgesic regimens and drug management. *Methods*: A retrospective survey was conducted among 292 eligible patients from September 2022 to August 2023. Data on departmental distribution, timing of pump removal, adverse reactions, and antiemetic addition were collected. *Results*: Among the 292 patients, gastrointestinal surgery accounted for 78.42%. Pump removal was concentrated on postoperative days 3–4 (51% combined). The most prevalent adverse reactions were poor sleep (28.42%), nausea (19.86%), and non-pain complaints (23.96%). Notably, 97.94% of PCA pumps were prescribed without antiemetics. *Conclusion*: Postoperative nausea and vomiting, non-pain discomfort, and sleep disturbances are key surface manifestations leading to premature pump discontinuation or clamping, resulting in residual drug volume. The insufficient addition of antiemetics and the urgent need for training in adverse reaction differentiation within the intelligent closed-loop management system require immediate attention.

Keywords: Intelligent closed-loop management; Patient-controlled analgesia pump; Residual volume; Postoperative nausea and vomiting; Lower abdominal surgery; Opioids

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1. Introduction

Postoperative pain is an acute pain that occurs immediately after surgery and is commonly observed in major procedures such as gastrointestinal and thoracic surgeries. If postoperative pain is not adequately controlled at the initial stage, it may progress to chronic postsurgical pain. The World Health Organization has

designated pain as the fifth vital sign, following blood pressure, pulse, respiration, and temperature; therefore, effective postoperative pain control is of critical clinical importance [1,2]. Patient-controlled analgesia (PCA) is currently recognized as one of the most effective modalities for alleviating postoperative pain [3]. PCA pumps typically contain opioids and adjuvant analgesics. However, over extended clinical use, a considerable number of PCA pumps have been found to retain excessive residual drug volumes upon removal. This not only leaves the underlying causes unclear and unresolved but also significantly increases the clinical burden associated with the management of residual opioids in the pumps.

The intelligent closed-loop management model operates through a continuous cycle of "decision, monitoring, and feedback", forming a closed-loop circuit that enables the identification and iterative resolution of clinical problems. Our hospital has implemented this model in postoperative pain management; however, in routine practice, we observed that some patients undergoing abdominal surgery still had substantial residual PCA volumes upon pump removal. To clarify the underlying reasons and to facilitate the rational configuration of PCA pumps and the provision of more appropriate analgesic regimens, this study analyzed the causes of excessive residual PCA volume (≥ 100 mL) within the framework of the intelligent closed-loop management model.

2. Materials and methods

2.1. General data

A retrospective survey was conducted. From September 1, 2022, to August 31, 2023, a total of 11,678 patients requiring postoperative PCA at our hospital were screened, and 292 patients met the inclusion criteria for this study.

2.1.1. Inclusion criteria

(1) Patients who returned to the general ward after surgery and used PCA pumps;
(2) Patients who underwent lower abdominal surgery;
(3) Patients with residual PCA volume ≥ 100 mL at pump removal;
(4) Patients using intravenous PCA pumps;
(5) Patients receiving hydromorphone as the sole opioid (no other psychoactive medications), with hydromorphone dosage ranging from 8 to 14 mg;
(6) Patients with body weight between 42 kg and 78 kg (i.e., within ± 30% of 60 kg).

2.1.2. Exclusion criteria

(1) Patients with American Society of Anesthesiologists (ASA) physical status class IV or V, or those transferred to the intensive care unit immediately after surgery;
(2) Patients using epidural or nerve-block PCA pumps.

2.2. Methods

2.2.1. Establishment of the PCA closed-loop management team

A PCA intelligent closed-loop management team was established by the Department of Anesthesiology, consisting of PCA round physicians (responsible for scoring adverse patient conditions), PCA management nurses (responsible for outcome analysis within the quality control module), anesthetic pharmacists

(responsible for anesthetic drug management), and engineers from the Renshi Intelligent System Management group (responsible for intelligent system maintenance). The team was responsible for the management and continuous improvement of the intelligent closed-loop model.

2.2.2. Survey instruments

A questionnaire was developed based on an extensive literature review of PCA, encompassing patient sex, age, weight, ASA classification, PCA pump status, general patient conditions, pain status, and adverse events. By logging into the REHN mobile ward-round application (Jiangsu Renshi Medical Technology Co., Ltd.) with designated credentials, data on adverse reactions and pain scores during PCA use were retrieved.

3. Results

3.1. Departmental distribution of the 292 lower-abdominal surgery patients

As shown in **Table 1**, among the 292 patients with residual volume ≥ 100 mL, gastrointestinal surgery accounted for the highest proportion, with 229 cases (78.42%), followed by biliary-pancreatic surgery with 32 cases (10.96%) and hepatic surgery with 29 cases (9.94%). Gastroenterology accounted for the lowest proportion, with 2 cases (0.68%). See **Table 1**.

Table 1. Departmental distribution of the 292 lower-abdominal surgery patients

Department	Number of cases	Percentage
Biliarypancreatic surgery	32	10.96
Hepatic surgery	29	9.94
Gastrointestinal surgery	229	78.42
Gastroenterology	2	0.68

3.2. Timing of PCA pump removal in the 292 lower-abdominal surgery patients

As shown in **Table 2**, among the timing distribution of pump removal, the largest number of patients had their pumps removed on postoperative day 4 (76 cases, 26.03%), followed by postoperative day 3 (72 cases, 24.66%), with the two combined accounting for 50.69% (approximately 51%). Pump removal on postoperative days 1 and 2 accounted for 19.52% combined. Only 8 cases (2.73%) never used the pump. Pump removal on postoperative day 5 and ≥ postoperative day 6 accounted for 27.06% combined. See **Table 2**.

Table 2. Timing of PCA pump removal in the 292 lower-abdominal surgery patients

Time point	Number of cases	Percentage
Not used	8	2.73
Postoperative day 1	10	3.42
Postoperative day 2	47	16.10
Postoperative day 3	72	24.66
Postoperative day 4	76	26.03
Postoperative day 5	32	10.96
≥ Postoperative day 6	47	16.10

3.3. Analysis of reasons for PCA pump removal in the 292 lower-abdominal surgery patients

As shown in **Table 3**, among the 292 patients with residual volume ≥ 100 mL, the most prevalent adverse reaction was poor sleep (83 cases, 28.42%), followed by nausea (58 cases, 19.86%). Non-pain-related complaints (non-resting pain: 38 cases + non-activity pain: 32 cases) totaled 70 cases, accounting for 23.96%. Vomiting (30 cases, 10.27%) and dizziness (28 cases, 9.59%) also accounted for a considerable proportion. Sedation (3.4%), abdominal distension (1.4%), and pruritus (0.3%) had relatively low incidence rates. Foreign body sensation in limbs and limb weakness were both 0 cases.

Table 3. Analysis of reasons for PCA pump removal in the 292 lower-abdominal surgery patients

Adverse reaction	Number of cases	Percentage
Nonresting pain	38	13.01
Nonactivity pain	32	10.95
Sedation	10	3.40
Poor sleep	83	28.42
Pruritus	1	0.30
Nausea	58	19.86
Vomiting	30	10.27
Dizziness	28	9.59
Abdominal distension	4	1.40
Foreign body sensation in limbs	0	0.00
Limb weakness	0	0.00

3.4. Proportion of antiemetic addition in PCA pumps among the 292 patients

As shown in **Table 4**, among all 292 patients, only 6 cases (2.06%) had antiemetics added to their PCA pump formulations, while 286 cases (97.94%) were prescribed without antiemetics.

Table 4. Proportion of antiemetic addition in PCA pumps among the 292 patients

Antiemetic addition	Number of cases	Percentage
Added	6	2.06
Not added	286	97.94

4. Discussion

This study found that, under the intelligent closed-loop management model, gastrointestinal surgery accounted for as high as 78.42% of lower-abdominal surgery patients. This may be related to the greater surgical trauma and more pronounced visceral referred pain associated with gastrointestinal procedures, resulting in higher analgesic demands. However, these patients are also more likely to discontinue PCA prematurely due to adverse reactions, making this cohort particularly suitable for the analysis of excessive residual volume.

From the timing of pump removal, most patients with residual volume ≥ 100 mL had their pumps removed between postoperative days 1 and 4, with days 3 and 4 combined accounting for 51%. This suggests that the early postoperative period, especially 48–96 hours, represents a critical window for PCA

management and a peak period for premature pump discontinuation due to adverse reactions. Patients who never used the pump accounted for only 2.73%, indicating that the vast majority of patients did press the PCA button at some point, and that excessive residual volume was more likely attributable to "premature discontinuation" rather than "complete non-use".

In terms of adverse reactions, non-pain-related complaints (non-resting pain 13.01% + non-activity pain 10.95%) accounted for a combined 23.96%. Combined with clinical pain follow-up observations, this may suggest that some patients have a higher pain tolerance threshold or that their actual analgesic needs were lower than anticipated. In addition, poor sleep accounted for 28.42%, which clinical observations suggest may be related to patients' self-clamping of the PCA line due to fear of adverse drug reactions, with pain or discomfort after clamping further interfering with sleep, forming a vicious cycle. The combined incidence of nausea (19.86%), vomiting (10.27%), and dizziness (9.59%) approached 40%. These symptoms are important triggers for medical staff to take clamping measures in clinical practice. According to our hospital's current clinical protocol, when patients present with the above adverse reactions, medical staff first clamp the PCA line to observe the patient's response and determine whether the symptoms are directly caused by the PCA pump. If symptoms resolve, the infusion may not be resumed, ultimately resulting in substantial residual drug volume upon pump removal.

It is noteworthy that the incidence rates of nausea, vomiting, and dizziness in this patient group were relatively high. Some of these reactions may be related to incomplete metabolism of opioids following general anesthesia, with residual anesthetic side effects; however, in actual clinical decision-making, medical staff may tend to directly attribute these symptoms to the opioids in the PCA pump and thus choose to clamp it. This difficulty in differential diagnosis may result in some patients, who could otherwise have had their symptoms alleviated through rate adjustment or addition of adjuvant medications, losing the opportunity for PCA analgesia prematurely. Furthermore, previous studies have confirmed that postoperative PCA use is an important risk factor for postoperative nausea and vomiting [4,5]. However, the present study found that the proportion of routine antiemetic addition in PCA prescriptions by anesthesiologists at our institution was extremely low (only 2.06%). Although whether the addition of antiemetics would significantly reduce the incidence of nausea and vomiting in this patient group cannot be directly confirmed in this descriptive study, this extremely low utilization rate at least suggests that prophylactic use of antiemetics has not received sufficient attention in clinical practice.

PCA is essentially a patient-driven analgesic modality, and the guidance and education provided by anesthesia medical staff to patients are particularly important, as they are the mainstay of pain management. Therefore, in the "feedback" and "improvement" phases of the intelligent closed-loop management model, we recommend incorporating the following elements:

(1) Strengthening the training of anesthesiologists to promote the selective addition of antiemetics in PCA pump formulations based on patients' PONV risk levels;
(2) Enhancing the ability of pain nursing staff to differentiate the attribution of adverse reactions, with assessment of whether to resume PCA use after symptom resolution following clamping, rather than immediate pump removal; and
(3) Strengthening anesthesiologists' assessment of patients' actual PCA needs during preoperative visits, for patients with low analgesic requirements, local anesthetics or non-opioid intravenous analgesics may be prioritized, which not only helps reduce medical waste but also decreases patients' healthcare expenditures.

5. Conclusion

Under our hospital's intelligent closed-loop management model, the superficial manifestation of excessive PCA residual volume in lower-abdominal surgery patients is primarily associated with postoperative nausea, vomiting, dizziness, and other opioid-related adverse reactions, as well as non-pain complaints and poor sleep leading to premature clamping. The current proportion of antiemetic addition in PCA pump formulations is extremely low, indicating that there is considerable room for optimization in the "decision" phase of the closed-loop management system. In the future, we should strengthen adverse reaction differentiation training and adjuvant medication decision support within the closed-loop management system, with the aim of reducing drug waste and improving analgesic safety.

Disclosure statement

The authors declare no conflict of interest.

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