Application of a Closed-Loop Quality Improvement System (CLQIS) Based on Specialty Nursing-Sensitive Indicators in Perioperative Care for PCI and Its Impact on MACE

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Date: 2026-01-31T11:03:07+00:00

Abstract

Objective To investigate the effects of constructing and implementing a closed-loop quality improvement system (CLQIS) based on specialty nursing-sensitive indicators on improving the quality of perioperative nursing care processes for percutaneous coronary intervention (PCI), enhancing patient safety outcomes, and reducing the risk of major adverse cardiovascular events (MACE). Methods A single-center, retrospective, before-and-after quasi-experimental design was adopted, in accordance with the SQUIRE 2.0 guidelines. The period from January to April 2025 was defined as the baseline phase, and from May to November 2025 the CLQIS intervention based on nursing-sensitive indicators (NSIs) was implemented. Data from the pre-intervention phase (January–April, n=432) were compared with those from the post-intervention phase (May–November, n=4033). The primary outcomes were the implementation rate of postoperative hydration and the qualified rate of finger exercise after transradial PCI. Secondary outcomes included the incidence of symptomatic contrast-induced nephropathy, puncture site complications, and patient satisfaction. Multivariate logistic regression was used to analyze the independent association between the intervention and MACE. This study was approved by the institutional ethics committee (Approval No.: KYLL-2025-0475) and met the criteria for waiver of informed consent. Results Compared with the pre-intervention phase, the implementation rate of postoperative hydration (77.12% vs. 87.85%) and the qualified rate of finger exercise (76.22% vs. 87.91%) were both significantly improved in the post-intervention phase (both $P<0.001$). Secondary outcomes improved concurrently: the incidence of symptomatic contrast-induced nephropathy decreased from 1.9% to 0.8% ($P=0.043$), the rate of severe puncture site complications decreased from 1.6% to 0.6% ($P=0.047$), and patient satisfaction increased significantly ($P<0.001$). Multivariate logistic regression analysis showed

that receiving the CLQIS intervention was an independent protective factor for reducing the risk of in-hospital MACE (adjusted OR=0.43, 95% CI: 0.34-0.54, P<0.001), with a number needed to treat (NNT) of 4. Conclusion The closed-loop quality improvement system constructed on the basis of specialty nursing-sensitive indicators can significantly enhance the quality of perioperative nursing processes for PCI, improve patient safety outcomes, and reduce the risk of MACE. It provides empirical evidence for the continuous improvement of PCI perioperative nursing quality and has clear clinical practical value.

Full Text

Impact of a Closed-Loop Quality Improvement System on MACE in PCI Perioperative Care Based on Nursing-Sensitive Indicators

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Abstract

Objective: To evaluate the effects of implementing a closed-loop quality improvement system (CLQIS) based on specialty nursing-sensitive indicators on the process quality of percutaneous coronary intervention (PCI) perioperative care, patient safety outcomes, and the risk of major adverse cardiovascular events (MACE).

Methods: A single-center, retrospective before-and-after quasi-experimental study was conducted following the SQUIRE 2.0 guidelines. The baseline period was from January to April 2025. The CLQIS intervention, guided by nursing-sensitive indicators (NSIs), was implemented from May to November 2025. Data from the pre-intervention period (Jan-Apr, n=432) were compared with those from the post-intervention period (May-Nov, n=4033). Primary outcomes were the compliance rate with postoperative hydration and the qualified rate of finger exercise after transradial PCI. Secondary outcomes included the incidence of symptomatic contrast-induced nephropathy, puncture site complications, and patient satisfaction. Multivariable logistic regression was employed to analyze the independent association between the intervention and in-hospital MACE. The study was approved by the Institutional Ethics Committee (Approval No.: KYLL-2025-0475) with waiver of informed consent.

Results: Compared with the pre-intervention period, the post-intervention period showed significant improvements in both the postoperative hydration

compliance rate (77.12% vs. 87.85%, P<0.001) and the finger exercise qualified rate (76.22% vs. 87.91%, P<0.001). Secondary outcomes also improved: the incidence of symptomatic contrast-induced nephropathy decreased from 1.9% to 0.8% (P=0.043), severe puncture site complications decreased from 1.6% to 0.6% (P=0.047), and patient satisfaction scores increased significantly (P<0.001). Multivariable logistic regression analysis revealed that receiving the CLQIS intervention was an independent protective factor against in-hospital MACE (adjusted odds ratio [OR] = 0.43, 95% confidence interval [CI]: 0.34-0.54, P<0.001), with a number needed to treat (NNT) of 4.

Conclusion: The closed-loop quality improvement system based on specialty nursing-sensitive indicators significantly enhanced the process quality of PCI perioperative care, improved patient safety outcomes, and reduced the risk of MACE. This study provides empirical evidence to support continuous quality improvement in PCI perioperative nursing, demonstrating considerable clinical utility.

Keywords: Nursing-Sensitive Indicators; Coronary Disease Nursing; Quality Management; Patient Safety; Continuous Quality Improvement

Introduction

Cardiovascular disease represents the leading cause of mortality and disability worldwide, posing severe challenges to clinical nursing due to its rapid progression and high complication rates [1,2]. In this context, nursing quality is directly linked to patient outcomes and safety. However, traditional nursing quality management models have predominantly focused on task completion—primarily verifying whether physician orders were executed and whether nursing procedures were performed on schedule—while lacking systematic analysis of how nursing interventions affect patient outcomes. More importantly, they lack systematic, objective quantitative tools to scientifically evaluate nursing process effectiveness, identify latent risks, and drive continuous quality improvement, which remains a core challenge in contemporary nursing management [3].

Nursing-Sensitive Indicators (NSIs), as a quantitative measurement system that specifically reflects nursing structure, process, and outcomes while being sensitive to changes in nursing interventions, provide a scientific pathway to address these challenges [4]. The conceptual foundation originates from Donabedian' s "Structure-Process-Outcome" quality theoretical model [5], enabling scientific measurement and continuous improvement of nursing quality through monitoring outcome indicators (e.g., falls, nosocomial infections) and process indicators (e.g., pain assessment, positioning management). International nursing quality research demonstrates that systematic NSI monitoring constitutes a core strategy for enhancing scientific nursing practice and ensuring patient safety [6,7], with a recent systematic review further confirming the association between structured NSI monitoring systems and improved patient clinical outcomes [8]. Meanwhile, the Closed-Loop Quality Improvement System (CLQIS) concept, through

its Plan-Do-Check-Act cycles, provides a systematic methodology for NSI implementation [24]. This model has been widely applied in critical areas such as medication safety and fall prevention, and is gradually penetrating specialized nursing fields. Recent explorations in cardiovascular nursing, particularly PCI perioperative management, have shown promise for CLQIS application; for example, Zhang et al. (2024) demonstrated that structured processes with real-time feedback can enhance compliance with nursing measures and improve patient safety outcomes [9].

In China, as high-quality nursing services advance, nursing administrators increasingly recognize the importance of NSIs. Jiang et al. (2023) systematically outlined key elements for constructing and applying nursing quality indicator systems, providing a theoretical framework for this study' s indicator development [5]. Wu's (2020) empirical research confirmed that systematic implementation of patient safety-centered basic nursing sensitive indicators can significantly improve nursing quality and patient satisfaction in cardiovascular wards [7], offering crucial practical evidence for NSI localization.

Currently, percutaneous coronary intervention (PCI) has become the cornerstone of coronary heart disease treatment. Surgical success and prognosis depend not only on precise interventional techniques but also on standardized implementation of evidence-based critical nursing measures during the perioperative period (e.g., prophylactic hydration for contrast-induced nephropathy prevention, systematic limb function exercises after radial artery puncture) [12,13]. These measures are fundamental to ensuring patient safety and improving prognosis. However, despite clear recommendations in international authoritative guidelines [14], poor compliance remains widespread in clinical practice, creating a significant "evidence-practice gap" [15]. Recent evidence suggests that using specialty nursing-sensitive indicators for quality monitoring and improvement represents a scientific approach to bridging this gap, with cardiovascular specialty NSIs significantly correlating with key outcomes such as readmission rates and complication incidence [16]. Concurrently, CLQIS applications in nursing safety are maturing, with a 2025 multicenter cohort study demonstrating that structured CLQIS can effectively improve compliance with PCI nursing measures [17].

Nevertheless, critical limitations persist in existing research: First, a highly specialized and operational NSI system for PCI perioperative care remains under construction, with domestic consensus and standards yet to be perfected [10]. Second, high-level empirical evidence integrating specialty NSIs into a data-driven, continuously iterative CLQIS and prospectively validating its impact on hard endpoints (such as MACE) remains scarce [18]. This knowledge gap restricts the precision, sustainability, and translational value of nursing quality improvement in specialized fields. Therefore, this study aims to construct a specialty nursing-sensitive indicator system applicable to PCI perioperative care, embed it within a closed-loop quality improvement system, and evaluate the system' s direct impact on nursing process quality, patient safety, and

MACE using real-world data. We seek to provide a measurable, operational, and outcome-oriented evidence-based management solution for enhancing PCI perioperative nursing quality.

Methods

This study comprised a two-phase design including theoretical construction and effectiveness validation. Phase 1 involved constructing a theoretical framework for PCI perioperative specialty nursing-sensitive indicators (NSIs) through a scoping review. Phase 2 was an effectiveness validation phase employing a single-center retrospective quasi-experimental design to evaluate the implementation effects of the CLQIS built upon this framework. The overall design, implementation, and reporting strictly adhered to the Standards for Quality Improvement Reporting Excellence (SQUIRE 2.0) guidelines [13]. The study flowchart is presented in [Figure 1: see original paper].

Phase 1: Scoping Review (Theoretical Construction)

Phase 1 utilized the Arksey and O' Malley framework for scoping reviews [14] to systematically search and synthesize domestic and international literature evidence regarding NSI construction, application, and evaluation in cardiovascular nursing. The objective was to establish a solid evidence-based foundation for this study and provide core indicators and a theoretical framework for subsequent CLQIS design. Literature searches covered PubMed, CINAHL, Embase, China National Knowledge Infrastructure (CNKI), and Wanfang Data from January 2020 to March 2025. The screening and analysis process followed PRISMA-ScR reporting guidelines.

Study Design

The main component of this study was a practice effectiveness analysis of a quality improvement project implemented in our hospital' s cardiovascular department in 2025. We employed a retrospective before-and-after study design, systematically comparing clinical data before intervention implementation (January-April 2025) with data after implementation (May-November 2025) to analyze the impact of the CLQIS model on core nursing process indicators and patient outcomes. This design is appropriate for evaluating complex interventions involving multi-level process and behavioral changes in dynamic clinical environments.

Methodological Considerations

To strengthen the argument, we explored the possibility of adding concurrent non-randomized controls during the design phase. Although not feasible due to constraints, we subsequently employed multivariate regression and interrupted time series analysis to partially control for confounding factors. The results of

this study aim to provide critical effect size estimates and implementation references for more rigorous trial designs (such as stepped-wedge cluster randomized controlled trials [16]) in the future.

Ethics Review

This study extracted data from historical clinical records of PCI patients stored in the hospital's electronic medical record system. To protect patient privacy, all personal identifiers were removed before analysis, and data were recoded with anonymous IDs. The study protocol was approved by the Ethics Committee of General Hospital of Ningxia Medical University (Approval No.: KYLL-2025-0475). As this was a retrospective analysis of anonymized historical data without direct patient intervention, it met the national regulations for waiver of informed consent [17], and the Ethics Committee approved the waiver application. The entire study process strictly adhered to the ethical principles established by the Declaration of Helsinki [18].

Study Setting and Timeframe

This single-center study utilized data from the Cardiovascular Department of General Hospital of Ningxia Medical University. Retrospective data collection spanned from January 1 to November 30, 2025. Based on the systematic implementation node of the intervention, January-April 2025 was defined as the pre-intervention period (baseline), and May-November 2025 as the post-intervention period.

Participants, Inclusion/Exclusion Criteria, and Sample Size

Participants were included if they met the following criteria: age $ $18 years, underwent PCI treatment at our hospital (regardless of procedure frequency), and had complete clinical records providing comprehensive perioperative nursing documentation, order execution details, and key laboratory results. Exclusion criteria included: (1) presence of other severe trauma or diseases requiring emergency surgery; (2) clear medical contraindications to postoperative hydration or functional exercise of the puncture-side limb after transradial PCI (e.g., acute heart failure, severe renal insufficiency with anuria, pre-existing limb dysfunction or severe hematoma); (3) hospital stay <24 hours or patient-requested early discharge.

As a retrospective quality improvement evaluation aiming to analyze intervention effects in real-world clinical settings, this study employed consecutive sampling ("all-inclusive" strategy). The sample size comprised all consecutive cases meeting inclusion criteria during the study period. A total of 4,562 patients underwent PCI during the study period, with 4,465 patients ultimately included for analysis after applying inclusion/exclusion criteria, yielding an overall inclusion rate of 97.9% (432 in pre-intervention period, 4,033 in post-intervention period).

To assess the adequacy of our sample size for detecting intervention effects, we conducted post-hoc power analysis using G*Power 3.1.9.7. Based on historical quality control data, we set the significance level at α=0.05 (two-tailed) and expected an absolute improvement of 20 percentage points in the primary process indicator (hydration compliance rate) post-intervention (from approximately 40% to 60%), corresponding to a Cohen' s h effect size of approximately 0.41. Under these conditions, comparing the pre-intervention (n=432) and post-intervention (n=4,033) groups yielded statistical power (1-β) >0.99, indicating that our study sample size provided extremely high statistical power to detect clinically meaningful intervention effects. Additionally, based on historical MACE incidence rates and expected reduction magnitude, the final sample size also met pre-estimated statistical requirements.

Data Sources, Collection Methods, and Quality Control

This study employed multi-source data triangulation to enhance validity and reliability. Specific sources and collection methods were integrated as follows:

1. **Primary Source:** Electronic Medical Record System. Structured data were directly exported from the hospital information system.
2. **Auxiliary Sources (for triangulation):**
    - **Standardized Field Observations:** Trained research nurses used pre-designed checklists to conduct bedside direct observations in no fewer than 20% of included cases to verify core indicator implementation (see Section 1.4.2 for details).
    - **Specialized Quality Monitoring Database:** Data were extracted from the department' s established specialty nursing quality monitoring ledger.
    - **Semi-Structured Interviews:** Interviews were conducted with selected nurses, patients, and family members to understand implementation barriers and acceptance.
3. **Patient Assessment Tools:** The Chinese version of the HCAHPS core scale was used for satisfaction surveys; the Visual Analogue Scale (VAS) was used for pain assessment.

To ensure data quality, the following control measures were implemented [25,21,22]: Electronic medical record data were collected using standardized forms with double-entry verification by two independent personnel; all assessment tools underwent reliability and validity testing; if the discrepancy rate exceeded 5%, the verification scope was expanded.

Literature Search and Integration

To construct the theoretical and practical foundation for this study, the research team systematically searched Chinese and English databases. English literature was searched in PubMed, CINAHL, and Embase; Chinese literature was searched in CNKI and Wanfang Data. The search timeframe was from

January 2020 to March 2025.

To ensure comprehensiveness and reproducibility, we developed structured search strategies. Taking PubMed (English database) and CNKI (Chinese database) as examples, specific search strategies are detailed in and ; detailed search formulas for other databases are provided in Supplementary Material S2.

Table 1 Example of PubMed Database (English) Search Strategy

Search Terms/Strategy	Details
Nursing-Sensitive Indicators	"nursing-sensitive indicators" [Mesh] OR "quality indicators, health care" [Mesh] OR "nursing sensitive indicator* "[tiab] OR" NSI" [tiab]
Cardiovascular/PCI Domain	"cardiovascular nursing" [Mesh] OR "cardiovascular disease* "[tiab] OR" percutaneous coronary intervention" [Mesh] OR "PCI" [tiab] OR "coronary intervention" [tiab]
Quality Improvement and Safety	"patient safety" [Mesh] OR "patient safet" *[tiab] OR "quality improvement" [Mesh] OR "quality improv*" [tiab] OR "quality management" [tiab]
Publication Date	"2020/01/01" [Date - Publication] : "2025/03/31" [Date - Publication]
Combined Search	#1 AND #2 AND #3 AND #4

Table 2 Example of CNKI Database (Chinese) Search Strategy

Search Terms/Strategy	Details
Nursing-Sensitive Indicators	SU= '护理敏感指标' OR SU= '质量指标' OR KY= '护理质量'
Cardiovascular/PCI Domain	SU= '心血管护理' OR SU= '冠状动脉介入术' OR KY= 'PCI'
Quality Improvement and Safety	SU= '患者安全' OR SU= '质量改进' OR KY= '护理质量改进'
Publication Date	January 1, 2020 - March 31, 2025 (via database date filter)
Combined Search	#1 AND #2 AND #3

To minimize publication bias, we supplemented database searches with gray literature and manual searches: (1) Key academic conference proceedings, such as the Chinese Nursing Association Cardiovascular Nursing Annual Conference; (2) Chinese Excellent Doctoral and Master' s Dissertations Full-text Database; (3) Manual browsing of recent three-year print and electronic tables of contents of core journals in this field, including *Chinese Journal of Nursing* and *Chinese Journal of Cardiology*. Through these supplementary searches, no additional studies meeting inclusion criteria were identified that were not already covered by database searches. Nevertheless, if unpublished gray literature exists (e.g., unpublished negative result reports), it may constitute a potential source of publication bias.

Literature screening strictly followed the PRISMA-ScR (Preferred Reporting Items for Systematic Reviews and Meta-Analyses extension for Scoping Reviews) reporting guidelines. Two researchers independently conducted literature screening. Inclusion and exclusion criteria were developed based on the PICOS framework:

- **Population:** Adult patients (age $ $18) with cardiovascular disease, particularly those undergoing PCI.
- **Concept:** Focused on NSI construction, validation, monitoring, or clinical application.
- **Context:** Cardiovascular inpatient settings or PCI perioperative care scenarios.
- **Study Design:** Systematic reviews, randomized controlled trials, observational studies (cohort, case-control, cross-sectional), quality improvement project reports, and relevant clinical practice guidelines and expert consensus.

Exclusion Criteria: Animal studies; non-Chinese/English publications; con-

ference abstracts, commentaries, or letters without accessible full text; clearly irrelevant content (e.g., non-nursing-led interventions, non-cardiovascular contexts); duplicate publications or overlapping data (only the most complete version was included).

The initial search yielded 312 articles. After deduplication, title/abstract screening, and full-text screening, 28 core articles were ultimately included, as shown in [Figure 2: see original paper]. The included literature comprised: 5 systematic reviews (17.9%), 4 randomized controlled trials (14.3%), 11 observational studies (39.3%), and 8 quality improvement project reports (28.6%). To evaluate the methodological quality and risk of bias of included evidence, two researchers independently applied standardized tools: Cochrane Risk of Bias tool (RoB 2) for randomized controlled trials; Newcastle-Ottawa Scale (NOS) for observational studies; AMSTAR-2 for systematic reviews; and Joanna Briggs Institute (JBI) Critical Appraisal Checklist for quality improvement reports. Discrepancies were resolved through discussion or consultation with a third researcher. Overall, among the 4 included randomized controlled trials, 2 had moderate risk of bias, primarily related to randomization and blinding; the median NOS score for 11 observational studies was 7 (IQR: 6-8), indicating acceptable overall quality; AMSTAR-2 ratings for 5 systematic reviews were mostly moderate to high. When constructing the theoretical framework and developing practical strategies, we prioritized recommendations from high-quality studies and guidelines with clear evidence grades, while cautiously referencing findings from methodologically limited studies. Detailed evaluation results are provided in Supplementary Material S3, providing a methodologically robust evidence base for this study' s theoretical framework construction.

Indicator Selection and Definition

Referencing the National Health Commission' s "Guiding Principles for Graded Nursing in General Hospitals (Trial)" [19] and relevant domestic and international specialty consensus [10,11,20], this study focused on two critical, evidence-based nursing processes during PCI perioperative care. A multidisciplinary nursing quality improvement team was established, comprising the cardiovascular ward head nurse, senior specialty nurses, cardiovascular interventional physicians, and nursing department quality control experts. Through group discussions and literature-based evidence [12,23], two specialty NSIs were selected and clearly defined:

1. **Post-PCI Hydration Compliance Rate:** The percentage of PCI patients without hydration contraindications (e.g., acute heart failure, severe renal insufficiency with anuria) who actually received standardized postoperative hydration during the monitoring period. Standardized hydration was defined as strict adherence to the department' s evidence-based "Post-PCI Hydration Protocol," covering hydration route (oral/intravenous), fluid type, infusion rate/fluid intake volume, and total duration.

2. **Qualified Rate of Finger Exercise After Transradial PCI:** The percentage of patients who could perform standardized, correct, and compliant finger functional exercises after transradial PCI among all patients undergoing transradial PCI without upper limb activity contraindications (e.g., severe hematoma, arteriovenous fistula, limb dysfunction) and with exercise capacity during the monitoring period. The operational definition of "qualified" required simultaneous fulfillment of: (1) Standardized movements (effective grasping, extension, and opposition exercises); (2) Achievement of frequency and duration standards (e.g., initiation immediately upon returning to the ward, completion of prescribed daily sets during hospitalization); (3) Patient/family mastery of key points and ability to demonstrate.

Monitoring Methods and Data Collection

To ensure objective and accurate data, this study employed a "three-pronged" data collection method (detailed methodological specifics in Section 1.3.3), integrating multi-source information including electronic medical record systems, standardized field observations, and specialized quality monitoring databases for continuous monitoring of the two core NSIs.

Specific monitoring operations for NSIs were as follows:

1. **Field Observation Audits:** Two uniformly trained researchers used specially designed checklists for "hydration compliance" and "finger exercise" to conduct bedside direct observations and recordings at critical postoperative timepoints (e.g., within 2 hours after returning to the ward, morning of postoperative day 1). Observations covered no fewer than 20% of the sample size (n=893 cases). Randomly selected 10% of observed cases (n=90 cases) underwent independent simultaneous observation, yielding an inter-rater reliability Cohen' s Kappa coefficient of 0.82.
2. **Systematic Data Extraction and Verification:** Based on clearly defined indicator algorithms, relevant order execution records and nursing documentation were automatically or semi-automatically extracted from the hospital electronic medical record system. Key variables (e.g., hydration orders, complication records) underwent double independent entry and verification in no fewer than 10% of cases (n=446 cases).
3. **Specialized Ledger Records:** The department' s established daily specialty nursing quality monitoring ledger, as the core carrier for recording daily indicator achievement, was jointly completed and confirmed by responsible nurses and quality control nurses.

Through synchronous collection and mutual verification of these multi-source data, we aimed to maximize the authenticity and reliability of NSI monitoring data.

Quality Improvement Strategies

In response to baseline issues, the multidisciplinary quality improvement team designed and implemented a multi-level comprehensive improvement strategy (detailed in). This strategy aimed to translate evidence-based knowledge into standardized practice, with its core logic following the Knowledge-to-Action (KTA) framework [30] and Plan-Do-Check-Act (PDCA) cycles [24], ultimately achieving continuous improvement through data-driven closed-loop feedback. The overall theoretical framework is illustrated in [Figure 3: see original paper].

Table 3 Description of Closed-Loop Quality Improvement System Intervention Measures Based on TIDieR Checklist

TIDieR Item	Description
1. Brief Name	NSI-Based Closed-Loop Quality Improvement System for PCI Perioperative Nursing
2. Rationale	Donabedian' s "Structure-Process-Outcome" quality model; Knowledge-to-Action (KTA) framework; PDCA cycle
4. Procedures	**Paper-based:** "PCI Postoperative Hydration Clinical Pathway," "Transradial PCI Postoperative Finger Exercise SOP," "Hydration Risk Stratification Assessment Form," "PCI Postoperative Rehabilitation Manual," "Exercise Check-in Form." **Electronic:** Standardized teaching videos (QR codes), monthly quality monitoring ledger
5. Provider	Cardiovascular Department Nursing Quality Improvement Team (Core members: 1 head nurse, 2 senior specialty nurses, 1 nursing department quality control expert). All-staff training conducted by core team.

TIDieR Item	Description
6. Delivery	**Training:** Face-to-face lectures, workshops, bedside teaching. **Implementation:** Bedside execution and education by responsible nurses. **Material Distribution:** Paper manuals and check-in forms distributed bedside; videos played via bedside QR codes and ward televisions.
7. Location	Cardiovascular Ward, General Hospital of Ningxia Medical University
8. Dose & Intensity	**Training Dose:** Mandatory all-staff training, 2-week duration, 10 total hours (4 hours theory + 4 hours workshop + 2 hours bedside teaching). **Implementation Intensity:** Hydration protocol for all patients without contraindications (100%); finger exercise guidance for all transradial PCI patients (100%). **Monitoring Frequency:** Daily data collection, monthly indicator summary and feedback.
9. Tailoring	**Hydration Protocol:** Mandatory use of "Hydration Risk Stratification Assessment Form" (based on eGFR, cardiac function, age, contrast volume) to output low/medium/high risk stratification, matching individualized hydration pathways (oral/intravenous combined/intravenous rate-limited monitoring). **Exercise Guidance:** Standardized movements with daily exercise sets adjusted based on patient tolerance.

TIDieR Item	Description
10. Adherence Assessment	**Nurses:** Post-training theory exam ($ $80 points required) and 100% operation assessment pass rate; monthly NSI achievement rate incorporated into performance evaluation. **Patients:** Execution verified through bedside observation audits, check-in form records, and interviews.
11. Modifications	At monthly quality analysis meetings, processes, training, or tools were fine-tuned based on RCA results of non-achievement cases and recorded in PDCA documentation.
12. Unplanned Variations	No major unplanned variations during study period. Individual patients with hydration protocol adjustments due to condition changes were recorded as "reasonable modifications" and not counted as non-compliance.

Statistical Analysis

Data Description and Inter-Group Comparison Data analysis was performed using SPSS Statistics 26.0 software supplemented by R (version 4.3.0). Continuous variables were described according to their distribution: normally distributed variables were expressed as mean ± standard deviation, while non-normally distributed variables were expressed as median (interquartile range). Categorical variables were described as frequencies and percentages (n, %). To compare differences between pre- and post-intervention groups, appropriate statistical tests were selected based on data type and distribution: independent samples t-test for normally distributed continuous variables; Mann-Whitney U test for non-normally distributed variables; chi-square (χ^2) test for categorical variables, with Fisher' s exact test used when theoretical frequencies were too small. All hypothesis tests were two-tailed, with $P<0.05$ considered statistically significant.

Multivariate Logistic Regression Analysis To control for potential confounders, multivariate logistic regression analysis was employed to assess the independent effect of the intervention on outcomes ([Figure 4: see original paper]). In-hospital MACE occurrence was the dependent variable, with "intervention period" as the core independent variable, and covariates were included based on univariate analysis ($P<0.1$) and clinical importance (e.g., age, emergency PCI,

baseline LVEF). All variables entered into the model underwent collinearity diagnosis (variance inflation factor VIF<5). Results were expressed as adjusted odds ratio (aOR) with 95% confidence interval (CI).

Interrupted Time Series Analysis To evaluate immediate and trend effects of the intervention, interrupted time series analysis was performed for the two core process indicators [15]. A segmented regression model was applied: $Y = \beta_0 + \beta_1 \times T + \beta_2 \times X + \beta_3 \times T \times X + \epsilon$, where Y represents monthly indicator rate, T represents time (monthly sequence), and X represents intervention dummy variable (pre-intervention=0, post-intervention=1). β_2 represents immediate level change from intervention, and β_3 represents change in trend slope post-intervention.

Sensitivity Analysis and Negative Control To verify effect specificity, "inpatient fall incidence" —theoretically not directly affected by this intervention —was selected as a negative control indicator to analyze changes before and after intervention.

Missing Data Handling and Multiple Comparison Correction Missing data rate for key variables was below 2%, handled using multiple imputation with sensitivity comparison to complete case analysis. When multiple tests within the same hypothesis family required overall inference, Bonferroni correction was applied to control Type I error. All statistical tests were two-tailed, with $P<0.05$ considered statistically significant.

Results

Patient Baseline Characteristics

This study included 4,465 patients who underwent PCI treatment from January to November 2025, comprising 432 in the pre-intervention period (Jan-Apr) and 4,033 in the post-intervention period (May-Nov). Comparison of key baseline characteristics between the two groups showed no statistically significant differences ($P>0.05$), indicating comparability (detailed in Table 1).

Table 1 Comparison of Patient Baseline Characteristics Between Pre- and Post-Intervention Periods (n=432 vs. n=4,033)

Characteristic	Pre-Intervention (n=432)	Post-Intervention (n=4,033)	Test Statistic	P-value
Age (years)	65.4 ± 9.2	64.8 ± 10.1	t=1.32	0.19
Gender (Male, %)	312 (72.2)	2,865 (71.0)	χ^2=0.28	0.60
Hypertension (%)	328 (75.9)	3,101 (76.9)	χ^2=0.22	0.64

Characteristic	Pre-Intervention (n=432)	Post-Intervention (n=4,033)	Test Statistic	P-value
Diabetes (%)	145 (33.6)	1,290 (32.0)	χ^2=0.51	0.48
Chronic Kidney Disease (%)	38 (8.8)	322 (8.0)	χ^2=0.34	0.56
Prior PCI History (%)	65 (15.0)	605 (15.0)	χ^2=0.00	0.99
Emergency PCI (%)	89 (20.6)	788 (19.5)	χ^2=0.30	0.58

Impact on Major Adverse Cardiovascular Events (MACE)

After adjusting for potential confounders including age, gender, diabetes, and emergency PCI proportion, multivariate logistic regression analysis demonstrated that intervention period was an independent protective factor against MACE risk (pre-intervention vs. post-intervention, adjusted OR=0.43, 95% CI: 0.34-0.54, P<0.001). Based on risk reduction magnitude estimated from this model, the number needed to treat (NNT) for this closed-loop quality improvement system was calculated as 4 (detailed in Table 2).

Table 2 Multivariate Logistic Regression Analysis Results for MACE

Variable	aOR (95% CI)	P-value
Intervention Period (Pre vs. Post)	0.43 (0.34-0.54)	<0.001
Age (per 1-year increase)	1.02 (1.00-1.04)	0.03
Gender (Male vs. Female)	1.15 (0.89-1.48)	0.28
Diabetes (Yes vs. No)	0.78 (0.62-0.98)	0.03
Hypertension (Yes vs. No)	1.21 (0.96-1.53)	0.10
Emergency PCI (Yes vs. No)	1.65 (1.30-2.08)	<0.001
Baseline LVEF (per 1% increase)	0.97 (0.95-0.99)	0.01
Smoking History (Yes vs. No)	1.32 (1.05-1.66)	0.02
Admission STEMI (Yes vs. No)	1.41 (1.11-1.79)	0.01

Variable	aOR (95% CI)	P-value
Baseline Troponin I (per 1 ng/mL increase)	1.08 (1.03-1.14)	0.01
Model Statistics	C-statistic=0.76; Hosmer-Lemeshow χ^2=6.32, P=0.61	

Specialty Nursing-Sensitive Indicator Monitoring Results

To present a comprehensive quality improvement panorama, historical baseline data from October-December 2024 are first presented to describe typical pre-intervention practice levels. Formal statistical comparisons were strictly limited to within the study design framework, i.e., between pre-intervention (Jan-Apr 2025) and post-intervention (May-Nov 2025) data; historical baseline data were used for descriptive reference only and not for inferential statistical testing.

Historical baseline trends and study period performance for the two specialty NSIs are shown in Table 3. The "Total Study Period" column in Table 3 represents the overall average from January to November 2025. Results demonstrated that both core indicators improved significantly in the post-intervention period (May-Nov) compared with the pre-intervention period (Jan-Apr) (P<0.001), detailed in Table 4.

Table 3 Historical Baseline (2024) and Study Period (2025) Performance of Specialty Nursing-Sensitive Indicators

Indicator	Historical Baseline (Oct-Dec 2024)	Pre-Intervention (Jan-Apr 2025)	Post-Intervention (May-Nov 2025)	Total Study Period (Jan-Nov 2025)
Postoperative Hydration Compliance Rate	41.67%	77.12%	87.85%	84.30%

Indicator	Historical Baseline (Oct-Dec 2024)	Pre-Intervention (Jan-Apr 2025)	Post-Intervention (May-Nov 2025)	Total Study Period (Jan-Nov 2025)
Finger Exercise Qualified Rate	40.00%	76.22%	87.91%	83.99%

Table 4 Comparison of PCI Perioperative Specialty Nursing-Sensitive Indicators Between Pre- and Post-Intervention Periods (2025)

Indicator	Pre-Intervention (Jan-Apr) Rate (%)	Post-Intervention (May-Nov) Rate (%)	Absolute Improvement (Percentage Points)	P-value
Postoperative Hydration Compliance	77.12%	87.85%	10.73	<0.001
Finger Exercise Qualified Rate	76.22%	87.91%	11.69	<0.001

Comprehensive Nursing Quality and Patient Safety Outcome Improvements

To more precisely estimate intervention effects while controlling for long-term trends, we conducted interrupted time series analysis for the two core process indicators (detailed in Supplementary Material S5). Results showed significant immediate level increases at the intervention point (May 2025) (postoperative hydration compliance rate β_2=19.1%, P<0.001; finger exercise qualified rate β_2=18.5%, P<0.001), with significantly higher monthly improvement trends post-intervention compared with pre-intervention.

The systematic NSI-CLQIS produced positive impacts on overall nursing quality and patient safety. To provide richer practical context, this study compared 2025 post-intervention data with historical data from the same period (May-Nov) in 2024, with results shown in Table 5. Key nursing quality and safety indicators demonstrated improvement trends after the 2025 intervention.

Table 5 Comparison of Key Nursing Quality and Safety Indicators Between 2024 and 2025 (May-Nov)

Indicator	2024 Same Period (May-Nov)	2025 Post-Intervention (May-Nov)	Test Statistic	P-value
High-Risk Drug Management Standardization Rate	85.2%	94.7%	χ^2=12.4	<0.001
Symptomatic Contrast-Induced Nephropathy (CIN) Incidence (%)	1.9 (15/792)	0.8 (7/872)	χ^2=4.10	0.043
Severe Puncture Site Complication Rate (%)	1.6 (13/792)	0.6 (5/872)	χ^2=3.96	0.047
Inpatient Satisfaction Score (0-100)	87.1 ± 4.9	93.2 ± 3.8	t=15.34	<0.001

Indicator	2024 Same Period (May-Nov)	2025 Post-Intervention (May-Nov)	Test Statistic	P-value
Puncture Site Pain Score (VAS, 0-10)	3.2 ± 1.5	2.1 ± 1.2	t=5.87	<0.001

Discussion

Main Findings and Clinical Value

This study confirmed that constructing and implementing a closed-loop quality improvement system (CLQIS) based on specialty nursing-sensitive indicators significantly improved key PCI perioperative nursing process indicators (postoperative hydration compliance rate and finger exercise qualified rate), enhanced patient safety outcomes (e.g., reduced symptomatic contrast-induced nephropathy and puncture site complication rates), and ultimately substantially reduced in-hospital MACE risk (adjusted OR=0.43, NNT=4). These findings demonstrate that implementing CLQIS for specialty nursing-sensitive indicators is an effective lever for driving evidence-based practice implementation, ensuring patient safety, and ultimately improving hard endpoints.

Comparison and Positioning with International Studies

This study achieved an absolute improvement of over 10 percentage points in postoperative hydration compliance rate. This magnitude of improvement is comparable to high-level improvement effects reported in a recent international multicenter CLQIS study (Chen & Wang, 2025) [9]. This indicates that our system provides an effective solution from a large Chinese medical center to address the global challenge of "suboptimal real-world implementation of prophylactic hydration" identified in the AHA/ACC guidelines (2024) [12]. Simultaneously, this study focused on and confirmed the system' s positive impact on patient hard endpoints (MACE), addressing the gap in existing literature that predominantly focuses on process indicators while lacking high-level outcome evidence.

Mechanism Analysis of CLQIS Success

The success of this system is essentially a systematic project "guided by the Knowledge-to-Action (KTA) framework [30], powered by PDCA cycles [24], and navigated by nursing-sensitive indicators (NSIs) as feedback signals." Its mechanisms can be analyzed from three dimensions:

1. **NSIs as Precise Measurement Tools Connecting Theory and Practice:** This study deconstructed the macro goal of "high-quality

nursing" into quantifiable indicators such as "hydration compliance rate" and "exercise qualified rate," essentially operationalizing Donabedian' s "Structure-Process-Outcome" model [29]. Continuous monitoring of process indicators drove nursing practice from experiential execution toward evidence-based and risk-based precision management.

2. **KTA-PDCA Integration Forming Systematic Implementation and Iteration Mechanisms:** System success depended on systematic knowledge translation and deep clinical integration. Retrospective analysis using the Consolidated Framework for Implementation Research (CFIR) [33] revealed that success benefited from multi-level synergies: relative advantage and robust evidence support for intervention characteristics; policy support from the hospital' s "Smart Nursing" initiative for external environment; stable teams, positive learning culture, and quality improvement consensus for internal environment; and robust Hospital Information System (HIS) providing "hard technology" support. During implementation, we comprehensively applied multiple evidence-based implementation strategies (ERIC) [28], such as "audit and feedback" and "local opinion leaders" to promote change, and "continuous education" and "patient self-management facilitation" to ensure intervention implementation and maintenance. These targeted strategies effectively overcame "implementation gaps."

3. **Structured Tools Precisely Addressing Key Obstacles in the "Evidence-Practice Gap" :** Research identified that core barriers were not "knowledge gaps" but "implementation gaps" and "feedback gaps." The system introduced specific tools: for hydration management, the "Post-PCI Hydration Risk Stratification Assessment Form" transformed guidelines [14] into visual clinical decision support, with its core concept consistent with AMACING trial results [23]; for functional exercise, the "Patient Rehabilitation Check-in Form" and nurse "Bedside Guidance Checklist" constructed a bidirectional, real-time visual feedback loop between nurses and patients. These tools transformed practice dependent on individual consciousness into sustainable behavior patterns driven and reinforced by systematic processes. The systematic application of PDSA (Plan-Do-Study-Act) cycles [24] and use of NSIs as core monitoring tools [26] jointly ensured improvement activity continuity and effectiveness. Simultaneously, the system promoted nurse-patient collaboration through tools like the Rehabilitation Check-in Form, embodying patient-centered care philosophy [27].

Study Limitations and Future Directions

Despite employing multiple strategies to strengthen the argument, this study has several limitations:

Design Limitations: The single-center before-and-after quasi-experimental

design cannot completely exclude time-related confounding. Although we partially controlled for these through multivariate regression, interrupted time series analysis, and negative controls, higher-level causal evidence awaits further validation through multicenter stepped-wedge cluster randomized controlled trials [16]. Additionally, as the study sample originated from a single large tertiary hospital, the generalizability (external validity) may be influenced by specific organizational contexts (e.g., resources, culture, information systems), requiring careful contextual adaptation assessment when generalizing to other institutions.

Measurement and Reactivity Bias: Core process indicators partially relied on nursing documentation, and Hawthorne effects from close monitoring could not be completely excluded. Although we enhanced objectivity through multisource data triangulation (system records, field observations, interviews) [31], assessments of "finger exercise qualified rate" regarding "standardized movements" and "frequency compliance" still involved some subjectivity. Future studies could employ more covert or objective data collection methods (e.g., smart device data) to address this limitation. The system' s success through multidisciplinary team collaboration also confirms the positive value of interprofessional collaboration for practice improvement [32].

Implementation Burden and Long-term Effects: System operation added extra work for education, monitoring, and data feedback. This study controlled burden through information technology support and clear division of labor, but its long-term impact on nursing staff job satisfaction and burnout, as well as whether system effects are sustainable or subject to "audit fatigue," require longer-term follow-up evaluation.

Based on these analyses, future research should: (1) Employ more rigorous designs (e.g., stepped-wedge trials [16]) to provide high-level evidence; (2) Develop low-cost digital toolkits integrated with smart nursing platforms to reduce implementation barriers; (3) Explore integration of IoT sensors, wearable devices, and other objective monitoring tools into CLQIS for automated, unobtrusive collection and real-time feedback of patient rehabilitation exercise execution and vital sign data [36-39], further enhancing monitoring objectivity and efficiency; (4) Incorporate patient-reported outcomes [34,35] and health economic indicators into comprehensive evaluation systems to construct a new value-oriented management paradigm.

Conclusion and Implications

In conclusion, constructing and systematically applying an evidence-based specialty nursing-sensitive indicator system in cardiovascular departments represents an effective strategy for implementing refined, data-driven nursing quality management. This study confirms that continuous monitoring and closed-loop quality improvement of the two indicators— "post-PCI hydration compliance rate" and "transradial PCI postoperative finger exercise qualified rate" —are

significantly associated with improved compliance of key nursing measures, enhanced overall nursing quality, and reduced in-hospital MACE risk. This system provides an actionable practical pathway for scientific and structured improvement of clinical nursing quality management.

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Supplementary Materials

Figure S1 Monthly Trend Chart of Core Indicators

Supplementary Material S2 Table 1: Detailed Search Strategies and Results for Each Database

Database	Search Strategy (Simplified)	Strategy Characteristics
PubMed	(cardiovascular nursing[Mesh]) AND (nursing-sensitive indicators[Mesh]) AND (patient safety[Mesh])	MeSH terms combined with free text
CINAHL	(MH "Cardiovascular Nursing") AND (MH "Nursing-Sensitive Outcomes") AND "Patient Safety"	Subject heading search
Embase	'cardiovascular nursing' /exp AND 'nursing sensitive indicator' /exp AND 'patient safety' /exp	EMTREE terms
CNKI	(SU='护理敏感指标') AND (SU='心血管护理') AND (SU='患者安全')	Subject terms
Wanfang	主题:("护理敏感指标") AND 主题:("心血管护理") AND 主题:("患者安全")	Subject terms
Total (before deduplication)	**312**	
Total (after deduplication)	**267**	

Supplementary Material S3: Methodological Quality Assessment Results of Included Literature

Evaluation Tools and Methods

Methodological quality assessment of included literature was independently conducted by two researchers (A, B) using internationally recognized standardized tools for different study designs:

Study Design	Evaluation Tool	Evaluation Dimensions/Standards
Randomized Controlled Trials	Cochrane Risk of Bias Tool (RoB 2)	Randomization process, deviations from intended interventions, missing outcome data, outcome measurement, selective reporting. Each domain rated as "low risk," "high risk," or "some concerns."
Observational Studies	Newcastle-Ottawa Scale (NOS)	Study population selection (4 points), inter-group comparability (2 points), outcome measurement (3 points). Total score 9 points; $ $7=high quality, 5-6=moderate, $ $4=low.
Systematic Reviews	AMSTAR-2	16 items, 7 critical. Overall quality rated as "high," "moderate," "low," or "critically low" based on critical item compliance.
Quality Improvement Reports	JBI Critical Appraisal Checklist	Assessment from problem clarity, method rationality, data collection, analysis, conclusions, and practical significance. Rated as "yes," "no," "unclear," or "not applicable."
Expert Consensus/Guidelines	JBI Expert Consensus and Clinical Practice Guideline Appraisal Checklist	Assessment from consensus formation method, participant representativeness, evidence base, recommendation clarity, and operability.

During evaluation, two researchers first underwent unified training to familiarize themselves with each tool's application standards. After independent evaluation, results were compared. Disagreements were resolved through discussion; if consensus could not be reached, a third senior methodology expert (C) arbitrated. Final results are summarized below.

Randomized Controlled Trials (4 articles) **Table S3.1** Risk of Bias Assessment (RoB 2) Results for RCTs

Study	Randomization Process	Deviations from Interventions	Missing Outcome Data	Outcome Measurement	Selective Reporting	Overall Risk
RCT-01	Low	Low	Some concerns	Low	Low	Some concerns

Study	Randomization Process	Deviations from Interventions	Missing Outcome Data	Outcome Measurement	Selective Reporting	Overall Risk
RCT-02	Low	Low	Low	Low	Low	Low
RCT-03	Some concerns	Low	Low	Low	Low	Some concerns
RCT-04	Low	Low	Low	Low	Low	Low

Summary: Among 4 RCTs, 2 (50%) had low risk of bias and 2 (50%) had some concerns. Main risk sources were inadequate reporting of randomization sequence generation and allocation concealment (RCT-03) and high missing outcome data rates (>10%) (RCT-01). All studies performed well on blinding (outcome assessment) and selective reporting.

Observational Studies (11 articles) **Table S3.2** NOS Scale Scoring Results for Observational Studies

Study	Selection (0-4)	Comparability (0-2)	Outcome (0-3)	Total (0-9)
Obs-01	4	2	3	9
Obs-02	3	1	3	7
Obs-03	3	1	2	6
Obs-04	4	2	3	9
Obs-05	4	2	2	8
Obs-06	3	1	2	6
Obs-07	4	2	3	9
Obs-08	4	2	3	9
Obs-09	3	1	3	7
Obs-10	4	2	3	9
Obs-11	4	2	2	8

Summary: Among 11 observational studies, 8 (72.7%) were high quality (NOS$ $7) and 3 (27.3%) were moderate quality (NOS=6). Point deductions primarily involved insufficient description of control group comparability (Obs-02, Obs-03, Obs-06, Obs-09) and inadequate follow-up duration or high loss-to-follow-up rates (Obs-03, Obs-06).

Systematic Reviews (5 articles) **Table S3.3** AMSTAR-2 Quality Rating Results for Systematic Reviews

Study	Critical Items Compliance (7 items)	Non-Critical Items Compliance (9 items)	Overall Quality Rating
SR-01	6/7	8/9	High
SR-02	6/7	7/9	Moderate
SR-03	7/7	9/9	High
SR-04	6/7	8/9	High
SR-05	6/7	7/9	Moderate

Summary: Among 5 systematic reviews, 3 (60%) were high quality and 2 (40%) were moderate quality. Moderate ratings primarily resulted from failure to provide lists of excluded studies (SR-05) or report prior study protocols (SR-02).

Quality Improvement Reports and Expert Consensus (8 articles) **Table S3.4** Overview of JBI Evaluation Results for Quality Improvement Reports and Expert Consensus

Study	Type	Key Assessment Points Compliance Rate
QI-01	Quality Improvement Project	9/10 items
QI-02	Quality Improvement Project	8/10 items
QI-03	Quality Improvement Project	7/8 items
QI-04	Quality Improvement Project	10/10 items
QI-05	Quality Improvement Project	6/10 items
QI-06	Quality Improvement Project	8/8 items
QI-07	Quality Improvement Project	7/10 items
QI-08	Quality Improvement Project	9/10 items

Summary: Among 8 articles, 6 (75%) were high quality and 2 (25%) were moderate quality. Moderate-quality reports (QI-05, QI-07) primarily had insuf-

ficient description of improvement measure implementation context and overly simple result data analysis without adequate confounding control.

Overall Quality Assessment Summary

In summary, the 28 included articles had acceptable overall methodological quality, providing a relatively robust evidence base for the theoretical framework construction of the main study.

- **Randomized Controlled Trials (4):** Moderate-to-high quality; although half had some deficiencies in randomization or data integrity, core intervention and outcome assessment bias risks were low.
- **Observational Studies (11):** Majority (72.7%) were high quality with good reporting on population selection and exposure/outcome measurement; a few studies needed strengthening in control group comparability.
- **Systematic Reviews (5):** Moderate-to-high quality with 60% high-quality ratings; all clearly proposed research questions with systematic literature search and screening.
- **Quality Improvement Reports and Expert Consensus (8):** Acceptable reporting on key items with 75% high quality; these provided important practical evidence for nursing quality improvement strategies, process design, and multidisciplinary collaboration.

Supplementary Material S4: Post-hoc Power Analysis

To assess the adequacy of our study' s sample size for detecting intervention effects, we conducted power analysis using G*Power 3.1.9.7 software. The analysis primarily focused on the core process indicator "postoperative hydration compliance rate," as it is the key nursing behavior driving subsequent patient safety outcome improvements.

Analysis Type and Parameter Settings

- **Test Type:** Test for two independent proportions
- **Test Direction:** Two-tailed
- **Significance Level (α):** 0.05
- **Sample Size Allocation:** Based on actual data, pre-intervention group (n_1)=432, post-intervention group (n_2)=4,033, allocation ratio (n_2/n_1) 9.34
- **Effect Size:** Cohen' s h was used as effect size measure for between-group proportion differences, calculated as: $h = 2 \times \arcsin(\sqrt{P_2}) - 2 \times \arcsin(\sqrt{P_1})$

Power Analysis Under Two Scenarios We established two analysis scenarios: conservative expectations during study design and actual observations after study completion.

Table S4.1 Power Analysis Parameters and Results

Scenario	Pre-Intervention Rate	Post-Intervention Rate	Improvement (P_2-P_1)	Effect Size (Cohen' s h)	Power (1-β)
A (Conservative)	41.67%	61.67%	20.00 percentage points	0.41	>0.999
B (Observed)	41.67%	84.30%	42.63 percentage points	0.95	>0.999

- **Scenario A (Conservative Expectation):** During project design, a 20-percentage-point improvement in hydration compliance rate (from historical baseline of 41.67% to 61.67%) was set as the minimum clinically meaningful target. Analysis showed that even with this conservative effect size (h=0.41), our sample size provided power far exceeding conventional standards (>0.8).
- **Scenario B (Actual Observation):** The actual observed improvement (42.63 percentage points) far exceeded expectations, with corresponding effect size (h=0.95) representing a very large effect. Under these conditions, statistical power was also extremely high.

Conclusion Whether based on conservative pre-project expectations or actual post-project large improvements, our study' s sample size (N=4,465) provided near-complete statistical power (>0.999). This indicates that the study had extremely high statistical power to detect intervention effects, and the sample size was adequate and sufficient. This analysis supports the reasonableness of using an "all-inclusive"approach to include consecutive cases to maximally reflect real-world practice changes.

Supplementary Material S5: Detailed Results of Interrupted Time Series Analysis

Parameter	Postoperative Hydration Compliance Rate	Finger Exercise Qualified Rate
Intercept (Pre-Intervention Level)	0.771 (SE=0.032), P<0.001	0.762 (SE=0.031), P<0.001
Time Trend (Pre-Intervention)	0.008 (SE=0.009), P=0.38	0.012 (SE=0.008), P=0.18

Parameter	Postoperative Hydration Compliance Rate	Finger Exercise Qualified Rate
Intervention Effect (Level Change)	0.191 (SE=0.028), P<0.001	0.185 (SE=0.027), P<0.001
Trend Change (Interaction Term)	0.021 (SE=0.007), P=0.01	0.018 (SE=0.006), P=0.02

Supplementary Material S6: Analysis Results of Negative Control Indicator (Fall Incidence)

Period	Total Patient-Days	Fall Cases	Fall Rate (‰)
Jan 2025	12,500	1	0.08
Feb 2025	11,800	2	0.17
Mar 2025	13,200	1	0.08
Apr 2025	12,900	2	0.16
May 2025	13,500	2	0.15
Jun 2025	12,700	1	0.08
Jul 2025	13,800	2	0.14
Aug 2025	13,200	1	0.08
Sep 2025	12,900	2	0.16
Oct 2025	13,400	1	0.07
Nov 2025	13,100	2	0.15

Pre-Intervention Comparison (Jan-Apr): Average fall rate = 0.12‰
Post-Intervention (May-Nov): Average fall rate = 0.13‰
Difference: 0.01‰ (95%CI: -0.05‰ to 0.07‰)
P-value (t-test): 0.742

Conclusion: Fall incidence showed no significant change before and after intervention, indicating that specialty indicator improvement measures did not negatively affect unrelated nursing safety indicators.

Note: Figure translations are in progress. See original paper for figures.