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Research on the Application Effect of a Residual Liquid Measurement and Discharge Device for Analgesic Pumps

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Abstract: This invention provides a metering and discharge device for measuring residual liquid in analgesic pumps, addressing the field of volume measurement for residual liquid in such devices. Analgesic pumps typically administer neuromedicinal drugs, and hospitals maintain strict control over dosage administration. The technical solution comprises a storage tank equipped with a liquid level sensor, a laser emitter mounted on the tank's top or upper surface, and a photosensitive plate positioned at the tank's bottom to detect laser signals. The laser emitter, liquid level sensor, and photosensitive plate are interconnected via electrical or signal links. The storage tank is connected to a liquid discharge system for removing residual medication. This innovation enables precise measurement of post-administration liquid volume in analgesic pumps and automatically discharges it into drainage systems through standardized metering mechanisms. This implementation facilitates closed-loop management of drug consumption, enhances precision and intelligence in controlled substance administration, significantly improves measurement accuracy and efficiency, and supports hospitals in achieving comprehensive closed-loop management of analgesic pump medications.

Keywords: Analgesic pump; Residual liquid; Dosage and discharge

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1. Background and pain points

With the continuous advancement of accelerated recovery and patient-centered care, the clinical demand for analgesic pumps has been increasing significantly. Patient-controlled analgesia (PCA) stands as one of the effective approaches for individualized postoperative pain management [1]. Recognized as a critical component due to its simple operation, superior analgesic efficacy, and ability to meet patients' pain control needs at different times [2,3], analgesic pumps serve as core devices for postoperative pain management. Strict control over medication dosage, patient usage volume, and remaining solution levels is essential to achieve closed-loop medication safety management. However, current residual volume measurement methods rely on manual operations (e.g., graduated cylinder readings), which introduce subjective errors. Automated systems utilizing liquid level sensors face challenges such as data distortion caused by liquid level fluctuations and prolonged measurement intervals, resulting in low efficiency. These issues hinder the effective implementation of closed-loop management systems. Additionally, nurses must perform manual procedures under video surveillance to

aspirate the inner capsules from analgesic pump cartridges, measure residual volumes, and dispose of waste through drainage systems. This process not only fails to ensure precise dosing accuracy but also leads to operational inefficiencies, increased labor costs, and potential occupational hazards for healthcare workers.

2. Innovative solutions

The core of this invention lies in the dual technological integration of "laser dynamic monitoring + precise liquid level sensing," with the specific design as follows:

2.1. Overall structure of the device

The storage tank unit adopts a multi-compartment independent design, capable of simultaneously processing 10–20 residual fluids from analgesic pumps. The tank body features a fixed geometric structure with smooth inner walls for easy cleaning, and is equipped with a high-precision liquid level sensor (**Figure 1**).

The laser monitoring system is equipped with a laser emitter installed at the top and a corresponding photosensitive plate at the bottom. The laser beam penetrates the liquid vertically, and the stability of the liquid level is determined by analyzing changes in the light spot.

The central controller integrates data processing, logical judgment, and instruction output functions, receiving laser signals and liquid level data in real time, automatically calculating residual liquid volume, and controlling the liquid discharge process. It can be interfaced with hospital HIS systems and narcotic drug management systems.

The automated drainage system consists of a solenoid valve, a liquid extraction pump, and multi-path pipelines. After metering is completed, the system automatically discharges the liquid, which is then uniformly directed into the hospital's medical wastewater treatment system for harmless disposal.

The information traceability module is equipped with a barcode scanner and surveillance cameras, supporting the binding of analgesic pump information, patient information, and operational data, with full-process video recording for traceability. It also features safety functions such as alarms for abnormal cabinet door opening and for operational interruption.

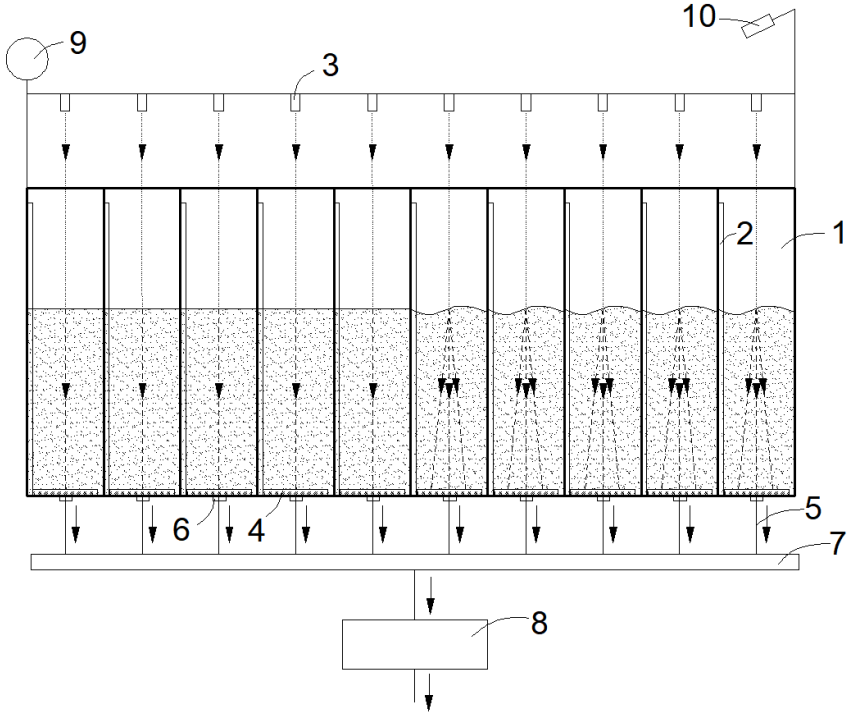

Figure 1. Schematic diagram of metering device structure

2.2. Working principle

2.2.1. Automatic determination of liquid level stability

After residual liquid is poured, fluctuations in the liquid surface may alter the laser refraction path, causing the photosensitive plate to detect light spot drift. When the signal remains stable for approximately 5 seconds, the system determines that the liquid level is stable and eliminates interference from fluctuations.

2.2.2. After precise measurement of residual liquid and stabilization of the liquid level, the level sensor collects the liquid height

Combining this with the fixed volume parameters of the tank, the controller automatically calculates the residual liquid volume with a measurement error ≤± 1%.

2.2.3. Upon completion of automated process handling and measurement, data is automatically uploaded

The system initiates the drainage program to discharge residual liquid and clean the tank, achieving full automation without manual intervention. This realizes an integrated workflow of "pouring–measurement–recording–drainage–cleaning."

3. Technical advantages: Core innovations

(1) Dual technology integration enhances precision through laser monitoring for liquid level status assessment. The liquid level sensor collects data, addressing fluctuation interference issues at their source.

(2) Significantly improved processing efficiency: Liquid level detection time ≤5 seconds, average single pump operation time ≤18 seconds, with efficiency exceeding 80% higher than traditional modes.

(3) The system features end-to-end closed-loop traceability with information binding, video surveillance, and tamper-proof data, fully complying with the regulatory requirements for psychotropic and narcotic drugs throughout their lifecycle.

(4) Reducing occupational exposure: Nurses only need to scan the code and dispose of residual liquid, significantly minimizing direct contact with medicinal solutions.

(5) Multi-scenario scalability compatible with analgesic pumps of varying capacities, expandable to special liquid solutions such as chemotherapeutic agents, anesthetics, and psychotropic drugs

4. Technical advantages and performance indicators of the device

(1) High measurement accuracy

The combination of laser dynamic monitoring and high-precision liquid level sensing achieves an error control of ±1%, significantly superior to manual measurement and traditional single-sensor devices.

(2) Significant improvement in operational efficiency

Traditional manual single-pump processing takes approximately 180 seconds, while this device achieves an average processing time of about 18 seconds per pump, resulting in an overall efficiency improvement of approximately 90%. It supports batch parallel processing.

(3) Reduction of labor costs

Traditional models require two-person operation, whereas this device enables single-person batch processing, reducing labor input and minimizing repetitive tasks.

(4) Strong safety compliance

Equipped with abnormal alarm, video surveillance, operation traceability, and data upload functions, it achieves 100% traceability and fully complies with the regulations for controlled substances management.

(5) High level of informatization

It can integrate with hospital information systems to automatically generate ledgers, statistical reports, and usage analysis, replacing manual recording and promoting intelligent management.

5. Implementation cases

The preliminary model of this product has been applied in clinical practice, achieving favorable therapeutic outcomes:

5.1. Closed-loop management

The application of the residual liquid metering and discharge device system, combined with the analgesic pump system, achieves closed-loop management of narcotic and psychotropic drugs in the analgesic pump, ensuring that the usage volume + residual liquid volume = dispensing volume. This guarantees refined, closed-loop, and safe management of narcotic and psychotropic drugs in the analgesic pump. The implementation of this product significantly enhances the safety of narcotic and psychotropic drug usage and the scientific management approach.

5.2. Nurse workload

Due to the device's capability to simultaneously discharge residual fluid from 10–20 analgesic pumps, time efficiency is significantly improved. The single-dose measurement operation time is reduced from 180 seconds to 18 seconds, resulting in a 10–20-fold increase in daily processing capacity. This substantially reduces the human resource costs for nurses.

5.3. Management compliance

The product is equipped with scanning and camera functions, enabling one-to-one matching of analgesic pumps after scanning. The entire drainage process of the analgesic pump is monitored by cameras during liquid discharge. Additionally, the device features an abnormal interruption and cabinet door opening alarm system, effectively monitoring the entire metered drainage process to achieve visual management. This also prevents abnormal behaviors such as unintended device activation, ensuring 100% traceability of operational records and compliance with the discharge specifications for narcotic and psychotropic substances.

6. Application prospects

This device is not only applicable for residual liquid management in analgesic pumps but can also be extended to other precision liquid dosing scenarios, such as closed-loop monitoring of high-risk pharmaceuticals including chemotherapeutic agents and anesthetics. In the future, integration with IoT and AI algorithms will further enable predictive maintenance and medication risk alerts, driving intelligent upgrades in medical equipment.

7. Summary

7.1. Narcotic drugs and psychotropic substances of Category I (collectively referred to as "narcotic and psychotropic drugs") are substances subject to special state control due to their significant medical and scientific value

However, they also induce physiological dependence and exhibit high addictive potential. Improper management or misuse of these drugs may lead to drug loss or abuse, resulting in severe public health, social, and economic issues. Strengthening clinical application management of narcotic and psychotropic drugs is crucial for ensuring medical quality and safety, safeguarding patients' health rights, and constitutes an essential aspect of pharmaceutical administration and hospital

management [4,5].

7.2. Psychotropic and narcotic drugs are classified as controlled substances under China's legal framework, requiring rigorous clinical management by health administrative authorities and medical institutions at all levels

Healthcare facilities must implement comprehensive oversight throughout the prescription and administration processes, with particular emphasis on implementing effective measures to prevent patient duplication of drug access, minimize residual solution usage, and continuously enhance monitoring systems to curb drug abuse. The objective of strengthened regulation is to achieve "effective control and practical application," thereby safeguarding individuals and society from drug-related harm while ensuring effective pain management for patients [6].

7.3. Analgesic pump is a liquid infusion device that maintains a stable drug concentration in the bloodstream, enabling better analgesic efficacy with reduced medication dosage

Analgesic pumps typically administer neuromedicaments, and hospitals enforce strict control over dosage parameters, including withdrawal volume, patient dosage, and residual solution volume post-administration. The sum of residual solution volume and patient dosage must precisely equal the withdrawal volume to establish closed-loop management of analgesic pump medication volume.

7.4. An efficient and precise solution for medication management

By innovatively integrating laser technology with automated systems, this invention provides an efficient and precise solution for medication management in analgesic pumps, ensuring patient medication safety while enhancing hospital resource management efficiency, demonstrating significant clinical value and social benefits.

8. Conclusion

The management of psychotropic and narcotic drugs is a critical component of healthcare quality and safety. As an essential delivery system for clinical use of these medications, analgesic pumps directly impact drug safety control through residual solution dosing and disposal. Traditional manual methods, characterized by insufficient precision, low efficiency, high risks, and difficult traceability, can no longer meet the refined and intelligent management requirements of modern hospitals.

The pain pump residual liquid metering and discharge device developed in this study addresses clinical pain points through technological innovation: precise and rapid metering achieved via dual technologies of laser and liquid level sensing; automation systems replacing manual operations to enhance efficiency and reduce risks; and information modules establishing a closed-loop management system to meet regulatory compliance requirements. Clinical applications have demonstrated that this device significantly improves management efficiency, ensures medication safety, and reduces nursing workload, exhibiting strong practicality and promotion value. Compared with similar technologies domestically and internationally, this device demonstrates superior compatibility with domestic hospital workflows in terms of metering accuracy, processing speed, operational convenience, and closed-loop management, along with lower implementation costs. This study currently represents a single-center application, with future multi-center, large-sample clinical validation planned to further optimize performance and provide robust evidence for comprehensive promotion.

Disclosure statement

The authors declare no conflict of interest.

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