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Strategic Life Cycle Management Approaches for Smart Maintenance of Diverse-Brand Infusion Pumps in Hong Kong Public Hospitals

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Abstract **–** As the only governmental medical equipment maintenance body for Hong Kong public hospital, Health Sector Division of the Electrical and Mechanical Services Department (EMSD) of HKSAR developed a novel smart strategic life cycle management approach using workflow innovations and I&T solutions to enhance maintenance for over 15,000 diverse-band infusion pumps across 43 hospitals. In this paper, we conducted study in the development of centralizing maintenance line, shortening flow rate testing protocols for maintenance, digitalizing workflows with Biomedical Engineering Services e-form platform, incorporating big data-driven predictive maintenance from e-form and AI-assisted maintenance checklist reviews. The results shows that smart maintenance approach can improve cost-effectiveness, labor efficiency and workflow streamlining while maintaining equipment safety and performance.

Keywords**:** Biomedical Engineering, Biomedical Device, Life Cycle Management, Infusion Pump, Smart Maintenance, Predictive Maintenance, Workflow Digitalisation, Artificial Intelligent

1. Introduction

Infusion pump is one of the widely utilized medical device in hospitals, designed to accurately and continuously deliver fluids, nutrition or medication into patients' bloodstream at a programmed rate, supporting precise and reliable intravenous therapy in clinical settings [1]. However, inappropriate maintenance management remains a predominant cause for medical equipment failure which is avoidable.

Since Health Sector Division of the Electrical and Mechanical Services Department (EMSD) of HKSAR serves as a crucial and specialized role as the official governmental body responsible for the maintenance of medical equipment. Currently, EMSD oversees the maintenance of over 15,000 infusion pumps, including more than 60 brands of volumetric and syringe pumps, across 43 public hospitals in Hong Kong. In our conventional maintenance practice, large quantities of infusion pumps' maintenance are carried out separately on-site in various local hospital workshops which is labour-intensive and cost-consuming. With the increasing variety, quantity, and technological complexity of infusion pumps, results in a growing demand for advanced maintenance management [2] and risk assessment for ensuring high-quality performance of these Class III high-risk infusion pump devices to guarantee optimal infusion.

In this study, we developed a novel smart maintenance approach for multi-brand infusion pumps in Hong Kong public hospitals including a centralized maintenance line, standardized flow rate testing protocols, digitalized workflow platform, and the integration of big data–driven predictive maintenance alongside AI-assisted checklist reviews.

The insights from this study could be used to transit from conventional maintenance practices to smart management of large-scale infusion pump, improving cost-effectiveness and labor efficiency while streamlining maintenance workflows without compromising equipment safety and performance.

2. Methodology

2.1. Centralizing infusion pump maintenance line

To streamline the maintenance workflow, a Centralized Infusion Pump Maintenance Workshop was established. A centralized maintenance line trial was conducted for infusion pumps collected from eight hospitals in central Kowloon. All incoming infusion pump units followed the process flow outlined in Figure 1. Each preventive maintenance (PM) area was equipped with 10 tester ports, enabling each technician to service 5 to 10 more units compared to previous practices. Based on the findings presented in Section 2.3, flow rate test durations of 20 minutes for volumetric pumps and 1 hour for syringe pumps were sufficient to obtain accurate measurements. Consequently, centralization enhanced labor utilization and overall workshop efficiency.

A label note will be sticked for indicating the malfunction status of the pump, such as high/ low flow or occlusion, defect battery etc. and can facilitate tracking and acknowledgement of the device at every stage of delivery. This can optimize the tracking of equipment's status throughout the repair process and enhance the communication by allowing staff to quickly identify the equipment that need to be repair and the corresponding status.

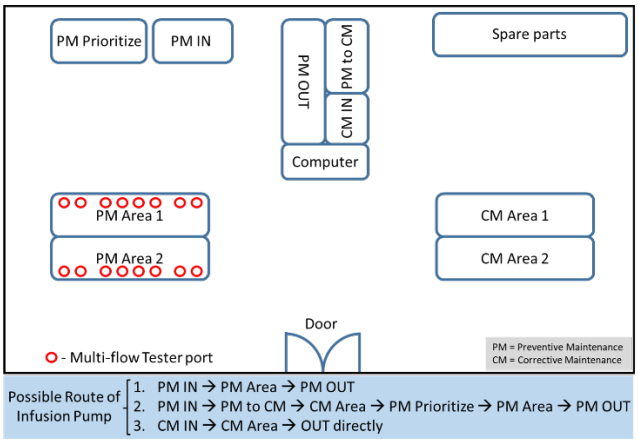

Fig. 1: Centralized Infusion Pump Maintenance Workshop.

An inventory list of specific spare parts for infusion pumps was developed, encompassing all available components for various models, along with their associated costs and supplier contact information. By analyzing the frequently failure parts from previous corrective maintenance activities, future maintenance needs can be planned more effectively, ensuring the timely availability of necessary spare parts. This inventory system provides a comprehensive overview of spare parts, facilitating improved resource allocation and reducing delivery times.

In addition, a master calibration system was implemented to support all workshops in calibrating their tester equipment with a well-organized calibration schedule. This system ensures that all testers used in workshops undergo calibration before the due date and prevents any shortage of testers. Both the database of spare parts inventory list and master tester calibration system will be linked to the BES e-Form in section 2.2

2.2. Digitalizing workflows with Biomedical Engineering Services e-form platform

To digitalize the maintenance workflow, a Biomedical Engineering Services e-Form platform (BES e-Form) was developed. This platform features model-specific electronic forms integrated with equipment maintenance manuals, where testing procedures, parameters, and tolerance limits are explicitly detailed within the eForm remarks to provide clear maintenance guidance. Numeric data entries are governed by validation rules that prevent the input of values outside predefined ranges or incorrect pass indications. The system mandates the submission of complete forms, thereby ensuring the accuracy and integrity of test data records. Additionally, the e-Forms are linked to a centralized tester database, allowing

users to record tester serial numbers and retrieve real-time calibration status, including the last calibration date, which is incorporated into maintenance reports.

The implementation of the BES e-Form platform aimed to enhance the efficiency, effectiveness, and documentation of service performance while ensuring compliance with ISO 13485 and ISO 14001 standards. By adopting digital technology, the platform streamlines and standardizes maintenance processes, ensuring that all checklists are accurate and consistent across maintenance practices. Maintenance and management personnel can use mobile devices to process documents and monitor maintenance progress through the platform anytime and anywhere, increasing accessibility and responsiveness. Compared to conventional paper-based reporting, the electronic forms reduce environmental impact, minimize storage requirements, and facilitate improved data retrieval, traceability, and auditability. Furthermore, the e-Form system reduces human errors, incorrect data entries, and issues related to illegible handwriting, thereby significantly improving the accuracy and reliability of maintenance records. Collectively, these features contribute to improved process quality and support elevated standards in engineering services.

Fig. 2: Using BES eForm platform on tablet in centralized infusion pump maintenance line

2.3. Study on Shortening flow rate testing protocols for maintenance

From our literature review of flow rate test requirements proposed by various parties, including infusion pump manufacturers, infusion pump analyzer manufacturers [3], ECRI and the IEC standard. We observed that flow rate test duration requirement differs significantly, with durations ranging from 10 minutes to 2 hours. While some organizations reference IEC 60601-2-24 and adopt a 2-hour testing protocol, which is time-consuming and labor-intensive. Notably, the IEC standard was originally designed for device validation during the development phase rather than for routine maintenance. Consider that EMSD is responsible for maintaining approximately 15,000 volumetric and syringe pumps, if each pump requiring two flow rate test settings with adherence to 2-hours test duration protocol, the total time and resources required for conducting the flow rate tests would be as shown in Eq. (1) below:

$$\textit{Total required Time} = 15{,}000 \text{ nos. x } 2 \text{ hours x } 2 \text{ flow rate settings} = 60{,}000 \text{ hours} \quad (1)$$

Given that there are over 60 models of infusion pumps under EMSD maintenance, establishing a standardized test requirement is preferable to ensure both safety and performance while balancing resource and operational needs. Similar to the U.S. Centers for Medicare & Medicaid Services' allowance [4] for an alternative equipment maintenance (AEM) program based on risk assessment performed by qualified personnel [5], this review aims to determine if flow rate test duration can be reduced and standardized to optimize resource allocation without compromising infusion pump safety and performance.

Infusion pump flow rates generally fluctuate initially before reaching stability. We hypothesized that the flow rate measurements taken at the point of stabilization would be sufficiently accurate and representative to compare with the performance data obtained from the two-hour flow rate testing period recommended by IEC 60601-2-24.

In this study, both relatively low and high flow rates were selected to simulate typical clinical use and align with the EMSD's preventive maintenance (PM) electronics form (eForm). Distilled water was used as the test solution and flow rates were measured using a Fluke IDA-4 Plus infusion pump analyzer, which began recording only after manual priming. For volumetric pumps, an infusion tube was inserted to the pump with the IV infusion set's head positioned approximately 50 cm above the pump, delivering fluid at 20 mL/hour and 200 mL/hour for two hours per setting. For syringe pumps, a 50 mL syringe was loaded to deliver fluid at 10 mL/hour and 50 mL/hour for two hours per setting. Each pump underwent a total of four hours of testing across both flow rates.

Meanwhile for the steady rate was defined as the flow rate maintained at a plateau for about one minute, while steady time was the interval from the start of measurement until this steady state was reached. The steady time, steady rate and flow rate percentage error at steady time were also recorded for the same aforementioned flowrate setting for both volumetric and infusion pump and compared to measurement data taken based on IEC 60601-2-24 two-hour test. A test was considered passed if the percentage error remained within ±5%, as recommended by manufacturers.

2.4. Big data-driven predictive maintenance from e-form

During preventive and corrective maintenance, extensive data are recorded in EMSD's BES e-Form platform, resulting in a comprehensive database of common faults and failure parts in infusion pumps. We are actively working to leverage the database with artificial intelligence techniques to analyze and correlate information such as average service duration, fault rates, and frequently used spare parts [6]. The resulting data visualization supports performance trend analysis and predictive maintenance capabilities, while also enhancing the monitoring of spare parts inventory. These efforts aim to improve maintenance productivity and elevate service quality.

2.5. AI-assisted maintenance checklist reviews

To validate the alignment of our maintenance checklist with original manufacturers' requirements, artificial intelligence and large language models were employed to automatically cross-reference the original service manuals. Generated summarized lists of required maintenance tasks, including all relevant test criteria and tolerance limits, will also be verified manually for maintenance checklist review.

3. Results

3.1. Possibility of shortening of flow rate test duration

To maintain an efficient management, it is suggested that the time required for flow rate test should be fixed and standardized. The cumulative graphs results presented in Figures 3 and 4 indicate that 95% of the pumps reached a steady state within specific timeframes. Volumetric pumps achieved steady flow rates after 16 minutes at 20 mL/hour and 12 minutes at 200 mL/hour. In comparison, syringe pumps required longer durations, reaching steady state after 52 minutes at 10 mL/hour and 29 minutes at 50 mL/hour.

Considering the population size, sample size and margin of error, the estimated time required for 95% of the population to reach steady rates is presented in Tables 1 and 2. Hence, the results concluded that a flow rate test duration of 20 minutes is recommended for volumetric pumps operating at both 20 mL/hour and 200 mL/hour and flow rate test, while 60 minutes is recommended for syringe pumps operating at both 10 mL/hour and 50 mL/hour, since it is preferable to assess the entire movement of the syringe drive, without compromising the safety and performance of the equipment.

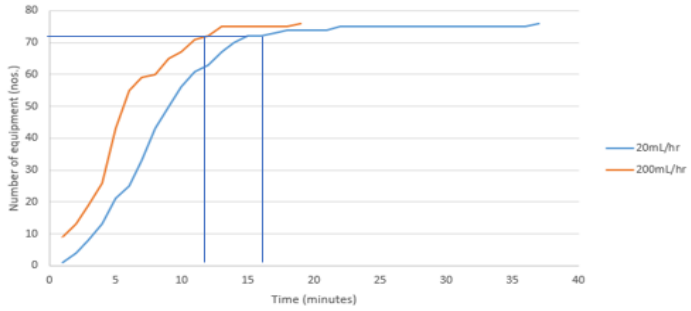

Fig. 3: Cumulative graph showing number of volumetric pumps reaching steady state.

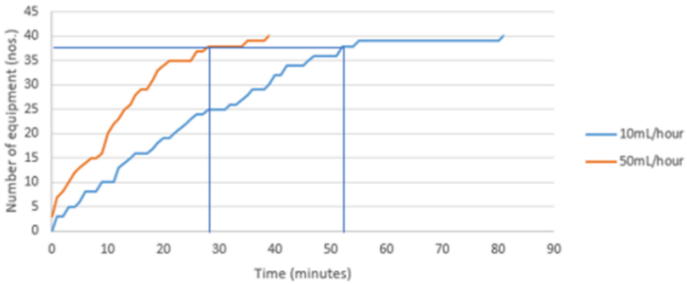

Fig. 4: Cumulative graph showing number of syringe pumps reaching steady state.

Table 1: Time necessary for 95% of the volumetric pumps reaching the steady rate.

Volumetric pump	
Population: 6,882 (Latest: 10980)	
Sample Size: 76	
Confident Level: 95%	
Margin of Error: 11%	
20mL/hour:	16 minutes +/-11% = 14.2 - 17.8 minutes
200mL/hour:	12 minutes +/-11% = 10.7 - 13.3 minutes

Table 2: Time necessary for 95% of the syringe pumps reaching the steady rate.

Syringe pump	
Population: 4,658 (Latest: 4183)	
Sample Size: 40	
Confident Level: 95%	
Margin of Error: 15%	
10mL/hour:	10mL/hour:
50mL/hour:	50mL/hour:

After shortening of flow rate test duration, the total time required for the flow rate test for all infusion pump would be as shown in Eq. (2) below:

$$\begin{aligned} \textit{Total required Time} &= (10{,}980 \text{ nos. x } 0.33 \text{ hour } + \ 4{,}183 \text{ nos. x } 1 \text{ hour}) \text{x } 2 \text{ flow rates} \\ &= 15{,}612 \text{ hours} \end{aligned} \tag{2}$$

Compared to the conventional 2-hour test, the total time required for flow rate testing of all infusion pumps would be reduced by approximately 74.3%. This significant reduction enhances efficiency, optimizes resource utilization and minimizes equipment downtime. However, advice and approval shall be seek from both clinical professionals and the original equipment manufacturers prior to adoption into routine maintenance practice.

3.2. Performance of Implementing Integrated Strategic Life Cycle Management Approaches

With the integrated smart maintenance of methods stated in section 2.1, 2.2, 2.3, 2.4 and 2.5. We able to achieve average availability of the 15,000 infusion pumps greater than 90% in the past 24 months as shown in Eq. (3) below.

$$\text{Average availability} = (1 - \text{down time in hours due to the Equipment fault/total time in hours in the concerned period}) \text{ x } 100\% \tag{3}$$

4. Conclusion

In conclusion, this study has developed and evaluated a smart maintenance approach that enhances cost-effectiveness, labor efficiency and workflow optimization while upkeeping equipment safety and performance. We believe this study offers valuable insights for transitioning from traditional maintenance practices to intelligent management of large-scale infusion pump fleets, particularly in densely populated urban healthcare settings such as Hong Kong, which has a hospital bed density of 4.9 beds per 1,000 inhabitants.

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