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Maintenance of Healthcare Equipment: System Development, Implementation Pathways, and Future Innovation

Lisu Jia
Jilin Jiahua Health Industry Co., Ltd., Jilin Province, China
Corresponding Author: Lisu Jia

ABSTRACT: *Healthcare equipment is fundamental to diagnostic accuracy, treatment continuity, and patient safety. However, many medical institutions, particularly primary hospitals, still rely on reactive repair and lack integrated governance, preventive planning, reliable records, and sufficient technical capability. This paper defines the core content of equipment maintenance, examines challenges in institutions of different sizes, and proposes a closed-loop system covering organization, policies, risk classification, workflows, technical support, personnel development, and performance evaluation. A four-stage implementation path is presented, together with organizational, financial, institutional, technical, and staffing safeguards. The paper also discusses predictive maintenance, connected monitoring, digital twins, lifecycle cost control, and regional collaboration. The proposed framework emphasizes prevention, standardization, adaptability, coordination, economy, and continuous improvement, providing a practical basis for safer equipment operation and higher-quality healthcare delivery.*

Keywords: *healthcare equipment; maintenance; preventive maintenance; lifecycle management; primary hospitals*

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I. INTRODUCTION

A. Background

Healthcare equipment is the material foundation of modern clinical services. Diagnostic systems such as digital radiography, ultrasound, and electrocardiography; therapeutic systems such as ventilators, infusion pumps, and electrosurgical units; monitoring systems; and laboratory analyzers all depend on stable technical performance. Their condition directly affects diagnostic accuracy, continuity of treatment, patient safety, and the ability of a medical institution to use its resources efficiently. As healthcare delivery expands and community-level services assume a larger role, the number and variety of devices in hospitals continue to grow. Equipment maintenance is therefore no longer a narrow repair activity. It is a core element of clinical governance and quality management [1-3].

Many institutions still manage equipment reactively. Devices are used until a failure occurs, maintenance records are incomplete, preventive tasks are irregular, responsibilities are fragmented, and technical staff are insufficient for the size and complexity of the asset base. These weaknesses are particularly visible in primary hospitals, where limited budgets and restricted access to manufacturer support can extend downtime. Repeated breakdowns shorten useful life, disrupt clinical schedules, increase emergency repair expenditure, and may create avoidable safety risks. A structured maintenance system must consequently combine governance, procedures, risk classification, technical support, personnel development, performance review, and continuous improvement [4-7].

B. Purpose and Significance

This paper develops an adaptable framework for the maintenance of healthcare equipment in institutions of different sizes. It clarifies the meaning and value of maintenance, identifies common operational problems, and proposes a closed-loop system covering organization, standards, workflows, technology, staff capability, and evaluation. The framework is intended to be practical: large hospitals can use it to refine lifecycle management, while smaller institutions can adopt a simplified version that protects essential functions without creating an unaffordable administrative burden.

The practical benefits are fourfold. First, regular inspection and preventive maintenance reduce avoidable failures and protect continuity of diagnosis and treatment. Second, timely servicing slows component deterioration and helps institutions obtain the intended service life from capital assets. Third, standardized records and differentiated plans improve the allocation of maintenance funds and labor. Fourth, clear responsibilities and measurable quality controls strengthen patient-safety assurance and support accreditation, internal audit, and broader

improvement in healthcare quality.

C. Development of Maintenance Practice

International practice has gradually moved from post-failure repair toward lifecycle management, risk-based planning, and condition monitoring. Mature systems link equipment inventories, service histories, calibration records, spare parts, failure data, and replacement decisions. Preventive maintenance is scheduled according to clinical criticality, operating frequency, environmental conditions, and manufacturer requirements. Remote monitoring and networked sensors are increasingly used to detect abnormal trends before a device fails. These approaches offer useful direction, but they cannot be copied mechanically. Differences in regulation, financing, staffing, equipment mix, and service capacity require local adaptation [8-11].

In China, research and practice have often concentrated on high-value devices in large hospitals or on isolated maintenance techniques. Primary institutions receive less attention, and many proposed models do not explain how responsibilities, records, budgets, training, and external service providers should work together. A useful framework must therefore connect management theory with an implementation path that can operate under real resource constraints.

II. CORE CONTENT AND MANAGEMENT VALUE

A. Core Content

Healthcare equipment maintenance consists of coordinated daily care, preventive maintenance, corrective repair, calibration or performance verification, and management review. Daily care is performed mainly by users and includes cleaning, visual inspection, accessory checks, start-up tests, environmental checks, and prompt reporting of abnormalities. It forms the first protective barrier because users are closest to the device and can recognize early changes in sound, heat, vibration, output, or alarm behavior.

Preventive maintenance is planned work performed before failure. It may include functional inspection, electrical-safety testing, lubrication, adjustment, software checks, calibration, replacement of wear parts, and confirmation that alarms and protective mechanisms operate correctly. The interval should not be identical for every device. High-risk life-support equipment, intensively used devices, aging assets, and units with repeated failures require closer attention than low-risk equipment with stable performance [12-18].

Corrective repair restores a failed device to a safe and usable condition. Simple faults may be handled on site, whereas complex failures may require manufacturer or third-party support. Every repair should generate a traceable record describing the fault, diagnosis, action, parts used, verification result, downtime, cost, and responsible person. Failure analysis should then feed back into preventive plans, staff training, spare-parts policy, and replacement decisions. The resulting model is a closed loop: prevention is the priority, repair restores service, analysis identifies causes, and improvement reduces recurrence.

B. Management Value

The first value is clinical safety. A ventilator, defibrillator, infusion pump, monitor, analyzer, or imaging system can influence a clinical decision immediately. Maintenance must therefore confirm not only that the device turns on, but also that performance, alarms, accessories, software, and electrical protection meet the intended standard. The second value is economic. Preventing accelerated wear and repeated emergency repair preserves asset value, reduces avoidable replacement, and makes expenditure more predictable. The third value is organizational. A reliable equipment system supports standardized clinical work, improves scheduling, and provides auditable evidence that the institution controls technical risks [12-13].

III. CURRENT CONDITIONS AND KEY CHALLENGES

A. Large Medical Institutions

Large hospitals usually own extensive and technically diverse equipment portfolios. Their difficulty is not simply a lack of resources; it is the mismatch between asset complexity and maintenance capacity. Biomedical engineering teams may be too small, skills may be concentrated in a few individuals, and proprietary technologies may limit access to diagnostic tools, software, or spare parts. Heavy reliance on external vendors can increase cost, delay response, and weaken the hospital's ability to judge service quality. Fragmented procurement, use, maintenance, and disposal records also prevent a complete view of lifecycle performance.

Another common problem is uniform scheduling. Applying the same inspection interval to devices with different risk levels wastes effort on low-risk assets while leaving critical equipment under-controlled. A rational program should distinguish life-support, diagnostic, therapeutic, monitoring, and general equipment; consider failure consequence and detectability; and then determine the depth and frequency of work. The program should also connect maintenance results with renewal planning so that repeatedly failing or obsolete devices are not kept in service merely because each individual repair appears affordable.

B. Primary Medical Institutions

Primary institutions face more fundamental constraints. Maintenance may be assigned informally to clinical or administrative staff without dedicated technical posts. Users may receive only brief operating instruction and may not recognize the importance of cleaning, environmental control, battery care, accessory inspection, or early fault reporting. Procedures can be incomplete, records may be scattered, and annual budgets may not reserve sufficient funds for inspection, calibration, tools, training, or urgent support.

Geographical distance and a small installed base can make commercial service slow or expensive. Complex faults may keep a device unavailable for an extended period, directly reducing service capacity. The appropriate response is not to reproduce the full organization of a tertiary hospital. A primary institution needs a concise inventory, clear user responsibilities, a risk-ranked maintenance calendar, regional technical support, standardized service forms, and simple digital tools that can be sustained by the available workforce.

IV. CONSTRUCTION OF A MAINTENANCE SYSTEM

A. Guiding Principles

The system should follow six principles. Adaptability requires plans that match institutional size, equipment structure, clinical demand, and available resources. Prevention places routine care and planned servicing ahead of emergency repair. Standardization defines consistent responsibilities, procedures, records, and acceptance criteria. Coordination connects users, biomedical engineering, clinical departments, procurement, finance, information technology, infection control, and external providers. Economy requires lifecycle decisions that balance safety, performance, and total cost. Continuous improvement uses operating data and review results to revise the system rather than treating policies as static documents.

B. Organization and Responsibility

A maintenance leadership group should provide governance. It may be chaired by a hospital executive and include the equipment-management unit, clinical departments, procurement, finance, information technology, and quality or safety functions. The group approves policy, allocates resources, resolves cross-department problems, reviews major failures, and monitors improvement. Day-to-day coordination should be assigned to a clearly identified equipment-management function rather than dispersed among unrelated offices.

Responsibilities should be explicit. Equipment managers maintain the asset register, classify risk, prepare plans, coordinate technical work, control documentation, and evaluate providers. Clinical departments perform daily care, pre-use checks, basic troubleshooting permitted by policy, and timely fault reporting. Procurement and finance support contracts, spare parts, and budgets. Information personnel maintain interfaces, cybersecurity controls, and data availability for networked devices. External providers must work under defined response times, competence requirements, service scope, parts controls, reporting rules, and post-repair acceptance.

C. Policies, Standards, and Risk Classification

The policy system should cover asset registration, acceptance, installation, training, daily care, preventive maintenance, calibration, fault reporting, emergency response, outsourced service, spare parts, software changes, relocation, decommissioning, and record retention. Every process requires a responsible role, trigger, action sequence, acceptance criterion, and record. Forms should use consistent identifiers so that an equipment item can be traced across procurement, use, service, cost, and disposal.

Risk classification is the basis for differentiated control. A practical method considers clinical consequence, probability of failure, detectability, operating frequency, device age, maintenance history, environmental exposure, and availability of backup equipment. High-risk assets receive shorter inspection intervals, deeper performance testing, stronger spare-parts protection, and priority response. Medium-risk assets follow standard preventive cycles. Low-risk assets rely more heavily on user care, periodic inspection, and condition-based intervention. Classification should be reviewed after serious faults, changes in use, relocation, or major software and hardware modification [14-18].

D. Closed-Loop Workflows

Daily maintenance begins with the user. A short checklist should confirm cleanliness, power supply, cables, consumables, accessories, alarms, and visible damage. Abnormal findings must be labeled, isolated when necessary, and reported through a single channel. Preventive work begins with an approved annual plan, is converted into monthly or weekly tasks, and ends only after results are recorded and exceptions are resolved. Corrective repair should include reporting, triage, safety isolation, diagnosis, authorization, repair, performance verification, return-to-service approval, and cause coding.

Records must be more than proof that a task occurred. They should enable analysis of failure frequency, recurring fault types, response time, repair time, downtime, preventive completion, cost, parts consumption, and repeat repair. A regular review meeting can identify equipment with abnormal trends, departments with weak user care, providers with poor response, and maintenance plans that require adjustment. Serious incidents should trigger a

focused investigation and corrective action.

E. Technical Support and Personnel Capability

A digital equipment-management system can integrate the asset register, maintenance calendar, work orders, calibration, contracts, costs, inventory, and dashboards. Mobile access or QR codes can simplify fault reporting and allow technicians to retrieve service history at the device. Where infrastructure is limited, a well-designed spreadsheet or lightweight application is preferable to an expensive system that staff cannot maintain. The essential requirement is data consistency, access control, backup, and routine use [9-11].

Capability development should distinguish users, general maintenance personnel, and specialists. Users need safe-operation and daily-care training. Maintenance staff need structured learning in electronics, mechanics, sensors, networks, software, metrology, infection control, and risk management. Complex modalities may require manufacturer training or regional specialist support. Competence should be assessed through practical tasks, not attendance alone, and individual authorization should match verified ability.

F. Performance Evaluation

Evaluation should combine process, outcome, economic, and safety indicators. Useful measures include preventive-maintenance completion, on-time completion, first-response time, mean time to repair, equipment availability, repeated-fault rate, record completeness, calibration status, user-training coverage, maintenance cost by asset class, provider compliance, and safety-event closure. Targets should reflect device criticality and local conditions. Results should support coaching and resource decisions, not encourage technicians to close work orders before the equipment has been properly verified.

G. Evidence-Based Optimization of Maintenance Intervals

Fixed service intervals are easy to administer, but they can produce both over-maintenance and under-maintenance. Evidence-based interval optimization begins by separating equipment according to clinical consequence, failure history, detectability, utilization, environmental stress, age, and availability of backup units. The maintenance team then compares preventive findings with corrective work orders, repeated faults, downtime, parts consumption, and post-service verification results. Where an interval repeatedly produces no meaningful findings, a carefully controlled extension may be considered for low-risk assets. Where failures or performance drift occur between scheduled visits, the interval, task content, or user inspection routine should be strengthened. Any change must remain consistent with regulation, the manufacturer's safety information, and documented institutional risk acceptance [12-18].

Interval review should be treated as a governed experiment rather than an informal shortcut. The institution should define the population of devices, baseline performance, decision thresholds, monitoring period, and authority for approval. Outcomes should be reviewed by both technical and clinical representatives because a statistically infrequent failure may still be unacceptable when the clinical consequence is severe. This approach converts maintenance history into operational evidence, improves the use of engineering time, and preserves a defensible link between workload reduction and patient safety.

V. IMPLEMENTATION PATH AND SAFEGUARDS

A. Phased Implementation

Implementation can proceed in four stages. During preparation, normally one to two months, the institution establishes a leadership group, assigns responsibilities, inventories all equipment, cleans duplicate records, identifies critical assets, and assesses current maintenance capability. It then defines the target system, schedule, responsible departments, and minimum resources. The inventory should record the device name, model, serial number, location, owner department, risk class, service status, key dates, contract information, and available technical documents.

During system development, normally two to three months, the institution issues core policies, creates standardized forms, classifies equipment, prepares preventive plans, defines reporting and escalation routes, selects external support, and trains users and maintenance staff. Digital records should be introduced at the same time so that new work does not continue to generate disconnected paper files.

A trial period of three to six months should follow. Selected departments or equipment groups operate the full workflow while managers collect completion, downtime, fault, cost, and user-feedback data. Review meetings identify unclear responsibilities, unrealistic intervals, unnecessary approvals, missing acceptance tests, and training needs. After correction, the system enters routine operation. Annual review then considers changes in equipment, clinical services, staffing, regulation, vendor performance, and incident experience.

B. Safeguards

Organizational support requires visible executive ownership and a permanent coordination mechanism. Financial support requires a maintenance budget covering planned service, calibration, test equipment, essential spare parts, training, software, and emergency contingencies. Policy support requires internal audit, document control, and

enforcement of safe isolation and return-to-service rules. Technical support may combine in-house capability, manufacturer service, qualified third parties, and regional collaboration. Personnel support requires sufficient staffing, clear career development, competency assessment, and incentives linked to quality and reliability rather than repair volume.

VI. INNOVATION AND FUTURE DEVELOPMENT

A. Intelligent and Predictive Maintenance

Artificial intelligence and machine learning can support failure prediction when institutions have reliable operating data, consistent fault coding, and enough historical cases. Models may identify abnormal patterns in temperature, current, vibration, pressure, alarms, usage hours, or image-quality indicators. Their role is to prioritize investigation, not to replace technical judgment. False alarms, data drift, cybersecurity, explainability, and validation must be controlled before predictive outputs influence clinical availability decisions [19-20].

Internet-of-Things sensors and secure device interfaces can enable continuous or near-real-time condition monitoring. Dashboards may show utilization, environmental conditions, battery health, error codes, and maintenance due dates. Digital twins can extend this approach by linking a physical asset with a virtual model used to simulate degradation and compare maintenance strategies. These technologies are most valuable for critical or high-cost systems; routine devices may be managed more economically through inspection and simple condition indicators [11,19-20].

B. Lifecycle and Quality Management

Future maintenance will be integrated more closely with procurement and renewal. Tender evaluation should consider reliability, service access, training, software support, spare-parts availability, cybersecurity updates, and total lifecycle cost, not only purchase price. Maintenance data should inform whether an asset is retained, upgraded, redeployed, or replaced. Quality control should similarly extend from acceptance and installation through routine operation, calibration, repair, modification, and disposal. This lifecycle view aligns safety with economic performance.

C. Accessible Regional Models

Primary institutions need affordable tools and shared expertise. Regional maintenance centers can provide pooled inspection, repair, calibration coordination, training, spare parts, and remote consultation. Larger hospitals can support smaller facilities through technical networks, while standardized digital forms allow comparable records across sites. Low-cost mobile tools, simple knowledge bases, and guided troubleshooting can raise reliability without demanding a full specialist department at every location. Governance must still define accountability, data protection, response priorities, and acceptance of outsourced work.

D. Governance of Outsourced Service and Maintenance Data

Outsourcing can supplement scarce specialist capacity, but responsibility for equipment safety remains with the healthcare institution. Contracts should define the covered assets, preventive tasks, response and restoration targets, qualification requirements, access to diagnostic software, use and traceability of spare parts, cybersecurity obligations, escalation routes, documentation format, and the tests required before return to clinical service. Performance review should distinguish rapid attendance from verified restoration: a work order is not complete until the device has passed functional and safety checks and the user department has received clear release information. The recurring demand for integrated maintenance services in Chinese hospitals illustrates the operational importance of transparent scope, acceptance, and vendor-accountability rules [4-7].

Maintenance data also require governance. Equipment identifiers, fault codes, timestamps, cost fields, and completion statuses should be defined consistently across departments and external providers. Access should be role-based, changes should be auditable, and records should be backed up for the period required by institutional and regulatory policy. High-quality data support inventory control, budgeting, risk review, replacement planning, and machine-learning applications; incomplete or inconsistent data can create false priorities and undermine predictive models. Current WHO guidance therefore treats inventory and maintenance information systems as part of lifecycle health-technology management rather than as isolated administrative software [9-11].

VII. CONCLUSION

Healthcare equipment maintenance is a patient-safety, quality, and asset-management function. An effective system connects daily user care, risk-based preventive maintenance, controlled repair, performance verification, reliable records, and management review. Its foundation is clear governance; its operating mechanism is a standardized closed loop; and its long-term strength depends on competent personnel, proportionate technology, adequate resources, and measurable improvement.

Across all settings, the objective remains safe, available, traceable, and economically supportable equipment.

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