



Maintenance management strategies for medical equipment in healthcare institutions: a review

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Abstract

A large amount of medical equipment is now extensively utilized in healthcare institutions to assist clinical practitioners in the diagnosis and treatment of diseases. And the applications of such advanced and sophisticated medical equipment have greatly improved the quality of patient care, significantly alleviated the sufferings of patients, and facilitated their rehabilitation. Nevertheless, failures and malfunctions of medical equipment have compromised its reliability and effectiveness as well as jeopardizing the safety of patients and clinical staffs. And a majority of the failures can be attributed to the insufficient and inappropriate maintenance. Therefore, it is imperative to implement effective maintenance management to ensure that medical equipment is in its optimal function, and thereby mitigating the clinical risk resulted by adverse events. The presented review mainly discussed the maintenance strategies of medical equipment including corrective maintenance, preventive maintenance and predictive maintenance. In order to replace the fixed-interval of preventive maintenance, we systematically discussed methods to adjust the maintenance period. Additionally, two strategies to predicting future failures of medical equipment through processing and analyzing the maintenance data obtained from the historical maintenance logs and condition data collected by the embedded sensors are elaborated. Besides, the classification and life cycle of medical equipment are also summarized.

Keywords: Medical equipment, maintenance, healthcare institutions, management

1. Introduction

Medical equipment is playing a vital role in clinical practices and is becoming an indispensable component of healthcare institutions^[1-3]. And the continuous advancement and widespread application of medical equipment have greatly enhanced the quality and effectiveness of healthcare services^[4-6]. The utilization of medical equipment, ranging from sophisticated and large-scale products such as linear accelerator, magnetic resonance imaging and computerized tomography to low-risk and small products such as pulse oximeter and microscope, has significantly facilitated the diagnosis and treatment of diseases or injuries^[7-11]. And with the help of medical equipment, clinical professionals can provide a more comprehensive evaluation of the patient's physical state, and thereby developing an effective and suitable treatment strategy to curb health deterioration^[12].

However, the growing variety and number of medical equipment is imposing elevated demands on its maintenance management^[13]. And the escalating technological complexity of medical equipment has led to the increase in the probability of failure, because the failure trend of medical equipment is proportional to its technological complexity^[14]. Meanwhile, the maintenance expenditure of medical equipment is becoming burdensome to healthcare institutions due to the high failure rate^[15,16]. Moreover, malfunctions of medical equipment can reduce its reliability and availability, which will compromise the quality and effectiveness of healthcare services delivered to the public^[17]. Medical equipment failures can result in the occurrence of adverse events and jeopardize the safety of patients and clinical staffs^[18]. In fact, inadequate and inappropriate maintenance management is the most common cause of medical equipment failures. And a majority of the equipment failures are resulted by avoidable factors^[19,20].

Therefore, implementing effective maintenance for medical equipment and ensure that it is in the optimal functional status is very important. Maintenance can be defined as the activities or actions that are carried out to restore a device or machine to a proper



condition^[21]. And as a vital link within the life cycle of medical equipment, it aims to improving the reliability and safety of medical equipment as well we reducing the maintenance expenditures^[21-23]. The appropriate and efficient maintenance practices of medical equipment can effectively mitigate the adverse consequence caused by equipment malfunctions^[24]. Furthermore, the implementation of effective maintenance can obviously improve the quality of healthcare services and patient satisfaction, thereby bolstering the reputation of hospitals or clinics.

In this review, we mainly discussed the maintenance strategies of medical equipment including corrective maintenance, preventive maintenance and predictive maintenance. In addition, the classification and life cycle of medical equipment is also proposed. The purpose of this review is to enhance the understanding of medical equipment maintenance strategies for clinical engineers and help them manage the maintenance of medical equipment more effectively.

2. Classification of Medical Equipment

The term “medical devices” typically refers to the instruments, equipment, appliances, or materials used alone or in combination on the human body directly or indirectly for the disease prevention, diagnosis, treatment, monitoring or alleviation^[25]. And medical equipment that includes necessary software is generally considered as a subcategory within the realm of medical devices. In hospitals, clinical engineers tend to roughly divide medical devices into two categories: medical equipment and medical consumables based on their physical form and attributes^[26]. The past decades have witnessed remarkable advancements in the field of science and technology, accompanied by the escalating diversity and intricacy of medical equipment, which have profoundly revolutionized the way healthcare is delivered^[27-29]. And modern hospitals greatly rely on a diverse range of medical equipment to facilitate early disease diagnosis and prevent health deterioration. Medical equipment has become an indispensable component of healthcare institutions and significantly enhanced the effectiveness of healthcare services^[30-33].

Different medical equipment possesses distinct functions, and the term “function” referring to their intended service or primary usage purpose. And medical equipment can be classified into five categories according to their functions, namely diagnostic, therapeutic, life support, analytical, and miscellaneous^[34]. Medical equipment that utilized for the identification of any disease or illness is classified into diagnostic equipment. Therapeutic equipment is designed to provide treatment or remedy for various diseases suffered by patients. The medical equipment with life support and emergency functions is regarded as life support equipment, which will result in harms to patients and even lead to fatality when equipment failures happened. Analytical equipment refers to laboratory procedures for analyzing samples from patients, while miscellaneous equipment refers to any equipment used to assist primary care and clinical process^[35].

3. Life cycle of Medical Equipment

The increasing complexity and growing significance of medical equipment in hospitals have led to a heightened demand for its management, prompting the introduction of the life cycle concept in medical equipment management^[36]. It utilizes contemporary management theory, advanced management technology and methods to ensure that safety and effectiveness are prioritized, with quality management serving as the core. This approach is closely integrated with clinical practice, reinforcing technical and application management throughout the life cycle of medical equipment to achieve the overarching objectives of high efficiency, low consumption, and optimal performance. It represents a comprehensive dynamic management system that combines technological management with economic management. The life cycle of medical equipment encompasses several stages^[37,38]: establishment of requirements, project assessment, procurement, installation and acceptance, training, quality control and assurance, maintenance, and decommissioning. The life cycle of medical equipment is shown in [Figure 1](#).

3.1 Establishment of requirements

According to their individual requirements and development plans, clinical departments draft medical equipment procurement plans, clearly specifying the type, quantity, and budget of the required equipment. Subsequently, a detailed report should be submitted to the hospital's medical equipment management committee for thorough evaluation. Medical equipment that is approaching its end-of-life or deemed irreparable should be promptly replaced. Furthermore, clinical departments may consider adopting more advanced medical equipment to support their innovative medical technologies.

3.2 Project assessment

After receiving the medical equipment procurement reports, the medical equipment management committee will assess it based on the hospital's overall development strategy, as well as the feasibility, cost-effectiveness, and related risks of the project. It is important to note that most hospitals have limited budgets allocated for medical equipment purchases annually. However, if the report submitted by clinical department is compelling and persuasive, their plans will be approved.

3.3 Procurement

Once the medical equipment procurement plan is approved, the procurement department can proceed with the purchasing process

in accordance with the allocated budget and relevant local guidelines or national regulations. It is generally recommended to conduct an official tender process to facilitate a comprehensive comparison of solutions offered by vendors. This comparison should take into account differences in cost, functionality, quality, and maintenance services provided, etc.

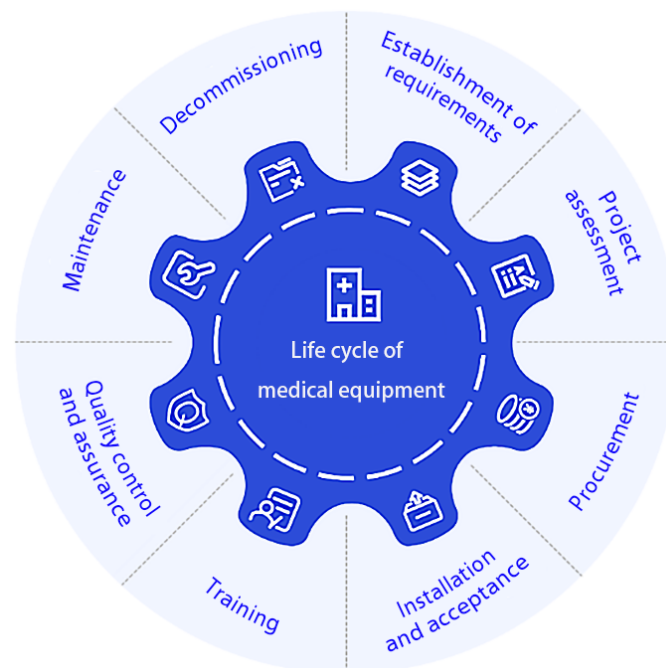


Figure 1. The life cycle of medical equipment.

3.4 Installation and acceptance

After the purchase contract is signed, the vendor is required to deliver the medical equipment to the designated location for installation within the specified timeframe as stipulated in the contract. Prior to installation, both the clinical user and vendor conduct an inspection of the installation site, ensuring compliance with country-specific regulatory requirements based on equipment type. The installation process is typically carried out by professional personnel from the vendor. Furthermore, it must be ensured that the installation does not exert a significant impact on the environment.

After the purchased medical equipment is successfully installed in the hospital, a commissioning and acceptance procedure will be carried out. Modern hospitals have established a systematic and rigorous medical equipment acceptance process that is both reasonable and feasible. The responsibility for the acceptance work generally lies with the clinical engineering department, while active participation from clinical users is also required. The final acceptance report typically requires signatures from three parties: the clinical engineering department, the clinical user, and the supplier. Ensuring high-quality acceptance work serves as a crucial guarantee for the stable and reliable operation of medical equipment in clinical practice. Therefore, medical institutions should place greater emphasis on this work.

3.5 Training

Before medical equipment is utilized in clinical practices, a systematic use training must be provided by the vendor. A well-designed use training project can effectively enhance the proficiency of technical personnel in utilizing the equipment, thereby reducing the failure rate and contributing to improved clinical efficiency. The training will be conducted by experienced application specialists, either on-site or online. For large medical equipment with intricate functions, a hands-on practical training is also needed. In addition to clinical technicians, active training for clinical engineers is also essential.

3.6 Quality control and assurance

To ensure the reliability and effectiveness of medical equipment, periodical performance and safety inspection is required, which is carried out by qualified laboratories. Besides, a routine check on the status of medical equipment is also necessary.

3.7 Maintenance

The performance degradation and malfunction of medical equipment are inevitable with long-term usage. To ensure the availability of medical equipment, clinical engineers need to actively engage in equipment maintenance and troubleshooting. Additionally, it is

crucial to meticulously record the specific maintenance processes and replaced components. This will enable future assessment of potential risks associated with the medical equipment based on the maintenance log, thereby determining optimal moment for upgrades, updates, or even replacements.

3.8 Decommissioning

The term “decommission” refers to the disposal of medical equipment that has reached the end of its service life and can no longer be utilized after undergoing technical evaluation or in compliance with relevant regulations. And the decommission of medical equipment should also be considered when it becomes irreparable or the cost of maintenance exceeds a reasonable threshold.

According to the above, the life cycle of medical equipment is beginning with requirements definition and ending with decommissioning. The advancement of technology has led to the increasing sophistication, advancement, and intelligence of medical equipment, thereby significantly enhancing the quality of healthcare services^[39-41]. As medical equipment plays a more vital role in medical activities, the maintenance of which is becoming more demanding^[13]. Malfunctions of medical equipment may compromise its performance and reliability which will effect the accuracy of diagnostic results and the effectiveness of treatment options^[42,43]. Moreover, the failures of medical equipment may even endanger patients and clinical staffs^[44,45]. Many studies have consistently demonstrated a significant correlation between adverse injuries resulted by failures of medical equipment and patient fatalities^[46-48]. And the most prevalent cause of medical equipment failure is believed to be inadequate maintenance^[34,36]. Accordingly, maintenance is a crucial stage in the life cycle of medical equipment. Therefore, in the subsequent section of this paper, the maintenance strategies of medical equipment will be extensively discussed.

4. The Maintenance Strategies of Medical Equipment

Maintenance of medical equipment refers to all activities and actions that are aimed at preserving the equipment in an optimal condition or restoring its functions in accordance with the specification of manufacturer^[21]. Proper and efficient maintenance management of medical equipment can improve its safety and reliability, which will not only ensure the safety of clinical users and patients, but also enhance the quality of healthcare services^[49]. Typically, maintenance strategies of equipment can be divided into corrective and preventive maintenance^[50-52]. Corrective maintenance presents the reactive maintenance activities that act only after the equipment failures occur, while preventive maintenance is one of the proactive maintenance which acts before malfunctions of equipment^[42]. And with the fast developing and applying of sensors, machine learning (ML) as well as the internet of things (IoT), the predictive maintenance has attracted much attentions^[53-55]. Three maintenance strategies of equipment are illustrated in Figure 2.

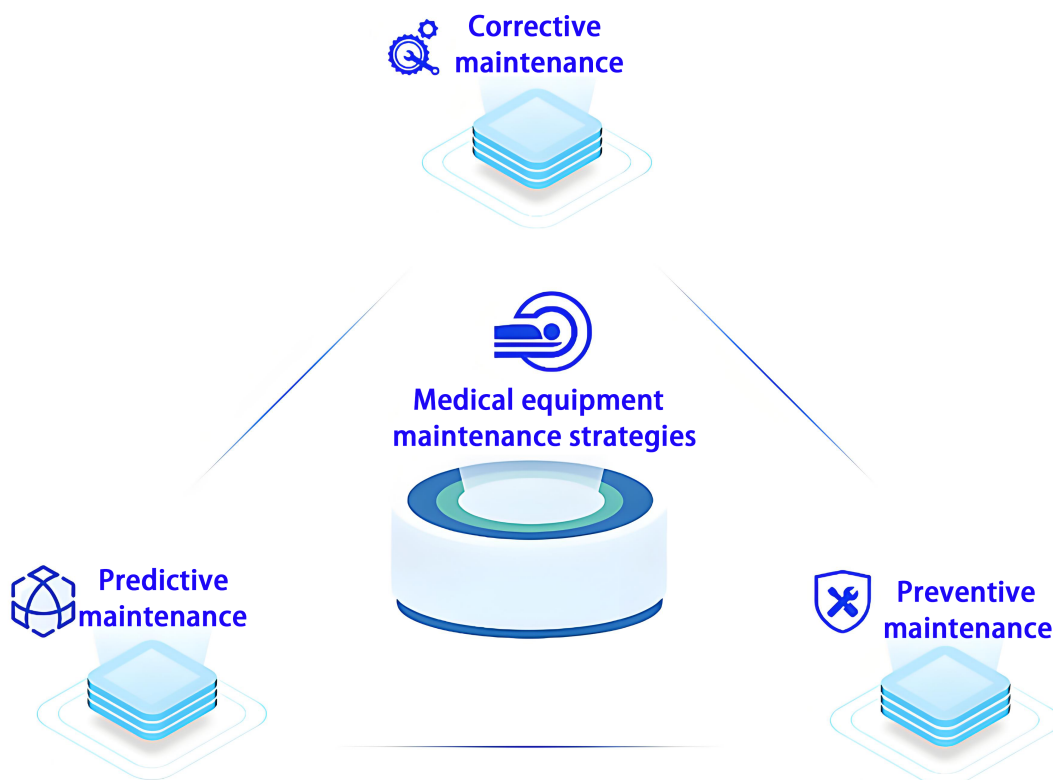


Figure 2. Three maintenance strategies for medical equipment.

4.1 Corrective maintenance

Corrective maintenance (CM) is also referred to as curative or palliative maintenance^[36], and is provided after a failure of medical equipment occurs or is discovered^[56]. And this maintenance strategy involves repairing equipment failures or replacing it when it cannot be repaired or the cost of maintenance is too high^[57,58]. Given that the actions of CM are not performed until the malfunctions of medical equipment are detected, the time and form of interventions cannot be accurately predicted, in other words, such maintenance strategy requires no planning or analysis. However, the utilization of such maintenance strategies often results in unforeseen equipment failure or downtime, which not only compromise the optimal function of medical equipment but also potentially leads to delays or even interruptions in clinical activities. The necessity to improve this traditional approach of medical equipment maintenance management has prompted the implementation of preventive maintenance for medical equipment.

4.2 Preventive maintenance

Preventive maintenance (PvM) is also referred to as periodic maintenance or time-based maintenance^[59,60]. In such maintenance strategy, medical equipment maintenance is performed regularly or at fixed intervals without considering the current condition of equipment^[61]. PvM is often carried out before equipment failures occur, and it aims to reduce unexpected malfunctions or breakdowns^[62]. Performing PvM enables clinical engineers to proactively identify potential issues of medical equipment at an early stage and intervene promptly, which can significantly reduce the failure rate of equipment and extend its lifespan^[44]. By emphasizing PvM strategy, healthcare institutions can ensure the optimal functions of medical equipment and guarantee its reliability and accuracy^[63]. Nowadays, the PvM strategy is widely implemented in the majority of healthcare organizations around the world^[64]. The procedures of PvM consist of several necessary steps, including inspection, electrical safety testing, cleaning, calibration, preemptive parts change, and lubrication^[63,65]. In addition to the procedures, another important concern for PvM is the execution frequency. Medical equipment manufacturers usually provide PvM intervals for each machine, which can be found in the user guide. And healthcare centers can also select a reasonable interval based on the long-term experience of clinical engineers^[66]. However, the determination of PvM intervals holds significant importance as medical equipment may be either over or under maintained if an inappropriate interval is selected^[67]. On the one hand, the high frequency of PvM can undoubtedly contribute to the reduction of equipment failure rate^[57]. However, it should be noted that the successful execution of PvM requires allocation of labor and budget. Besides, in PvM strategy, components that are vulnerable and fragile are usually replaced before failure occurs, although they may still be able to function for a period of time^[62]. Therefore, high frequency of PvM may lead to a sharp increase in the cost of maintenance and the mismatch between the increased workload and the actual returns should also be taken into consideration. On the other hand, if PvM is infrequent, the reliability as well as the safety of medical equipment may be compromised and the failure rate will also increase^[60]. Accordingly, it is a vital task to optimize the PvM interval to obtain a desirable maintenance result. And the optimization of PvM intervals can be achieved by assigning different PvM priorities to various medical equipment and subsequently implementing PvM activities at varying frequencies based on the priority levels. Another method to optimize the PvM intervals can be achieved through the methodology of failure mode and effect analysis (FMEA).

4.2.1 Determining PvM priorities via mathematical models

The PvM priorities of various medical equipment can be determined through establishing a mathematical model^[13]. Ortiz-Posadas *et al.* developed a mathematical model including seven variables to assess the PvM priorities of medical equipment and help clinical engineers schedule proper PvM management strategies. They defined qualitative and quantitative domains for each variable and assigned relative weightages to each variable which mainly depends on the experience of clinical engineers. A higher value of weighting factor indicates a greater importance. Then they used mathematical formulas to calculate the priority index of PvM, with values ranging from 0 to 1. The PvM priority was divided into three categories, each corresponding to a value interval, as shown in Table 1. And different categories require different frequencies of PvM interventions^[66]. Miniati *et al.* proposed a concept of maintenance priority index (MPI) to define the priority level of PvM required for medical equipment, and the MPI is determined by the criticality index (CI) and the type of medical equipment. The authors defined CI of medical equipment based on the technical complexity (denoted as complexity level) as well as the department in which it served (denoted as activity area), and both the complexity level and the activity area were given relative weighting factors, which are categorized in Table 2 and Table 3, respectively. The value of CI can be calculated through multiplying the complexity level by the activity area, and the results were then divided into different levels according to their values. And the CI was used to indicate the importance of a medical equipment. In combination with the type of medical equipment and its CI category, a PvM priority level can be determined. For a high-MPI medical device, PvM practice is required at least once a year. For a medium-MPI medical device, a PvM action is suggested for at least every two years. And as to the low-MPI medical device, a PM practice for at least every three years is demanded. While for the null-MPI medical device, PM is not required^[14].

These mathematical models tend to prioritize PvM based on the safety and failure risk of medical equipment, which is more rational than blindly following the manufacturers' recommendations. This is because manufacturers often suggest excessive preventive maintenance without considering the actual usage of medical equipment^[68].

Table 1. Intervals for PvM priority and its frequency.

Interval	PvM priority	PvM frequency
[0-0.39]	Low	Once a year
[0.4-0.69]	Medium	Twice a year
[0.7-1]	High	At least three times a year

PvM: preventive maintenance.

Table 2. The caterogies of the complexity level.

Categories	Medical equipment included	Weightages
High	Includes imaging, medical systems and miniaturized technology with high use of integrated software	3
Medium	Diagnostic, ultra-sounds, and electrosurgical devices	2
Low	Simple equipment such as defibrillators or ECGs	1
Very low	Tables, scialytic lamps, probes or accessories	0

ECGs: electrocardiographics.

Table 3. The caterogies of the activity level.

Categories	Definitions	Weightages
Urgent	All emergency areas and operating theatres	9
High intensity	All those areas within the hospital which furnish high intensity care such as resuscitation and ICU	3
Medium intensity	Day hospitals and diagnostic areas	2
Low intensity	Ambulatories, in-patient wards and laboratories	1
Clinical activity support	All areas that are regarded as non- clinical such as administration offices or sterilization units	0

ICU: intensive care unit.

4.2.2 Determining PvM priority levels via machine learning

Although a variety of mathematical models have been developed to determine the PvM priorities and help clinical engineering departments to schedule PvM activities more reasonably, these mathematical models do not adopt consistent approach, and the criteria weightages used in these models rely on the experience of clinical engineers, which will lead to inconsistant results^[14,35]. Therefore, it would be more practical to develop a method for PvM priority assessment without clinical engineers’ manual intervention to determine the weighting factors. Nowadays, ML as a part of artificial intelligence (AI), has significantly promoted the research of medical science^[69-71]. And ML exhibits better performance compared with mathematical models with regard to classiffication and regression tasks^[72]. Therefore, ML may also contribute to PvM priorities assessment of medical equipment due to its powerful computational ability. Zamzam *et al.* extracted 16 features (such as equipemnt age, function, current PvM status, maintenance complexity, maintenance cost, etc.) from 13,352 medical equipment used in the public healthcare facilities in Malaysia and conducted prioritization analysis through a modified k-Means clustering algorithm. The output of the developed prioritization evaluation system can help clinical engineers prepare work plans of PvM and ensure the reliability and safety of medical equipment. And such analysis system determining the PvM priority levels based on the database without the manual intervention of practitioners^[35]. The use of ML techniques to evaluate PvM priorities overcomes the limitation of mathematical models which requires manual intervention to determine the weighting factors. And ML can be expected to become a effective and useful tool to help clinical engineering departments manage the PvM activities of medical equipment.

4.2.3 Adjusting PvM intervals based on FMEA

Problems or failures discovered during the implementation of maintenance activities also play a vita role in adjusting PvM intervals^[73]. Based on the methodology of FMEA, Ridgway *et al.* divided the severity as well as the percentage of the PvM problems into 4 level, respectively. Both the severity and percentage of the PvM problems were given a specific weighting factor as shown in [Table 4](#), and the product of which was ultimately defined as risk score. The obtained risk score can be used to evaluated the effectiveness of PvM actions. When the risk score of a medical equipment is lower than 8, its PvM practice can be regarded as effective. And if the risk score is less than 6, the PM interval is suggested to be extended. But attention should be given to shortening

the PvM interval when the risk score is higher than 8^[46]. Li *et al.* designed a management platform for the maintenance of medical equipment which could help clinical engineers found out the reasons as well as distribution of equipment failures and guide technicians to develop more reasonable PvM plans based on analyzing the information produced by the maintenance of monitors. According to their work, the analysis and use of the maintenance data through such maintenance management platform effectively decreased the maintenance costs and equipment failure rate and enhanced the availability of equipment^[62]. Therefore, by analyzing the maintenance results, such information can serve as reliable indicator to optimize PvM intervals.

Table 4. Classification of the severity and percentage of the PvM problems.

PvM problem severity rating	PvM problem rate found	Both weighting factors
Level 1: potentially life threatening	High: > 25%	4
Level 2: serious	Moderate: 10%-25%	3
Level 3: minor	Low: 0.1%-9.9%	2
Level 4: unreported problem	Very low: < 0.1%	1

PvM: preventive maintenance.

4.3 Predictive maintenance

According to the above, the implementation of PvM with appropriate interval does, to a certain extent, reduce the probability of medical equipment failure. However, it is not always able to completely intercept failures before they occur, especially those random or sudden failures^[57]. Moreover, in PvM strategies, components of medical equipment may often be replaced before they reach the end of their service life. The practice of PvM undoubtedly enhances the reliability and safety of medical equipment, but it also means an increase in the maintenance costs^[64]. Hence, a maintenance strategy that can predict future failures according to the historical maintenance data or the current condition of medical equipment is urgently needed to avoid the unexpected malfunctions and reduce the maintenance costs^[60]. And such innovative maintenance strategy is called predictive maintenance (PdM). By analyzing and processing the large amount of data generated by medical equipment, hidden errors can be detected and possible failures can be predicted^[74]. Compared with PvM, PdM does not require a scheduled maintenance calendar, because this maintenance strategy can implement maintenance activities in a timely manner according to the analytic results. In the following section of this paper, we will discuss two approaches to implementing PdM.

4.3.1 Predictions based on maintenance data

Maintenance data of medical equipment including failure records and performance inspection results can serve as training data for ML models and the analytical outputs of which enable the prediction of future potential failures, the described process is shown in Figure 3. In their work, Badnjevic *et al.* collected measurement data from periodical performance and safety inspection of 1,221 defibrillators and developed an automated system through machine learning techniques which can effectively predict malfunctions of the equipment. They employed 5 various ML algorithms to develop predictive systems, including Decision Tree (DT), k-Nearest Neighbor, Random Forest (RF), Support Vector Machine (SVM), and Naïve Bayes. And among these algorithms, the RF algorithms exhibited the highest accuracy. The developed system can predict the performance and future failures of defibrillators with great accuracy, thus optimizing the present management strategies of medical equipment^[75]. Kovačević *et al.* employed ML algorithms to predict the performance and future failures of infant incubators based on their yearly inspection results from 2015-2017. And among 5 different ML algorithms, the DT algorithms exhibited the highest accuracy (98.5%)^[76].

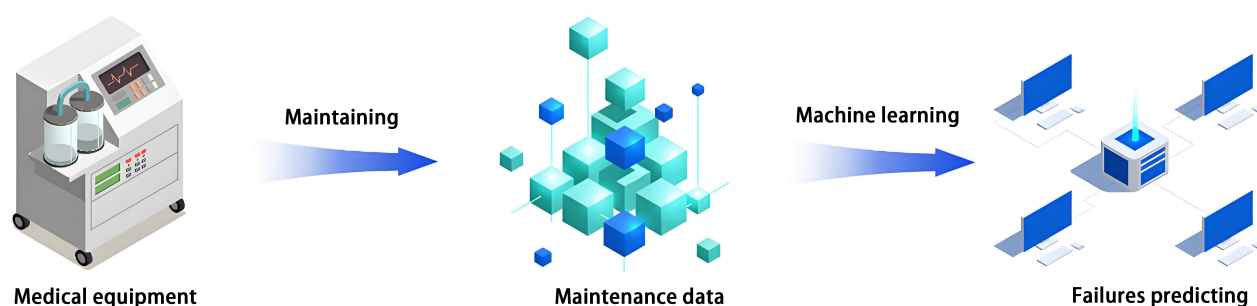


Figure 3. Schematic diagram of medical equipment failure prediction based on maintenance data.

These studies mentioned above demonstrate that the extensive maintenance data of medical equipment can be used to forecast equipment problems or malfunctions, and thereby mitigating failure risks, improving the reliability and availability of equipment as

well as reducing the maintenance costs. Nevertheless, these studies only focus on one type of medical device. And different kinds of medical devices possess various functions and require specific evaluation approaches to ensure their accuracy and safety. Therefore, a model that takes into account different kinds of medical devices will definitely be more suitable and practical for different healthcare facilities. Recently, Zamzam *et al.* studied 19 categories of 13,350 units of medical equipment used in several healthcare facilities and extracted 13 novel features to construct failure prediction model for medical equipment. In contrast to previous studies that involve only one type of medical equipment, their predictive model exhibited superior performance while mitigating the risk of overfitting. And such practical model effectively helped clinical engineers prepared maintenance plans and budget allocation before medical equipment failures take place, and eventually improving the medical equipment maintenance strategy^[77].

In addition to various kinds of medical equipment, a good failure predictive model must consider of different types of maintenance data. During the maintenance of medical equipment, two distinct types of maintenance data are generated, namely structured and unstructured data^[78]. Structure maintenance data refers to the categorical and numerical data, such as downtime, equipment age, etc., while unstructured maintenance data refers to historical failure records in the maintenance log. To the best of our knowledge, the majority of studies utilize structured data only, with a limited number of researchers devoting attention to unstructured maintenance data. Rahman *et al.* developed a data-driven ML model based on the multimodal maintenance data of 44 types of medical equipment from 15 healthcare structures to predict equipment failures. Their model took full advantage of both structured and unstructured maintenance data for predictive output. The unstructured data refers to the text records of equipment failure in the log history which were rarely utilized in other studies. In their work, the strategy of Latent Dirichlet Allocation was applied to process and analyze the text document^[79]. Predictive models based on multimodal maintenance data possess great potential as well as dependability and should receive more attentions.

4.3.2 Predictions based on condition monitoring

The historical maintenance data of equipment can only provide an average indication of its performance degradation, whereas the real-time condition data can reflect the health status of equipment more precisely^[80]. And a large volume of condition data of equipment can be obtained by the use of sensors, which can serve as evidence to predict failures^[81]. Figure 4 depicts the process of equipment failure prediction based on condition monitoring. Nowadays, medical devices are usually equipped with sensors and are linked to the internet, which significantly facilitates the real-time condition monitoring^[82]. Condition data captured by sensors such as noise, vibration, etc. can be transmitted to the management platform via the network, and subsequently be analyzed and processed by ML or AI, thereby enabling the effective failure prediction^[83]. In fact, this process is the application of the IoT technology, and this PdM strategy can also be referred to as condition-based maintenance. Proactive maintenance management for medical equipment can be achieved through IoT as it is able to provide real-time monitoring of medical equipment^[84]. Shamayleh *et al.* reviewed the maintenance data of medical equipment from maintenance logs of a local healthcare institution in the United Arab Emirates and identified the Vitros-Immunoassay Analyzer as the study candidate, because it exhibited the highest failure rate according to the record. They found that the belt slippage of metering arm is the major failure mode, which typically caused by the movement of pulley and the wear out of belt. Subsequently, they fixed accelerometers close to the belt to obtain vibration signature which usually changed when slippage happened. And the collected data was then transformed from time domain to frequency domain through Fast-Fourier Transform algorithm and the features extraction and selection were performed by SVM algorithm to predict the future equipment failures. Their proposed approach is effective with respect to the failure diagnosis and prediction^[85]. Zhou *et al.* collected real-time status data of three CT equipment during one year via sensors and proposed an intriguing data-driven model SAX-HCBOP based on the CoBOP and HIGB method for predicting equipment anomalies. Such novel model exhibited better performance compared to the benchmark models and effectively enhancing the reliability management of medical equipment^[64]. The application of the IoT technology will bring new opportunities to the maintenance of medical equipment in healthcare institutions. And the condition monitoring based PdM strategy will greatly improve the reliability and safety of medical equipment as well as reduce the maintenance expenditures.

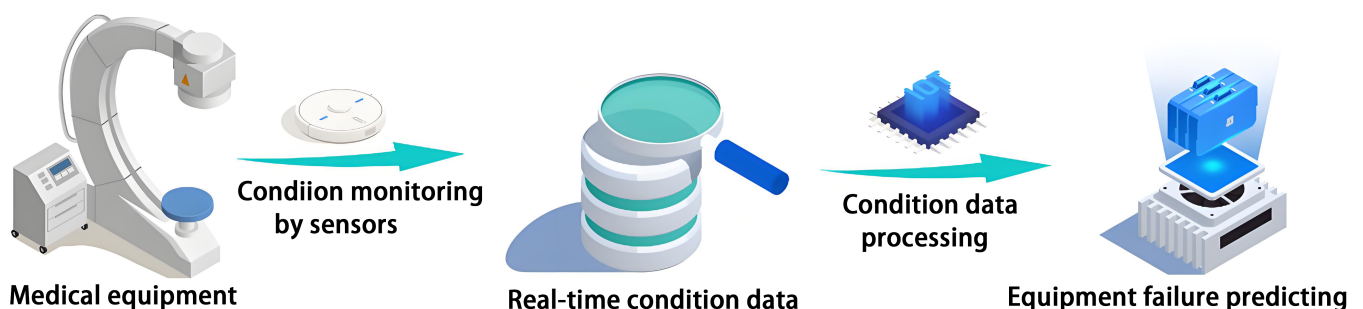


Figure 4. Schematic illustration of the process of medical equipment failure prediction based on condition monitoring.

Another new paradigm and concept that can implement the monitor of equipment condition and predict its future abnormalities is digital twin^[86-88]. Digital twin is a high-fidelity digital replicat of a physical equipment or system which can adapt to the changes of the physical asset through monitoring its condition in real time and then predicting the future failures based on the obtained information^[89]. Digital twin was initially developed by USA air force and NASA to ensure the reliability and safety of their air force vehicles^[80]. Since then, digital twin has been employed in various fields, of which equipment maintenance is the most application. However, the utilization of digital twin in medical equipment maintenance remains uncommon and requires more efforts. In their study, Madubuike *et al.* elaborated the basic concepts of digital twin and identified the needed components of digital twin platform applied in medical equipment maintenance. Besides, several scenarios have been developed to explain the application process of such digital twin platform. Through the embedded sensors on the medical equipment, the real-time performance information of equipment can be monitor and collected, which can be used as evidence to forecast the future malfunctions^[90]. The features of real-time update and bidirectional coordination of digital twin technology makes it another solution for condition-based PdM strategy for medical equipment. Although we have illustrated two approaches to implementing PdM strategy through literature review, more studies are needed to explore the practical challenges and limitations of such maintenance strategy in real-world applications, including the costs involved, staff training, and data management.

5. Conclusions

In this work, we firstly summarized the classification and life cycle of medical equipment. Medical equipment can be categorized into five types including diagnostic, therapeutic, life support, analytical, and miscellaneous based on its function. And the life cycle of medical equipment consists of eight stages, which begins with the establishment of requirements and ends with decommissioning. In addition, maintenance strategies of medical equipment are discussed in detail, which encompass CM, PvM and PdM. CM, as a traditional maintenance strategy, is performed after the medical equipment failure occurs, which may result in the unexpected downtime and costly repair. While the PvM and PdM are regarded as proactive maintenance and are carried out before failures, which can effectively enhance the reliability and safety of medical equipment as well as reducing the maintenance expenditures. As a core function of clinical engineering departments, PvM is now the main maintenance strategy applied in healthcare institutions. And such strategy performs maintenance at a fixed and scheduled interval. However, a more flexible interval that is determined by the analysis of priorities or maintenance information of medical equipment will be more practical than blindly adhere to the recommendations of manufactures. PdM can forecast future failures of medical equipment through continuously monitoring of equipment conditions by sensors or through analyzing the historical maintenance data in logs by the ML technology.

Although PdM exhibits huge potential in improving the reliability and availability of medical equipment, it is still in its early stages and needs more efforts. And when implementing PdM strategy in real-world healthcare settings, the security of clinical data cannot be ignored. Besides, more studies addressing the cost-effectiveness of such data-driven maintenance strategies are needed to improve their real-world applicability. And clinical engineers should proactively embrace big data-oriented technique and actively promote the exploration and application of information technology in the maintenance of medical equipment. In addition to the challenges mentioned above, the transition from tradition maintenance system to predictive maintenance system cannot be achieved without strong support from hospital decision-makers.

Declarations

Authors contribution

Lin Z: Investigation, visualization and writing-original draft.

Kang J: Investigation, visualization and formal analysis.

Wei Y: Software, conceptualization and supervision.

Zou B: Resource and formal analysis.

Conflicts of interest

The authors declare no conflicts of interest.

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