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Maintenance Management in Hospital Equipment: Systematic Review

Gestão da Manutenção em Equipamentos Hospitalares: Revisão Sistemática

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ABSTRACT

The maintenance of hospital equipment is of fundamental importance for an adequate medical diagnosis. The conduct of this maintenance can be managed in different strategies. The purpose of this study is to systematically review the main types of maintenance used by healthcare organizations to manage hospital equipment between the period 2010 and 2020. For this, a literature review was carried out in the electronic databases PubMed and Capes Journals Portal/MEC. The predominance of the application of preventive maintenance in the hospital sector was highlighted, however other methodologies such as predictive maintenance, evidence-based and reliability centered maintenance (RCM) were proposed as a way to obtain efficient results and mitigate the risk of failures. It has been proposed that the use of mathematical approaches should be further explored in this area. Therefore, increases in the overall effectiveness of hospital equipment are expected.

Keywords: Maintenance Strategies. Preventive Maintenance. Overall Equipment Effectiveness.

RESUMO

A manutenção dos equipamentos hospitalares é de fundamental importância para um diagnóstico médico adequado. A condução desta manutenção pode ser gerenciada em diferentes estratégias. O objetivo deste estudo é revisar sistematicamente os principais tipos de manutenção utilizados pelas organizações de saúde para gerenciar equipamentos hospitalares entre o período de 2010 a 2020. Para isso, foi realizada uma revisão de literatura nas bases de dados eletrônicas PubMed e Portal de Periódicos Capes/MEC. Destacou-se a predominância da aplicação da manutenção preventiva no setor hospitalar, porém outras metodologias como manutenção preditiva, manutenção baseada em evidências e manutenção centrada na confiabilidade (RCM) foram propostas como forma de obter resultados eficientes e mitigar os riscos de falhas. Foi proposto que o uso de abordagens matemáticas deve ser mais explorado nesta área. Portanto, são esperados aumentos na eficácia geral dos equipamentos hospitalares.

Palavras-chave: Estratégias de Manutenção. Manutenção Preventiva. Eficácia Geral do Equipamento.

1 INTRODUCTION

Medical equipment plays a crucial role in the provision of health services, so they are increasingly critical to the provision of efficient services. The absence or failure of medical equipment can significantly affect the sector and harm people's lives, so it is necessary to maintain strict standards and requirements to ensure the safety of patients and staff. As a result, it is extremely important to maintain a maintenance program to ensure that the equipment is in its best condition, to avoid failures and breakdowns during operation (Waeyenbergh and Pintelon, 2002).

In health organizations, the largest investment is usually in medical equipment, second only to the real estate sector (land and buildings). Thus, in addition to being essential to provide safe and effective care, it also has an impact on the income of health organizations. In view of this, the maintenance and management of medical equipment requires careful supervision from health administrators (Wang, 2012).

The medical field avoids acting with the possibility of “trial and error” and failures in the services provided to patients, as any mistake can represent a risk to the life of a human being (Verbano and Turra, 2010). There is now a wide variety of medical equipment and the criticality of its reliability may vary according to its application.

Dhillon (2011) categorizes as follows: “category I” includes devices that are directly and immediately responsible for the patient's life, such as respirators, cardiac defibrillators; “Category II” includes devices used for routine diagnostics, a failure in this equipment is not as critical as in those in category I, as in this case there is time for repair; “Category III” includes equipment not essential to the patient's life or well-being, such as electric beds, wheelchairs.

According to OMS (*Organización Mundial de la Salud* [OMS], 2012), maintenance can be divided into two main categories:

- Inspection and Preventive Maintenance (IMP): All essential programmed activities to ensure that medical equipment (EM) are functioning properly and are well maintained. Preventive maintenance (MP): All activities performed to extend the life of a device and prevent damage (such as: calibration, cleaning, lubrication, replacement of parts, etc.); Inspection: All scheduled activities essential to ensure that the equipment is functioning properly. It includes operational and safety inspections. They are performed in conjunction with PM, corrective maintenance or calibration, but can also be performed independently, as scheduled activity at defined intervals.

- Corrective maintenance (MC): Process to restore the integrity, safety or operation of equipment after a failure. MC and unscheduled maintenance are considered synonyms for repair.

Systematic reviews of the literature that assess the criticality of equipment and analyze the maintenance strategies applied in the context of health care, published between 2016 and 2018, point out additional gaps and research needs. Authors pointed out that few in-depth studies have been carried out to evaluate the efficiency and effectiveness of the maintenance strategies commonly implemented and present a raised debate about the credibility of the recommendations made by the manufacturers. Finally, they point out that there is evidence in the literature that indicates that mathematical modeling is significantly more flexible than empirical approaches, therefore, it would be beneficial for medical maintenance to explore this bias (Mahfoud, El Barkany and El Biyaali, 2016).

Another study based on a bibliographic review on optimization of maintenance based on reliability in healthcare organizations from 2000 to 2016, found several models of uncertainty in prioritizing medical equipment. The study highlights that this is the heart of medical equipment management programs, with risk being one of the most relevant criteria in most prioritization problems. In sequence, the function of the equipment, the need for maintenance and the rate of use appear. However, the study pointed out that experimental approaches for data collection and treatment are lacking in order to obtain reliable quantitative results (Mahfoud, Abdellah and El Biyaali, 2018).

It is essential, therefore, that health institutions, regardless of size, employ an appropriate maintenance program for medical equipment, which will vary according to the complexity of each location. Thus, the present systematic review aims to analyze how organizations performed the maintenance of hospital equipment between the period 2010 and 2020, through the analysis of case studies that directly explore the type of maintenance applied.

2 METHODS

The literature review was carried out in the electronic databases PubMed and Capes Journals Portal/MEC from May to July 2020 in order to systematically investigate original studies that evaluated the maintenance of hospital equipment.

For this purpose, keywords were continually referred to in studies in the area and the search was carried out using the following terms: *maintenance management in hospital equipment*

AND *maintenance and engineering, hospital* AND *maintenance management in medical equipment*. As additional filtering, only peer-reviewed articles were selected, in English and dated between 2010 and 2020, and after selecting the studies, through a complete reading and analyzing the eligibility criteria, only works published in the last 10 years remained.

The following eligibility criteria were selected to select the articles: I - be an original article; II - deal with maintenance of hospital equipment; III - deal with hospital maintenance management methods. Studies were excluded that had: I - focus on forms of administration; II - focus on creating computerized systems; III - focus on costs; IV - study on the equipment life cycle; V - systematic literature reviews; VI - building maintenance; VII - focus on patient risk; VIII - focus on equipment reliability.

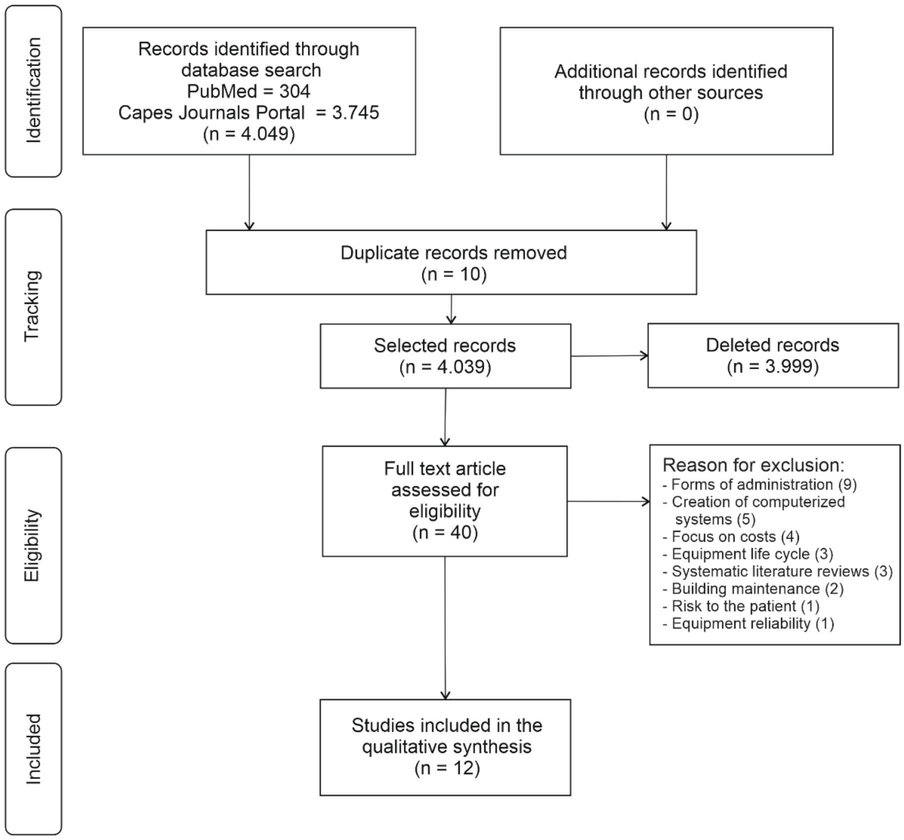
Following the criteria, the initial selection occurred by reading titles and abstracts. Then, the selected papers were read in full, and only those that met all the requirements were selected again.

In order to carry out the narrative synthesis of the characteristics and main results, the following information was extracted: title, year of publication, name of the authors, place where the study was carried out (country and type of institution), type of maintenance applied, equipment studied, cited failure. All data were tabulated in spreadsheets.

3 RESULTS

With keyword searches, 4.049 articles were obtained, among which 10 duplicate records were identified in the two databases. After the first selection by reading titles and abstracts, 3.999 articles were considered out of scope, all of which were removed. Of the 40 articles left to be read in full, a total of 12 articles met the eligibility criteria and were included in the qualitative summary. There was no additional search for papers through the list of references of the selected articles. The complete flowchart of the selection procedure is shown in Figure 1.

Fig. 1 – Flowchart of the selection process for the articles included in the systematic review.



a. Characteristics and Methodological Quality of Included Studies

The characteristics and methodological quality describe the publications included in this review. All articles included in this review were published in the last ten years, with 67% (eight) (Khalaf *et al.*, 2015; Sezdi, 2016; Vala *et al.*, 2018; Iadanza *et al.*, 2019; Pongrac *et al.*, 2019; Salim, Mazlan and Salim, 2019; Shamayleh, Awad and Abdulla, 2019; Shamayleh, Awad and Farhat, 2020) published between 2015 and 2020. Of these, 58% (seven) were conducted in developed countries and 42% (five) in developing countries.

Only one article was conducted using only questionnaires (Alikhani et al., 2013) as an instrument for obtaining information, one was through interviews (Salim, Mazlan and Salim, 2019), three performed equipment data collection on site (Vala et al., 2018; Iadanza et al., 2019; Salim, Mazlan and Salim, 2019; Shamayleh, Awad and Abdulla, 2019), four used an existing database (record / maintenance history) (Hamdi et al., 2012; Miniati, Dori and Gentili, 2012; Khalaf et al., 2013; Shamayleh, Awad and Farhat, 2020), another three did not inform how (Khalaf et al., 2015; Sezdi, 2016; Pongrac et al., 2019).

Of the selected works, five (42%) (Hamdi et al., 2012; Khalaf et al., 2013, 2015; Pongrac et al., 2019; Salim, Mazlan and Salim, 2019) did not specify the type of institution analyzed, another five (42%) (Miniati, Dori and Gentili, 2012; Alikhani et al., 2013; Sezdi, 2016; Vala et al., 2018; Iadanza et al., 2019) analyzed teaching hospital units (university students), one (8%) (Shamayleh, Awad and Farhat, 2020) in a public institution and one in a private institution (Shamayleh, Awad and Abdulla, 2019). Regarding the type of maintenance applied or encouraged by each job, most studies (58%) were about preventive maintenance (Hamdi et al., 2012; Miniati, Dori and Gentili, 2012; Alikhani et al., 2013; Khalaf et al., 2013, 2015; Vala et al., 2018; Pongrac et al., 2019). Corrective maintenance was mentioned, but it was not used alone and as the main in any work. Reliability-centered maintenance (RCM) was applied to two jobs (Salim, Mazlan and Salim, 2019; Shamayleh, Awad and Abdulla, 2019), predictive maintenance also in two (Sezdi, 2016; Shamayleh, Awad and Farhat, 2020), which is equivalent to 17% each. Finally, evidence-based maintenance was cited in an article (8%) (Iadanza et al., 2019). The prevalence of maintenance tools that seek to prevent the equipment from reaching the point of failure was found, this is due to the risk that failures in medical equipment represent to the patient and the operator, so it should be done as much as possible so that they do not happen. Table 1 summarizes this information.

Table 1 - Description of studies included in the review. (n = 12)

Study characteristics	N	%
Place of performance		
Developed countries	7	58%
Developing countries	5	42%
Year of publication		
2010-2015	4	33%
2015-2020	8	67%
Data collection form		
Interviews	1	8%
Questionnaires	1	8%
Maintenance records / history	4	33%
On-site data collection	3	25%
Other or not informed	3	25%
Type of health service		
Public Institution	1	8%
Private Institution	1	8%
Universitary hospital	5	42%
Others	5	42%
Type of maintenance applied		
Preventive maintenance (PM)	7	58%
Corrective maintenance (CM)	0	0%
Reliability-centric maintenance (RCM)	2	17%
Evidence-based maintenance	1	8%
Predictive Maintenance	2	17%

Table 2 highlights which equipment was analyzed in each study, which failure was observed and what type of maintenance was applied or indicated for each one. Some selected works did not make the indications of equipment or failure, even so they were considered eligible for fulfilling other criteria.

Table 2 - List of equipment studied, found faults of type of applied maintenance.

Author	Equipment studied or indicated	Failure types encountered	Type of maintenance applied / indicated
Alikhani et al. (2013)	Neurology medical equipment, such as electroencephalogram (EEG).	Don't quote	Preventive maintenance
Hamdi et al. (2012)	Don't quote	Don't quote	Preventive maintenance
Iadanza et al. (2019)	Operating tables, telemetry equipment, electrosurgery units and defibrillators	induced by use; unpredictable caused by normal wear; predictable and preventable; service-induced; evident; potential; and others.	Evidence-based; Scheduled maintenance; corrective maintenance
Khalaf et al. (2015)	Anesthesia machine	Don't quote	Preventive maintenance
Khalaf et al. (2013)	Infusion pumps and fans	Don't quote	Preventive maintenance
Miniati, Dori and Gentili (2012)	Don't quote	Don't quote	Preventive maintenance
Pongrac et al. (2019)	Computed tomography	Poor image quality; incorrect position sensor; the vertical column is not raised; among others.	Preventive maintenance
Salim, Mazlan and Salim, (2019)	State-of-the-art equipment, such as imaging equipment (for example, MRI, CT scan) and radiotherapy equipment	Type of maintenance services; Environmental factors; Human factors.	Reliability Centered Maintenance (RCM)
Sezdi (2016)	Old technology device (electrocardiogram, oximeter, defibrillates, and others). High-tech devices (tomography, mammography, magnetic resonance, and others)	High pressure leak; High temperature; low battery; power circuit error; sensitivity error; broken pressure gauge; missing piece; among others	Preventive maintenance (old) and predictive maintenance (Recent technology)
Shamayleh, Awad and Abdulla, (2019)	Ventilation devices - adults and neonates	Don't quote	Reliability Centered Maintenance (RCM)
Shamayleh, Awad and Farhat, (2020)	Vitros immunoassay analyzer (VIA)	Regular loading error; sliding of the belt; luminometer voltage out of range; calibration error; it is not possible to measure the sample fluid; and others.	IoT-based Predictive Maintenance (PdM)
Vala et al. (2018)	Radiotherapy; renal therapy unit; pulmonary ventilators.	Table error, brake failure, collimator error, system error, printer error, compressor error, gantry transducer error, and others.	Preventive maintenance

The study of Hamdi et al. (2012) introduced a smart work order prioritization system. Although it is about creating a system, the authors pay special attention to the way of prioritizing equipment and the need for preventive maintenance. They state that a failure of medical equipment is an extremely sensitive issue, since each device is directly and closely related to the health and well-being of patients, but that a properly weighted preventive maintenance strategy is necessary for the equipment to operate in a safe and economical.

Another study highlights the importance of maintenance to mitigate the clinical risk caused by adverse events in healthcare. It aims to develop a system that helps decision makers to plan preventive maintenance and safety controls, defining new technical indicators with a simple database. For this, it highlights the importance of defining maintenance priority index taking into account the functional importance of the device (criticality), the type of technology and the tendency of complexity and failure (Miniati, Dori and Gentili, 2012).

The other studies cited a very wide variety of equipment that ranged from older technologies, such as a pulse oximeter to high technologies, such as computed tomography(Sezdi, 2016). The failures were also diverse, with some studies citing the specific failure, such as "*battery failure*" (Iadanza et al., 2019), "*Luminometer voltage out of range*" (Shamayleh, Awad and Farhat, 2020), others classified it as "*types of maintenance services, environmental or human factors*" (Vala et al., 2018). Some works did not focus on the description of the flaws (Miniati, Dori and Gentili, 2012; Khalaf et al., 2015; Iadanza et al., 2019; Shamayleh, Awad and Farhat, 2020).

4 DISCUSSIONS

The review carried out during the research showed the predominance of the application of preventive maintenance in medical equipment. The studies presented ways to develop an adequate and efficient maintenance in order to mitigate the clinical risks caused by adverse events in the health area.

(Alikhani *et al.*, 2013) performed a descriptive analysis based on information from the year 2009 from a medical center located in Iran. The research was carried out considering only neurological devices that were classified into four categories according to their specificities. Based on historical data and categories, the authors established the ideal preventive maintenance periods for each piece of equipment. For some, such as magnetic resonance image (MRI), each part of the device requires different control periods, ranging from 4 to 24 months. Thus, the authors show that the implementation of a preventive maintenance system is crucial for the institutions, as it prevents problems, reduces costs and optimizes uptime

Decision support systems and software have been proposed which, through pre-established indexes and criteria, assist in maintenance management, prioritization of work orders, among other features. Such studies were included in the present review because they present detailed data on the preventive maintenance analyzed. The indices used take into account the area of activity and level of complexity of the equipment (Miniati, Dori and Gentili, 2012), function, place of use, hospital load, time since request, presence of an alternative and distance from the nearest hospital containing the same device (Hamdi et al., 2012). Both systems have proven their effectiveness for managing preventive maintenance.

The need to implement maintenance strategies that maximize equipment availability led the authors Vala et al. (2018) to use a risk-based approach. Through well-structured steps and the use of tools such as Pareto analysis, "5-Why" and FMEA, from which failure modes and component failures are analyzed and classified, in addition to identifying the root causes of failure modes, it was possible to develop operation and maintenance protocols for critical devices. The protocol proposed by the authors was divided into three parts that should be performed by biomedical engineers, being weekly tasks, monthly tasks and, finally, performing preventive maintenance every 3 months, which before the study was done every 6 months. This study proves the importance of data collection and analysis, as well as the definition of maintenance protocols to mitigate frequent failures and increase the availability of equipment.

In his work, Sezdi (2016), explored two different maintenance strategies, separating the devices between those of old technology to be managed with preventive maintenance and those of high technology that would receive predictive maintenance (PdM). The preventive maintenance was through performance verification and safety tests with intervals that varied from 6 to 12 months. The predictive, however, was through schedules and daily checks, ensuring that the smallest failure was reported. Trainings were provided, provided by the manufacturer, to users who would carry out daily checks, as the study considered that the level of knowledge could affect the standards of reliability and failure. The author stressed that predictive maintenance is not always ideal, as a device can receive more or less maintenance than necessary, in addition to being more expensive than preventive. The program based on two strategies has produced positive results, although preventive and predictive maintenance (PdM) are inconsistent in several ways, have led to a significant reduction in equipment failures.

Predictive maintenance (PdM) was addressed by the authors Shamayleh, Awad and Farhat (2020) who pointed out that its use reduces the number of unplanned stops of the analyzed equipment, increasing its availability. In this way, it generates more profit over time and also reduces the number of times the machine is disassembled, extending its useful life, in addition to reducing the cost of stock, as it is possible to predict failures.

The authors' research Iadanza et al. (2019) differentiated from the others in advocating the use of evidence-based maintenance to monitor maintenance performance in a hospital. This method uses the failure history to carry out continuous and improved monitoring of current maintenance strategies. The first stage of the research was, therefore, to classify maintenance work orders (analyzing scheduled / preventive and corrective maintenance). The second step was to develop a set of key performance indicators (KPIs). From the analysis of the KPIs, the authors concluded that scheduled / preventive maintenance cannot prevent all failures or problems before they arise. The adoption of the evidence-based maintenance approach would allow the hospital to monitor changes over time, being able to compare with previous results and, thus,

Another strategy used was the reliability-centered maintenance approach (RCM). The authors Shamayleh, Awad and Abdulla (2019) argued that it is more beneficial and more economical than preventive maintenance. The RCM methodology is based on the traditional Failure Modes and Effects Analysis (FMEA) and was used with a focus on reducing criticality. Through the maintenance record of medical equipment for one year, the authors sought to show the dependence and inefficiency of preventive maintenance activities and how the implementation of the RCM will result in a more adequate management program, in order to minimize the risk associated with failure.

The SmPC was also defended by Salim, Mazlan and Salim (2019), the authors stressed that it is a reliable tool and its principle is to do the right job, at the right time, according to the equipment conditions. However, it is a long-term process, and many organizations give up or fail, mainly in monitoring and analyzing data. When performed efficiently, it will result in the elimination of unnecessary tasks and the inclusion of actions to address omissions and deficiencies in maintenance programs.

4.1 Mathematical Approach

It was highlighted by a study that most of the methodologies used are empirical and those based on mathematical modeling are scarce (Khalaf et al., 2013). In the works included in this review, few presented mathematical analysis; only two emphasized this subject and developed mathematical models.

The authors Khalaf et al. (2013) proved that the use of mathematical modeling to analyze the effect of maintenance on the useful life of medical equipment is beneficial and revealed that preventive maintenance had an impact on it. The mathematical model proposed by the authors was simulated in Matlab using real data from three devices.

The work of Khalaf et al. (2015) pointed out that several mathematical models have been proposed to analyze the effect of maintenance on industrial equipment, however they are rarely used or considered for medical devices. The authors proposed a mathematical model that analyzes the probability of survival of medical equipment that combines the effects of random failures and deterioration failures by age, using real maintenance data and simulated in Scilab.

Although this is not a mathematical model specifically, the authors Shamayleh, Awad and Farhat (2020) performed mathematical analysis using the SVM forecasting model, which comprises finding a hyperplane, through an equation, capable of separating the data classes into healthy and defective ones. The model was based on four features and adjusted to an acceptable accuracy of 96%, a true positive rate of 93% and a false positive rate of 7%.

Finally, the authors Pongrac et al., (2019) claim that it is impossible to imagine the maintenance of medical devices without using the preventive maintenance method. They developed in their study a numerical way to find the frequency of preventive exams in equipment. Initially, they performed Pareto analysis to classify the causes of failures and defined preventive maintenance procedures. For the application of the mathematical formula they used values of maximum relative error, average time of failure, intensity of system failures and average duration of a preventive exam. Performing forecast calculations ensures greater equipment reliability and availability, increasing the overall quality of the system.

5 CONCLUSIONS

From the systematic review of the literature on the main types of maintenance used by healthcare organizations to manage hospital equipment, it is possible to conclude that preventive maintenance stands out with greater application in the sector. Most of the included studies sought efficient ways to optimize it. In addition, other methodologies have been proposed, such as predictive maintenance, evidence-based maintenance and reliability-centered maintenance (RCM), also as a way to obtain more efficient results and mitigate the risk of failures. The use of mathematical modeling proved to be efficient to assist maintenance decision-making, however it was observed in few studies that even mentioned that this approach is scarce in the field of maintenance of hospital equipment,

The use of strategies that are based on historical equipment data to analyze the cause of the failures and, then, establish maintenance intervals, proved to be efficient in the studies in which they were explored. Together with mathematical modeling, they can bring positive results to organizations, providing greater availability of equipment, increasing the reliability of patients and staff, in addition to reducing maintenance costs. To reinforce the evidence, future studies can be developed exploring this area.

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1) concepção e planejamento.	X	X
2) análise e interpretação dos dados.	X	
3) elaboração do rascunho ou na revisão crítica do conteúdo.	X	X
4) participação na aprovação da versão final do manuscrito.	X	X