Hospital medical equipment maintenance schedules using the mean time between failures

Estratégias de manutenção de equipamentos hospitalares por meio do mean time between failures

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Abstract
The objective of this study was to define a methodology to assist the definition of maintenance contract intervals and overall recommendations for a large hospital in the city of Rio de Janeiro, Brazil. The reliability of 161 cardiac monitoring and treatment devices was studied. Four indicators of equipment use conditions were developed, and, along with the year of manufacture of the equipment, were used as predictors in a logistic regression that had the occurrence of failure as outcome. The mean time between failures (MTBF) was then estimated for the categories of the indicators deemed relevant by the regression. Only one variable (intensity of use) was statistically significant in the final predictive model, and the MTBF, according to each category of this variable (low-average-high), ranged from 121.3 (low) to 5.8 days (high). The results indicated large inadequacies in the maintenance contract periods used by the hospital and suggested that a much better maintenance strategy would be the inspection periods compatible with the identified MTBF intervals.

Key words: Equipment failure, equipment failure analyses, equipment maintenance, mean time between failures

Resumo
O objetivo deste estudo foi definir uma metodologia para a definição de intervalos de contratos de manutenção e recomendações gerais em um grande hospital da cidade do Rio de Janeiro, Brasil. A confiabilidade de 161 dispositivos de monitoramento e tratamento cardíaco foi estudada por meio de quatro indicadores de suas condições de uso. Esses indicadores, juntamente com o ano de fabricação do equipamento, foram usados como preditores em um modelo de regressão logística que teve como desfecho a ocorrência de falha no equipamento. A seguir, o Mean Time Between Failures (MTBF) foi estimado para os indicadores apontados como relevantes pelo modelo. Apenas uma variável (intensidade de uso) foi considerada estatisticamente significante no modelo preditivo final. O MTBF, de acordo com as categorias dessa variável (baixo-médio-alto), tiveram valores compreendidos entre 121.3 (baixo) e 5.8 (alto) dias. Os resultados indicam grandes inadequações nos períodos de contratos de manutenção utilizados pelo hospital e sugerem que estratégias de manutenção mais eficientes seriam períodos de inspeção compatíveis com os intervalos de MTBF identificados.

Palavras-chave: Falha de equipamento, Análise de falha de equipamento, Manutenção de equipamento, mean time between failures

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Introduction

Hospital managers frequently have to deal with problems such as deficient personnel training, obsolete planning methodologies, inefficient financial controls and lack of long-range planning, leading to premature equipment disposal. This situation, coupled with the worldwide increase in health care costs and with the resource scarcity in the Health sector, further stresses the importance of developing maintenance policies capable of improving the overall reliability of medical equipment (Grant, 1998; Ramírez, Jeronymo Neto and Jannani, 2001; Coelli, Almeida and Coelho, 2009).

At the same time, maintenance strategies are quickly changing, due to the growing public demand for quality in health services (Dunn, 1998; Ogembo-Kachieng’a and Ogara, 2004; Bloom, 2006). Uncertainty on the definition of the best maintenance scheduling strategies under specific circumstances is common, with alternatives varying as a function of hospital needs and equipment use routines. Furthermore, it is known that manufacturers can recommend maintenance scheduling programs more frequent or more complex than actually necessary, in order to compensate for project problems, to reduce the probability of failure and to increase the price of maintenance contracts (ECRI, 1995).

It is well known that the two most common and traditional approaches for medical equipment maintenance are the preventive and the corrective strategies. The first can be thought as a set of procedures aimed to keep the equipment in perfect working conditions and without operation interruptions, while the second is concerned with repairs after a failure (Bronzino, 2006). Much room still exists for the development of predictive tools for better application of these strategies to hospital equipment maintenance (Cohen, et al. 1995; Dyro, 2004). Usually, the research objective in this area is that, with the identification of the more important risk factors for equipment failure, interventions could be proposed in order to minimize failure risk and maximize an equipment operating life.

This work studied, between January 02, 2002 and January 10, 2003, the reliability of 161 cardiac monitoring and treatment devices in a large hospital in the city of Rio de Janeiro, Brazil, using the failure data recorded by the hospital maintenance companies. The objective of the study was to define a methodology to assist the definition of maintenance contracts and to develop overall maintenance scheduling recommendations for the hospital.

Materials and methods

The hospital where the study was performed is considered a reference unit for emergency care in the city of Rio de Janeiro, Brazil. The hospital has 400 beds and a staff of about 1,500 people. Its emergency sector is one of the largest in Latin America, receiving a daily average of 900 patients. In the year of the study (2002-2003), the hospital performed 8,356 surgeries in more than 20 medical specialties.

Cardiology was chosen as a pilot research area, towards the overall review of the hospital equipment maintenance scheduling procedures. This specialty was chosen given the importance of cardiovascular diseases in terms of their mortality, morbidity and economical impacts. The studied equipment consisted of two brands, totaling 161 devices (e.g. cardiac monitors, electrocardiographs – ECG – and defibrillators). The newest equipment units of the first brand (77 devices) were already out of production by almost a decade by the time of the study, and some had 25 years of use. The equipment units of the second brand (84 devices) were, in general, newer, with devices still in production. At the time of the study, all equipment had standard maintenance contracts that included repairs and monthly visits for preventive maintenance. The hospital had no equipment maintenance department and no repairs were made “in house”.

Failure data were obtained from the administrative maintenance orders (AMO), used to record interventions performed by the companies in charge of equipment maintenance. At first, four indicators were developed by the present research team for the classification of equipment use conditions (Table 1). These indicators were defined taking into account the importance of developing an understanding of the equipment use conditions, especially in what would concern their time until failure.

The indicators, along with the variable “year of manufacture of the equipment”, were used as independent variables in a logistic regression model that had the occurrence or not of equipment failure as dependent variable, during the studied period. In the logistic model, indicators were treated as binary variables, obtained by collapsing their original categories into two (Table 1). Inactivated equipment (equipment definitely not used but still covered by maintenance contracts) are listed below, but were not included in the statistical analysis. All equipments were under preventive maintenance contracts during the time of the study, and all of them were subjected to the same (monthly) maintenance schedule.

As recommended by Hosmer and Lemeshow (2000), the model was developed into two stages: first, the five variables above were introduced together in the model, and, afterwards, a new model was developed, discarding those variables that did not attain statistical significance. The model was performed with the Statistical Package For The Social Sciences (SPSS), version 16. In this regression, the classic logistic model was
used (Hosmer and Lemeshow, 2000; Menard, 2009) (Equation 1):

$$E(Y) = \exp(b_0 + b_1X_1 + b_2X_2 + b_3X_3 + b_4X_4 + b_5X_5)/[1 + \exp(b_0 + b_1X_1 + b_2X_2 + b_3X_3 + b_4X_4 + b_5X_5)]$$

Equation (1)

Where:
- $E(Y)$: probability of failure;
- $X_1$: technological level;
- $X_2$: intensity of use;
- $X_3$: use stress;
- $X_4$: equipment importance (Table 1);
- $X_5$: year of manufacture of the equipment.

After the modeling, the failure rate $\lambda$ and the mean time between failures (MTBF) were computed for the equipment groups defined by the categories of the identified failure predictors. The MTBF is defined as the average time to failure (in days), and it is the inverse of the failure rate (Anderson, 1999; Bloom, 2006) (Equations 2 to 4):

$$\lambda = n/\Delta t$$

Equation (2)

$$MTBF = 1/\lambda$$

Equation (4)

Failure percents were computed as (Equation 5):

$$% failures = (n_g/n)(100)$$

Equation (5)

Where:
- $n$: total number of failures;
- $n_g$: failures in each equipment group.

The lower and upper confidence limits ($m_l$ and $m_u$) of the 95% confidence interval (CI) for the MTBF were calculated as (Lewis, 1995; Birolini, 2007) (Equations 6 and 7):

$$m_l = 2*\sqrt{\chi_2^{2}/n}$$

Equation (6)
Equation (7)

\[ ms = 2^*T/\chi^2_{1 - \alpha/2,n} \]

Where:
- \( m_i \): CI lower limit;
- \( m_s \): CI upper limit;
- \( T \): total time of study;
- \( \alpha \): significance level;
- \( n \): number of failures;
- \( \chi^2 \): chi-square distribution standardized statistic with \( 2n+2, 2n \) or 2 degrees of freedom.

## Results

Table 2 presents the total number of equipments, the number of equipments in the “critical” categories (e.g. high intensity of use – Table 1), and the total number of failures for each type of equipment. Forty-eight equipments did not present failures during the time of the study. Cables had a very large proportion of failures (above 50%), while the 48 defibrillators did not present failures during the period of the study, and this equipment category was excluded from the analysis. Table 3 presents the results of the logistic regression model. It can be seen that only one variable (intensity of use) could be associated with equipment failure (p=0.002).

Table 4 presents the number of devices and failures, the failure rates and the MTBF as a function of the categories of the only relevant variable identified by the logistic regression. It can be noticed that, at the time of the study, 5% of the assessed equipment were inactivated, but remained covered by maintenance contracts. There is a predominance of devices with high intensity of use (57.8%), and the largest proportion of failure takes place in this category. On the other hand, there is a small number of failures of devices in the low intensity of use category. The MTBF, according to each category, ranged from 121.3 (low) to 5.8 days (high).

<table>
<thead>
<tr>
<th>Equipment</th>
<th>Number</th>
<th>Use stress under pressure</th>
<th>High intensity of use</th>
<th>Obsolete/old technology level</th>
<th>High importance</th>
<th>Number of failures</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oximeters</td>
<td>12</td>
<td>08</td>
<td>12</td>
<td>0</td>
<td>0</td>
<td>2</td>
</tr>
<tr>
<td>Monitors</td>
<td>64</td>
<td>57</td>
<td>45</td>
<td>04</td>
<td>43</td>
<td>17</td>
</tr>
<tr>
<td>ECG</td>
<td>20</td>
<td>7</td>
<td>7</td>
<td>5</td>
<td>4</td>
<td>14</td>
</tr>
<tr>
<td>Oximeter sensors</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>11</td>
</tr>
<tr>
<td>ECG cables</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>4</td>
</tr>
<tr>
<td>Defibrillators</td>
<td>17</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>15</td>
<td>0</td>
</tr>
<tr>
<td>Monitor cables</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>42</td>
</tr>
<tr>
<td>Total</td>
<td>113</td>
<td>72</td>
<td>64</td>
<td>9</td>
<td>62</td>
<td>90</td>
</tr>
</tbody>
</table>

ECG: electrocardiograph.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Beta</th>
<th>Standard errors</th>
<th>p-value</th>
<th>OR</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Initial model</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Intensity of use low</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>1</td>
</tr>
<tr>
<td>high</td>
<td>1.33</td>
<td>0.71</td>
<td>0.063</td>
<td>3.8</td>
</tr>
<tr>
<td>Use stress normal</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>under pressure</td>
<td>-0.17</td>
<td>0.72</td>
<td>0.815</td>
<td>0.85</td>
</tr>
<tr>
<td>Technological level obsolete</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>state-of-the-art</td>
<td>0.14</td>
<td>0.85</td>
<td>0.865</td>
<td>1.1</td>
</tr>
<tr>
<td>Importance low</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>high</td>
<td>-0.17</td>
<td>0.41</td>
<td>0.676</td>
<td>0.84</td>
</tr>
<tr>
<td>Year of manufacture oldest</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>newest</td>
<td>-0.04</td>
<td>0.043</td>
<td>0.341</td>
<td>0.96</td>
</tr>
<tr>
<td>Constant</td>
<td>-1.21</td>
<td>1.00</td>
<td>0.229</td>
<td>0.30</td>
</tr>
<tr>
<td><strong>Final model</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Intensity of use low</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>1</td>
</tr>
<tr>
<td>high</td>
<td>1.51</td>
<td>0.48</td>
<td>0.002</td>
<td>4.5</td>
</tr>
<tr>
<td>Constant</td>
<td>-1.90</td>
<td>0.44</td>
<td>0.000</td>
<td>0.15</td>
</tr>
</tbody>
</table>

P-values rounded to three decimal places. OR: odds ratio.
Table 4 - Equipment totals and percents, failures totals and percents, failure rates, mean time between failures (MTBF) and 95% confidence intervals (95%CI) according to the categories of intensity of use

<table>
<thead>
<tr>
<th>Intensity of use</th>
<th>Equipment (%)</th>
<th>Failures (%)</th>
<th>Failure rates $\lambda$</th>
<th>MTBF in days (95%CI)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inactivated</td>
<td>8 (5)</td>
<td>3 (3)</td>
<td>0.0082</td>
<td>121.3 (41.5-588.4)</td>
</tr>
<tr>
<td>Low</td>
<td>38 (23.6)</td>
<td>3 (3)</td>
<td>0.0659</td>
<td>15.2 (10.2-23.7)</td>
</tr>
<tr>
<td>Average</td>
<td>22 (13.6)</td>
<td>24 (27)</td>
<td>0.1731</td>
<td>5.8 (4.5-7.5)</td>
</tr>
<tr>
<td>High</td>
<td>93 (57.8)</td>
<td>63 (70)</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Discussion

In the present study, the year of manufacture of an equipment was not a relevant predictor of equipment failure. Intuitively, it is expected that the older a device, the more times it will fail, which, however, does not necessarily correspond to the reality of equipment maintenance in the Health area. Blanch (2001) concluded that biomedical equipment reliability can remain unchanged or even increase with the passing of time. That study analyzed 66 pulmonary fans in two hospitals in the United States during 10 years, showing that, over the years, equipment became more reliable, with an increase in their MTBF. The author argued that this could be due to a decreasing number of operation errors the more a device is used. Conversely, new technologies, at first, may demand more attention in order to guarantee correct operation and reliability, which is a strong cautionary remark for countries without well-established hospital equipment acquisition and disposal systems (ECRI, 1995; Lewitt, 2003).

Four indicators were developed and introduced by the authors in order to characterize and predict equipment reliability: “technological level”, “intensity of use”, “use stress” and “equipment importance”. Given the difficulty in identifying such indicators in the literature, their application represents an important and original aspect of the present study. Their development took into account the expert opinion of the researchers, administrators and maintenance personnel working of the hospital, and special attention was given to the use of readily available and easy-to-collect data in their definition.

The main idea was that the indicators should be unambiguously defined in terms of their characteristics of use, and it was believed that there was enough detail so as to allow for their generalizability and applicability in other studies. However, a certain degree of confusion could be expected for the application of the indicator “technological level”, given that, inevitably, technologies change, such that what is state-of-the-art today will be obsolete after a certain time. For this reason, specific examples were introduced so as to illustrate what were (in the study) the indicator categories. For instance, fiber optics and liquid crystal technology were considered as state-of-the-art, while analogical technology (still found in operating conditions at the studied hospital) was defined as obsolete. Although, it is expected that due to the very nature of technological change, future studies with this indicator will have to introduce a certain degree of adaption to allow for its use.

It was found that the indicator that better characterized equipment failure was “intensity of use”. In fact, this was the only statistically significant variable in the logistic regression model, and was, therefore, used later for a detailed equipment evaluation, in which the MTBF was computed in each variable category. Examples of equipment with high intensity of use were the monitors in the intensive care units (ICUs) of the hospital, that operate uninterruptedly, or those installed in the Anesthesiology sector, which function during a considerable fraction of the time. As examples of devices with average intensity of use, one can mention those in the Emergency sector, constantly used (for small periods at a time), or the ECG operating in the ICU, which are also used daily, for short periods at a time. The backup devices or the devices operating in sectors with less demand (for instance, Neurosurgery) are examples of equipment with low intensity of use.

The main parameter selected to characterize the reliability of the equipment grouped according to the “intensity of use” categories was the MTBF, much used, for example, in the aeronautical industry. The MTBF is the average time of successive failures of a repairable product, and was used for helping the definition of the intervals between preventive maintenance interventions (James, 2000). As the period of study was small in comparison to the useful life of the devices, and as these were not brand-new, it could be assumed that the devices would be in the linear region of their failure rate curves, and, thus, that these curves would not vary as a function of time ($\lambda = constant$). Consequently, a simple exponential model could be applied to the data.

The majority of the devices (93) were classified as “high intensity of use”. The small MTBF (5.8 days) of the devices in this category (e.g. ECG and all the oximeters) allowed for the recommendation of a drastic shortening in their maintenance intervals, for example, towards 5-7 days of maintenance interval. Similarly, for equipment with an average intensity of use (MTBF=15.2 days), it was suggested that maintenance intervals should be defined as 15 days. It was also suggested that the maintenance companies could train personnel for a hospital clinical engineering sector for the simplest of these...
biweekly maintenance services. For the equipment in the “low intensity of use” category, the suggestion was that maintenance intervals should be increased to around 120 days, and, finally, (of course) the termination of the contracts for the “inactivated” category was also recommended.

In summary, the results indicated how maintenance contracts could be made more in accord with the operating conditions of the equipment, so that devices with high rates of failure would receive more frequent preventive maintenance inspections, while those with low rates could have a larger interval between inspections. Then, probably the hospital would achieve a higher degree of equipment availability, and the maintenance companies would be able to focus on more effective interventions.

It was also suggested that the services of a fully functional clinical engineering sector were much in need at the hospital, and that such services could also be useful at the central administrative level (the Municipal Health Department), for instance, for consulting in contract elaboration. Inside the hospital, it is enough to note the number of cable failures, which could be fixed “in house”, without the need for outside specialized intervention. This would allow for less expensive maintenance contracts, since maintenance companies would not have to use personnel for basic, simple interventions, with a resulting decrease in operational costs.

In conclusion, some recommendations could be made to the Health unit through the results of this study, which allowed for the identification of large inadequacies in the hospital maintenance contracts. Most of these could be easily remedied, indicating that much could be saved by adjusting maintenance periods to equipment operation conditions.

■ Referências


Received: 17/7/2009
Accepted: 8/7/2010