Risk adjusted statistical process control methods and their applications in simulations and a real-life study of ED intubation

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Context and problem
Monitoring performances, adverse effects and mortality in hospital or community care are considered critical processes for quality assurance. The monitor includes the process of gathering cumulative information and statistical process control analyses. Results of analyses are compared to the expected values on a regular basis such that any abnormality will be detected and alarms can be given to the relevant stakeholders. The conventional approaches used in statistical process control are cumulative sum chart (CUSUM), exponential weighted moving averages chart (EWMA) and sequential probability ratio test. These approaches have been advanced in combination with a risk-adjusted method to account for the variability of patient baseline risk, but few evaluations have been conducted on these methods for different types of outcomes. Our study aims to evaluate these methods in various monitoring settings.

Intervention and methodology
Simulations were used to create two types of scenarios: hospital indicator monitoring and community care surveillance. Outcomes with different statistical properties (continuous, binary or multiple categories) and baseline risk measurements of patients were simulated. Two different risk-adjusted methods: risk adjusted CUSUM and EWMA were applied to simulations and an ED intubation case study. Sensitivity, false alarm rates and performance in rare events are used as the criteria for the evaluations.

Measurement and results
In simulations, in-hospital mortality and reoperation are used as the hospital indicators, acute admission and SF36 quality of life measures are used as the community care indicators. In the ED case study, first attempt successful rate and adverse events are selected as hospital indicators. Results and criteria of these risk-adjusted methods were demonstrated.

Table 1. Characteristics of simulated data

<table>
<thead>
<tr>
<th>Simulated data</th>
<th>CUSUM</th>
<th>Distribution of simulated outcome</th>
<th>Associations between risk scores and outcomes</th>
</tr>
</thead>
<tbody>
<tr>
<td>SF-36 physical function</td>
<td>Normal</td>
<td>correlation coefficient of 0.6 and 0.8</td>
<td></td>
</tr>
<tr>
<td>Mortality rate</td>
<td>Binary</td>
<td>odds of 1.25 and 2.0</td>
<td></td>
</tr>
<tr>
<td>Length of stay</td>
<td>Log normal</td>
<td>correlation coefficient of 0.6 and 0.8</td>
<td></td>
</tr>
</tbody>
</table>

Results from the simulations

The functions of risk adjusted CUSUM and EWMA
In the quality improvement science, CUSUM represents cumulative departures from the targets in monitor series, and EWMA represents the weighted moving averages of monitor series. In the risk adjustment design, an established risk score is used to generate predicted CUSUM and EWMA which can be used to compare against the observed CUSUM and EWMA.

Risk adjusted EWMA /CUSUM(expected values): it is a bench mark for EWMA/CUSUM that is predicted from risk score of a patient. Lower limit (expected): the upper limit of the 95% confidence interval of expected CUSUM/EWMA
Upper limit (expected): the lower limit of the 95% confidence interval of expected CUSUM/EWMA

False Alarm Rate (FAR): The number of times when the observations are worse than expected outcomes but still within the control limit for a worse outcome.

First run length: The first number of observation in the series that gives the first alarm when observation is worse than expected outcome and control limit.

Table 2. Evaluation of the two risk adjusted charts

<table>
<thead>
<tr>
<th>Evaluation criteria</th>
<th>SF-36</th>
<th>Mortality</th>
<th>Length of stay</th>
<th>SF-36</th>
<th>Mortality</th>
<th>Length of stay</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sensitivity</td>
<td>56</td>
<td>95</td>
<td>0</td>
<td>32</td>
<td>63</td>
<td>96</td>
</tr>
<tr>
<td>False alarm rates</td>
<td>1</td>
<td>33</td>
<td>30</td>
<td>0</td>
<td>6</td>
<td>10</td>
</tr>
<tr>
<td>First run length</td>
<td>1</td>
<td>4</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>23</td>
</tr>
</tbody>
</table>

Evaluation and comparison of risk adjusted CUSUM and EWMA
Based on the simulated data for the SF-36 and the length of stay, the difference between the two correlations doesn’t affect the number of false alarms and the sensitivity of the EWMA and CUSUM control charts. While for the mortality data, the false alarm rate and the sensitivity is less for the strong association compared to the moderate association. The EWMA is more sensitive to detect abnormality in the mortality outcome. It is also more prone to the false alarm rates but performs better for the SF-36 outcome compared to the CUSUM.

Case study results

In the risk adjusted cumulative sum chart. We observe that from patients 25, the observed rates are better than expected results; from patients 70, the observed rates have a large trend of improvement. From 103 to the last patients, the first pass outcome are getting worse, but still higher than the expected results and the lower control limit. In the EWMA chart, similarly, we observe that from patient 103 to the last one, the observed pass rate is lower than expected results, although it is getting higher. EWMA is more sensitive to the changes, and expected values are not relying on a target value, but on the historical records. EWMA can give more false alarms than CUSUM.

Summary
Both simulated data and real case demonstrated that:

- Risk adjusted CUSUM has much lower false alarms than EWMA in the binary outcomes
- Risk adjusted EWMA performs better in continuous outcomes (SF-36 and length of stay) than risk adjusted CUSUM as it provides less false alarms and earlier detection of abnormality.

References

Nestorov M., Bouveyron C. Risk adjusted imputed probability ratio test and longitudinal correlation... J QI. 2016; 15: 479-487.
Zeng L, Bruce A, Barratt B. Recent approaches to risk adjusted outcomes monitoring and evaluation... J QI. 2010; 29: 55-55.

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