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Appendix I Description of the Shewhart-p-chart and CUSUM-chart.

Introduction and theory

In recent years, Statistical Process Control (SPC)-methods have gained growing interest in healthcare as a method to monitor quality of care and evaluate quality improvement initiatives.[1-3] In this study we opted for Shewhart-p-charts and CUSUM-charts, but other types of SPC-charts exist e.g. the exponentially weighted moving average (EMWA)-chart, and the g-chart. The general theory behind SPC-charts is that random variation is inherent in all processes, caused by common causes. A process is in-control when there is only random variation (common cause variation). However, situations may arise that cause a process to become out-of-control, due to the particular causes of this situation (special cause variation). SPC-charts with a control limit intend to distinguish between common cause variation and special cause variation, with the intention to investigate for possible causes when special cause variation is detected. The advantage of a SPC-chart over, for example, the funnel-plot where data of multiple years are taken together, is that the time variable is added by plotting the outcomes over time, showing the possible effect of changes in practice nearly real-time rather than that these remain hidden in the pooled data over a longer period.

Shewhart-p-chart

The Shewhart-p-chart generally uses a standard format, as shown in Figure 1 in the manuscript. The x-axis indicates time, e.g. weeks, months or quarters. Because it is a p-chart, the y-axis displays a proportion of a certain outcome (e.g. revision rate). The chart thus presents e.g. the weekly proportion of patients with a certain outcome over time. Three horizontal lines are depicted: the center line (CL), the upper control limit (UCL) and the lower control limit (LCL). The center line represents the average or median level of performance over a certain period. Given the random variation, an outcome will usually vary across this central tendency line and remain within the control limits, assuming that the long-term rate of that outcome does not change and will only present some random variation over time. Usually 2 and 3-sigma control limits are used, with a 2-sigma control limit having higher likelihood of type 1 error (false positive signal) and a 3-sigma control limit a higher likelihood of type 2 error (false negative signal). Control limits are computed statistically based on probability distributions such as the Gaussian ('normal' distribution), similar to hypothesis testing. In general, 95% of data will fall within ±2 standard deviations (SD) or 2 sigma and 99,7% within ±3 SD or 3 sigma. Values that fall outside the chosen upper and lower control limits exceed that range of most values, making it unlikely that this is due to random variation but rather reflects a true difference, in this study indicating that the revision rate has doubled.

CUSUM-chart

Where the Shewhart-p-chart works with aggregated data over weeks, months of quarters, the CUSUM-chart uses every patient to plot the graph chronologically. For each patient

undergoing an operation the expected chance on e.g. a revision is calculated based on certain patient characteristics and compared with the observed outcome, whether this patient has a revision or not. The line in the CUSUM-chart declines when ‘’good’’ outcomes occur (e.g. no revisions) representing better performance than expected and increases when ‘unfavorable’ outcomes occur (e.g. revisions) representing worse performance than expected (Figure 2 in manuscript). When performance is in balance, an increase in the line in the CUSUM-chart because of an ‘’unfavorable’’ outcome is counteracted by many small decreases in the line in the CUSUM-chart resulting from ‘’good’’ outcomes. Regardless of the use of the CUSUM-chart for detecting a better or worse outcome, the baseline always indicates that a surgeon or hospital is performing as expected. The more the CUSUM-chart line drifts away from the baseline, the more this proves that a surgeon or hospital is performing better or worse than expected. A signal for better or worse performance is generated when the control limit is exceeded, in this case to detect a doubling of the revision rate. Similar to the Shewhart-p-chart, control limit setting of CUSUM-charts allow us to balance the risk of false positive and false negative signals. The control limits in CUSUM-charts are most commonly set at 3.5 or 5, with the 3.5 having higher likelihood of false-positive signals but the 5 having higher likelihood of false negative signals.[4,9] The CUSUM-chart is reset to zero when the control limit is reached. For a detailed description of the Shewhart-p-chart and CUSUM-chart formulas, we refer to Neuburger et al and Benneyan.[9,14]

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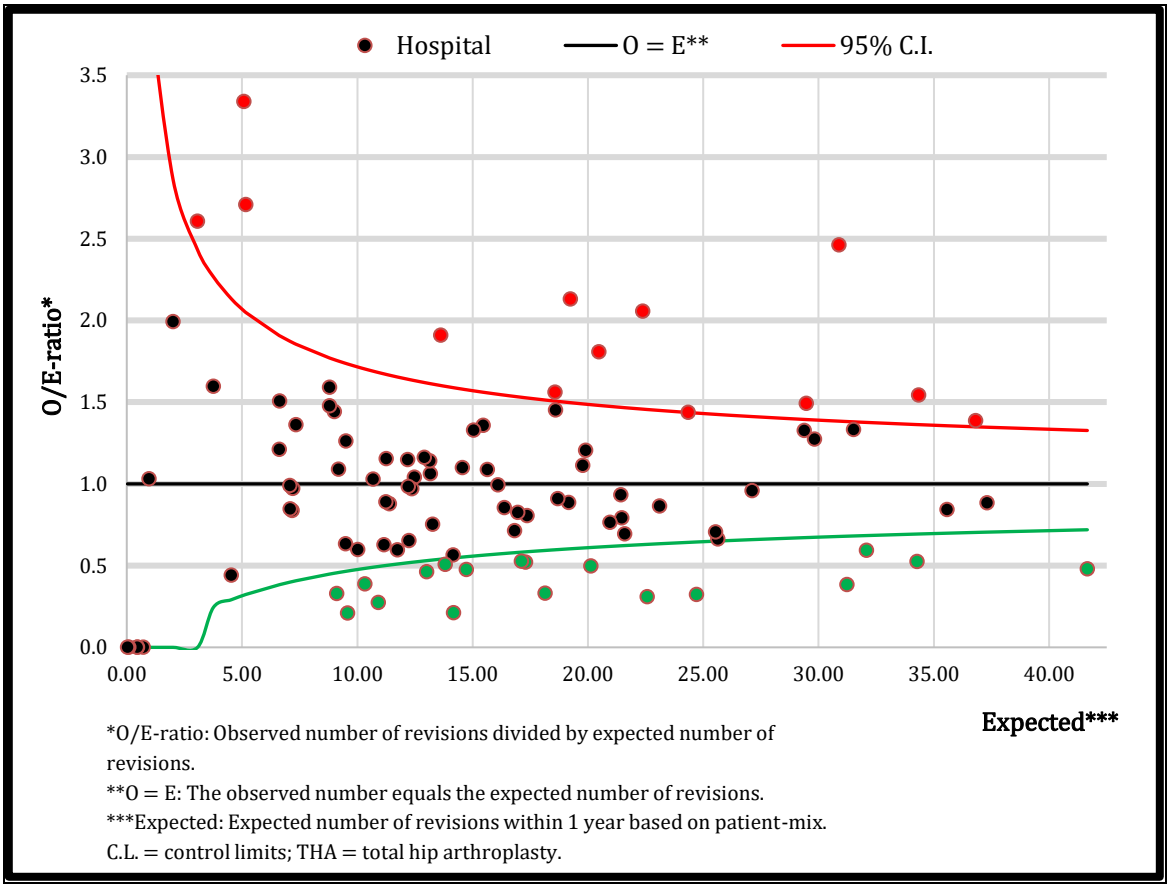
Appendix II Funnel-plot of between-hospital variation in 1-year revisions after THA during 2014-2016.



*O/E-ratio: Observed number of revisions divided by expected number of revisions.
**O = E: The observed number equals the expected number of revisions.
***Expected: Expected number of revisions within 1 year based on patient-mix.
C.L. = control limits; THA = total hip arthroplasty.

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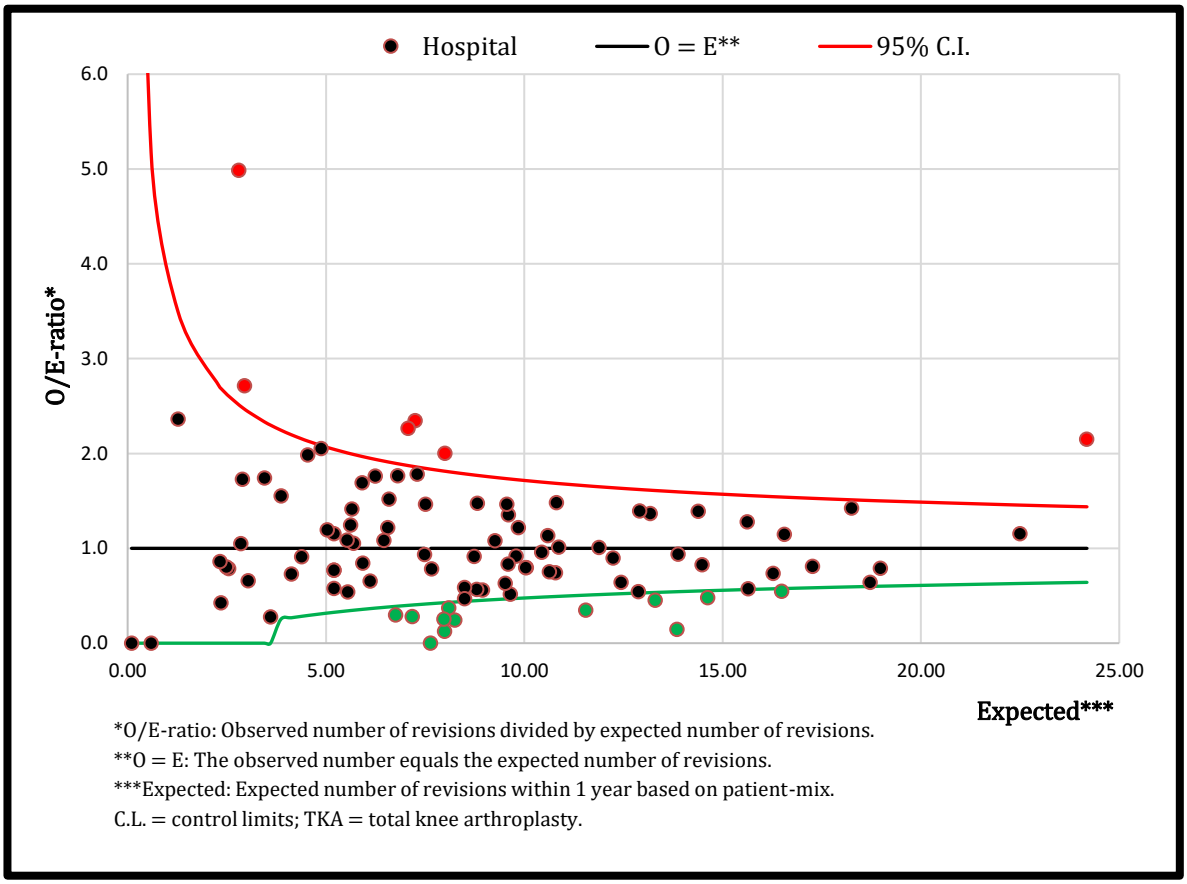
Appendix III Funnel-plot of between-hospital variation in 1-year revisions after TKA during 2014-2016.



*O/E-ratio: Observed number of revisions divided by expected number of revisions.
**O = E: The observed number equals the expected number of revisions.
***Expected: Expected number of revisions within 1 year based on patient-mix.
C.L. = control limits; TKA = total knee arthroplasty.