Supplementary Online Content

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This supplementary material has been provided by the authors to give readers additional information about their work.

eAppendix 1. Further explanation of use and interpretation of CUSUM with Figure 1.

The data provided by episodic analytic strategies and the CUSUM are similar in their intent but differ in several important aspects. When calculating and interpreting O-E ratios, the mathematical calculation is entirely predicated on the number of events in the numerator (observed events for the 'O' and expected [or predicted] events for the 'E') relative to the number of cases in denominator. What is missing from current episodic monitoring analyses (like O-E) is time—specifically, the timing of events in the numerator relative to each other. This is best conceptualized using an example of 2 hypothetical hospitals. Over the course of 100 observed cases performed at each hypothetical hospital, both end up with an outcome rate of 10%. At hypothetical hospital #1, the outcome pattern is 1 out of every 10 cases. In terms of numerator to denominator this is simply expressed as 10/100. At hypothetical hospital #2, the hospital also has a total of 10 outcomes at the end of the 100 cases. However, the pattern is different with 5 outcomes occurring over the last 20 cases while the other 5 outcomes occurred over the course of the first 80. Similar to hypothetical hospital #1, in terms of numerator to denominator this is also expressed as 10/100. Therefore, at the end of 100 cases, both hospitals have exactly the same outcome rate. But, one could contend that the pattern of outcomes is dramatically different and may be indicative of an emerging (or ongoing) quality and/or safety issue at hospital #2. However, because time (i.e., the timing of outcomes in the numerator relative to each other) is not accounted for in current episodic analytic strategies, the performance at both hospitals would likely be incorrectly characterized as similar. This highlights the potential value of the CUSUM as a monitoring and possible early warning tool. Because the CUSUM used in our study is based on a time-to-event model, not only are the cumulative number of outcomes in the numerator (relative to the denominator) considered, but so too is the rate at which outcomes are accumulating. In addition, whereas episodic analysis is performed on aggregated data at the end of a specified time period (e.g., a quarter), the CUSUM is able to incorporate cases and outcomes as they are occurring during a period of observation. An analogy to this difference would be if 100 light bulbs were made by a production line and the bulbs were tested for functionality for quality assurance. One option would be testing each bulb after all 100 bulbs were completed versus testing each bulb as it is coming off the production line. Testing each bulb as it comes off the line would allow for earlier identification of a potentially problematic production process (e.g., if 3 bulbs in row were non-functional).

The interpretation of Figure 1 is helpful to further elaborate this point. In each of the 4 panels of Figure 1, the x-axis represents time over the course of the quarter being monitored (i.e., each chart represents one quarter or 3-month period). The y-axis represents the hospital's 30-day mortality rate that the CUSUM is monitoring over the course of time. The line within each figure is the CUSUM as it is monitoring 30-day mortality in real-time. As the CUSUM line goes up, this suggests 30-day deaths are occurring and the steepness of the line is indicative of both the rate at which mortalities are accumulating as well as the degree to which the mortalities that are occurring were predicted to have occurred. By comparison, a line moving downward suggests 30-day mortalities are not occurring and that there were mortalities that may have been predicted to occur but have not. The V-mask is the technique used for signal detection and is based on a monitoring goal, or threshold, that is simultaneously defined by a slope (for a targeted level of observed versus expected deviation) and a radius (which tunes the sensitivity of the signal). The arrows with dates within the figure panels indicate when the CUSUM has crossed the V-mask threshold suggesting an out-of-control process (i.e., higher-than-expected mortality).

In order for CUSUM to signal, it must meet 2 criteria:

1.) The CUSUM must cross the specified V-mask radius (the radius is the specified boundary around the CUSUM monitoring line)
2.) The CUSUM must cross the specified radius at a rate that meets or exceeds the prespecified V-mask slope (i.e., a more dramatically up-trending line would indicate 30-day mortalities are accumulating at a rapid rate).

Therefore, for the CUSUM to signal, not only do 30-day mortalities need to occur, but they also need to be occurring in a relatively short time period (i.e., the mortality rate is high at the point in time monitored by the CUSUM).

With this as context, panel A demonstrates a hospital that was not identified as an O-E outlier at the end of the quarter. The corresponding CUSUM also does not demonstrate any signal suggesting the hospital is not having any concerning performance deviations (i.e., a high rate of mortality or mortality in patients predicted to be a low risk for death). By comparison, panels B-D demonstrate CUSUMs suggestive of accumulating mortality over time and/or deaths in patients predicted to have a low risk of mortality. In Panel B, the hospital was not identified as an O-E outlier at the end of the quarter, but did have a single CUSUM detection early in the quarter. While this might be considered a 'false positive', this could be indicative of an emerging quality problem that has not yet caused a confirmatory signal in terms of O-E. Panels C and D represent hospitals detected by O-E at the end of the quarter as well as accumulating CUSUM signals during the quarter. These panels are demonstrative of the opportunity the CUSUM presents for earlier detection. Put differently, the time between the first (or second) CUSUM signal and the end of the quarter (when O-E detection occurs) represents missed opportunities in the form of:

1.) lost time to critically evaluate the hospital's care processes
2.) patient's treated who are potentially at-risk for suboptimal outcomes and who may be exposed to potentially preventable harm.

eAppendix 2. Sensitivity analysis for comparison between CUSUM and 60-day episodic observation periods using O-E detection.

Among hospital quarters detected using O-E ratios calculated after 60-days (instead of quarterly), 49.9% were concurrently detected by at least 1 CUSUM signal versus 24.3% with more than 1 CUSUM signal. The observed mortality rate for 60-day and 90-day monitoring at outlier hospitals was 2.1% and 1.8%, respectively.

eTable. C-statistics of multivariable hierarchical regression model evaluating hospital factors in Table 2.

Single CUSUM signal	**C-statistic**
False positive	0.76
False negative	0.84
Multiple CUSUM signals	
False positive	0.78
False negative	0.90