SUPPLEMENTAL MATERIAL

Expanded Methods

Outcome Risk-adjustment

We calculated risk-adjusted outcomes for each encounter by building logistic regression models with a set of baseline predictors. Let *I* be a set of encounters. Given an encounter $i \in I$, the outcome for this encounter, y_i, can be defined as

$$y_i = \begin{cases} 1 \rightarrow positive\ outcome \\ 0 \rightarrow negative\ outcome \end{cases} \quad (1)$$

For our set of baseline predictors, we used logistic regression to model associations of baseline values with outcomes. We then estimated the probability of a positive outcome for each encounter. If $x_{1i}, x_{2i}, \dots, x_{ri}$ are values of *r* baseline predictors for the patient involved in encounter *i*, let

$$p_i = \Pr(y_i = 1) = \frac{e^{\beta_0+\beta_1 x_{1i}+\beta_2 x_{2i}+\cdots+\beta_r x_{ri}}}{1 + e^{\beta_0+\beta_1 x_{1i}+\beta_2 x_{2i}+\cdots+\beta_r x_{ri}}} \quad (2)$$

where the β parameters were estimated using logistic regression. Finally, we defined a risk-adjusted outcome, r_i, as follows:

$$r_i(y_i) = \frac{1 + (y_i - p_i)}{2} \tag{3}$$

Note that the expected value of r_i is:

$$\begin{gathered} E = P_i(Y_i = 0) r_i(0) + P_i(Y_i = 1) r_i(1) \\ E = P_i(Y_i = 0) \frac{1 + (0 - p_i)}{2} + P_i(Y_i = 1) \frac{1 + (1 - p_i)}{2} \\ E = (1 - p_i) \frac{(1 - p_i)}{2} + \frac{p_i(2 - p_i)}{2} \\ E = \frac{1 - 2p_i + p_i^2 + 2p_i - p_i^2}{2} \\ E = \frac{1}{2} \end{gathered} \tag{4}$$

Values of r_i relate to values of y_i and p_i in the following way:

$$y_i = \begin{cases} 1, high\ P_i \rightarrow r_i\ is\ close\ to\ 0.5 \\ 0, high\ P_i \rightarrow r_i\ is\ close\ to\ 0 \\ 1, low\ P_i \rightarrow r_i\ is\ close\ to\ 1 \\ 0, low\ P_i \rightarrow r_i\ is\ close\ to\ 0.5 \end{cases} \tag{5}$$

Glossary

Shared Positive Outcome Ratio (SPOR): This is a pairwise measure that quantifies the ratio of specific positive outcomes shared between two providers versus outcomes shared with other provider. It answers the following question: *How many*

more positives outcomes do these providers attain when they collaborate versus when they collaborate with other providers?

LTR (Likelihood to Recommend): This was the outcome used in our study. It is a response to a question in the Press Ganey Associates, Inc. Hospital Consumer Assessment of Healthcare Providers and Systems (HCAHPS) Hospital Survey that asks the patient how likely they are to recommend Northwestern Memorial Hospital to their friends and family. The LTR is measured on a 5-point Likert scale. We defined a positive outcome as an LTR score of 5/5 ("highly likely to recommend" or LTR+), the "top box" score as defined by the Centers for Medicare and Medicaid Services (CMS) scoring system, and a negative outcome as a score of 4/5 or below ("not highly likely to recommend" or LTR-).

Top Box: The Centers for Medicare and Medicaid Services (CMS) publishes a "top box" scoring system that reports the percentage of patients who respond in terms of "Always" or the highest possible ranking category. The comparison to the regional and national average can be viewed publically at http://www.hospitalcompare.hhs.gov and serves as guide for patients. For our study we used results from the HCAHPS survey, which is based on a 0-5 scale where a score of 5 represents the highest possible rank.

Provider-encounter network: One of two types of networks constructed in our study. It consisted of provider nodes and encounter nodes with directed

relationships originating at the provider and terminating at the encounter, indicating that a provider performed one or more activities during that encounter. This network was used to identify providers who shared encounters. The risk-adjusted outcomes of these shared encounters were used to calculate the SPOR metric and thus characterize collaboration for each pair of providers over their set of shared encounters.

Provider collaboration network: One of two types of networks constructed in our study. These were composed of provider nodes and relationships signifying that two providers share at least *x* patient encounters. Five provider collaboration networks were created in this study, each with a different threshold on the number of patient encounters required to define a collaborative relationship.

Patient acuity measure: In this study, we used the ESI-level (Emergency Severity Index) (http://www.esitriage.org) to risk-adjust encounter outcomes. The ESI is an acuity measure that also takes into account the operational resources expected to be required for the patient during their encounter.

Edge weight: In the provider collaboration network, each edge between two providers is weighted with a SPOR value. A higher SPOR edge weight indicates a better collaboration score between the providers.

Shared encounter threshold: In the collaboration network, a minimum number of patient encounters shared between two providers can be set as a requirement to define a collaboration in order to cull the network of nascent or newly developing relationships. Increasing this threshold yields a narrower distribution and lessens the effect of adding one shared encounter to a collaborative relationship, but may also remove potentially interesting collaboration results. Because of this, the choice of threshold should be determined on a case-by-case basis and informed by domain expertise and data content.