Risk Modeling in Healthcare

Reza Kazemi, currently at the USFDA
Ali Mosleh, UCLA
Meghan Dierks, Harvard Medical School
FOUR TOPICS TO COVER

1. Magnitude of the problem
2. Context: overview of a hybrid modeling approach
3. BBN for pressure ulcer
4. BBN for line infection
Magnitude of the Problem
Adverse events/errors remain a major concern in the healthcare system, despite efforts to improve quality and safety.

In the US healthcare system, estimated magnitude of problem:

- 4% of all hospitalized patients incur treatment-related injury (1984, NY)
- 14% of these injuries were fatal
- 48,000 to 98,000 people die in hospitals each year as the result of medical errors (IOM, 1999)
  - 2016 Hopkins study: 250,000 death/year
  - OIG: 180,000 in 2008
  - Mayo clinic study
- Cost of managing treatment-related injuries: $37.6 Billion
Despite awareness about adverse events, progress to render the system safer is slow. Why?

Many reasons, but at least some of the difficulty relates to:

- Complexity of the healthcare system
- Dynamic nature of risk
- Absence of good techniques to understand and model risk

Challenges to modeling and analysis:

- Wide variability in processes of care (non-standardization)
  - Organizational and human performance
  - Uncertainty
  - Reliability of information used in decision making
- Heterogeneity in the patient response to interventions
- Dynamic nature of risk in this environment
  - Exposure varies across time
  - Severity of effects changes with time
Formal approaches to risk modeling and analysis of adverse events:
  • Relatively uncommon, prior to 2000
  • Use of informal methods promoted by US regulatory and certification authorities (Joint Commission, Federal and private insurers)
  • Most notable tool – a simplified version of FMEA

Quantitative approaches
  • Application/use limited to a few research studies
Overview of methods applied in healthcare

Informal Risk Assessment Methods

**FMEA**
Promoted by JCAHO

Highly subjective

Rarely quantitative

Does not capture many potential failures

Incapable of displaying the influence of policies and decisions

**Miscellaneous Approaches**

Retrospective studies

Core: linear regression

Checklists for risk assessment
  • Reliability and validity

Formal Risk Assessment Methods

**PRA**

ESD, FT...

Linearity assumption in classical PRA

Much of what happens in HC is subject feedback

Contributing factors are more complex than mechanical systems

Useful for specific aspects of risk
  • Medication error

**HRA**

“cherry picked” theories and tools

Enormous diversity in healthcare and related tasks

Diversity in humans performing tasks

Response to human actions unpredictable

Wide range of tolerance to imperfect task execution
Desirable attributes of the model

- A tool to;
  - Provide a more realistic view, capture dynamics of risk/safety as function of policy and organizational decisions
  - Project unintended consequences of external and internal policies and decisions on safety
- Simple enough to be practical, detailed enough to be informative
- Comprehensive, integrating key elements: system, patient, provider
- Flexibility:
  - To tailor to individual hospital characteristics
  - Updatable with new qualitative and quantitative data
A Hybrid Modeling Approach
To realistically address system based risk it is necessary to:
  • Display the complexity of contributing factors
  • Capture dynamic effects (i.e. reinforcing loops and feedback)

The proposed model consists of two components:

- **System dynamics framework**
  - To represent change over time
  - Feedbacks
  - Delays

- **Bayesian belief network structure**
  - Causality
  - Uncertainty
  - Incorporation of new knowledge
Combination of increasing costs, decreasing reimbursement has created tremendous financial constraints for healthcare organizations.

Insurers have increased pressure by imposing penalties for adverse events.

This leaves hospitals in the following risk-relevant positions:
- Few resources to invest proactively in safety
- Operational decisions that focus on reducing costs may increase risk (e.g., staffing cuts, reducing patient length of stay)
- Effects of these factors also depends on individual patient’s conditions and provider’s decisions
Adverse events that will be emphasized

• Adverse events
  • Set of hospital acquired conditions (HAC) that patients can experience while in the hospital
• Focus on these AEs because
  • Preventable
  • No reimbursement
Model overview

• Limited utility of approaches adapted from engineering discipline in modeling system-based risk in healthcare
  • Underlying causal chains in healthcare are subject to feedback
  • Much greater number of contributing factors

• Hybrid modeling approach
  • Bayesian Belief Networks
    • Patient level, and patient provider level factors

  • System Dynamics
    • System level factors
Patients in hospitals are exposed to a certain level of risk of specific adverse events (e.g., pressure ulcer, line infection).

- Financial situation of the hospital
  - Level of dedication to safety
  - The organizational and policy level factors and
  - Decisions with regards to:
    - Staffing
    - Pressures to reduce LOS,
    - Investments in infection control etc.,

Which evolve dynamically over time, provide a background that determines where hospital is standing in terms of risk when the next patient comes in.
Model overview

Cost of Care Per Day
Variable Costs of Caring for Adverse Event (Supplies, etc.)
Total Admissions
Increase in Cost Due to Adverse Event
Total Expected Cost of Caring for the Adverse Event
Operating Margin
Pressure to Close the Revenue Gap
Pressure to Cut Operational Cost
Probability of Complexity Exceeding C3
Probability of Under staffing Probability
Probability of Critical Pressure Limit for Shortened LOS
Probability of Critical Pressure Limit for Prolonged LOS
Magnitude of Change in Risk of Adverse Event Due to Prolonged LOS
Magnitude of Change in Risk of Adverse Event Due to Shortened LOS
Magnitude of Change in Risk Due to Understaffing
Real Risk
Change in Win

View 1

View 2
Data sources

- 8 years of clinical data
- Adverse event data: 10000 cases, 400 root-cause analysis
- 17 experts with average of 20 years of clinical experience
• Overall 120 hours of expert interview
A Bayesian Belief Network Model for Risk of Pressure Ulcer
Pressure Ulcer (PU) is a localized injury to the skin and/or underlying tissue usually over a bony area, as a result of pressure in combination with shear and/or friction” (NPUAP)

- 4 stages of severity

- Prevalence:
  - Estimated at 15% by NPUAP
  - Estimated cost an average of $25000 per patient (Lyder, 2003)
  - Estimated Cost on healthcare as high as $11 billion (Reddy et al., 2006)
Current risk assessment tools for PU

Step 1
Set of internal and external factors (Mobility, nutrition, etc.)

Step 2
Assign a numerical value based on patient's conditions

Step 3
Compare the sum score to a threshold

Limitations
- Equal weighting
- Ignores synergic effects of factors
Bayesian Network are built based on the conditional probabilities, no equal weighting of the factors is assumed.

Using BBNs enables the analyst, to take into the account the fact that the degree of influence of one factor in risk of pressure ulcer may be different given the presence or absence of other risk factors.

Bayesian Belief Networks are probabilistic in nature and the uncertainty in our assessment of pressure ulcer risk, given the state of all relevant risk factors can be expressed explicitly.
### PU BBN model

<table>
<thead>
<tr>
<th>Factor</th>
<th>Description</th>
<th>Notes on quantification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Circulation Impairment</td>
<td>Poor blood circulation makes patients more susceptible to pressure ulcer</td>
<td></td>
</tr>
<tr>
<td>Peripheral Vascular Disease (PVD)</td>
<td>Diseases of blood vessels outside heart or brain</td>
<td></td>
</tr>
<tr>
<td>Sensory Impairment</td>
<td>Defect in sensing or passing on the impulse, which affects patients’ ability to respond to pressure related pain and discomfort</td>
<td></td>
</tr>
<tr>
<td>Skin Integrity</td>
<td>Description of whether patient’s skin is intact</td>
<td>Normal or abnormal</td>
</tr>
<tr>
<td>Mobility</td>
<td>Patient’s ability to change and control his/her body position</td>
<td>A patient with Focal Neurological Deficit, Central Nervous System Impairment, Weakness/Debilitation or Morbid Obesity has been counted as a case of impaired mobility</td>
</tr>
<tr>
<td>Frequency of Move</td>
<td>Whether the patient is being moved to different body positions frequently enough</td>
<td>Any patient with Central Nervous System Impairment, Morbid Obesity, Impaired Mobility or Counter Indication to Move (C-I Move) has been counted as patient with high aggregate effect on Frequency of Move</td>
</tr>
<tr>
<td>Assistive Devices</td>
<td>Include support surfaces such as cushions, mattress overlays, replacement mattresses or pressure relieving beds</td>
<td>Depends on their availability and also staff adequacy (whether or not the high level of workload prevents staff from providing patients with these devices)</td>
</tr>
</tbody>
</table>
Modeling techniques for quantification

- **Structure related**
  - Parent divorcing (Olesen, et al., 1989)

- **Probability distribution related**
  - Noisy-OR Gate (Pearl, 1988)

Assumptions:
- Xi's are each sufficient to cause Y
- Xi's are independent of each other in causing Y
- Xi has a probability, pi, of being sufficient to cause Y
Quantification

• 70,090 inpatients hospitalized over a 2 year period
• Queries were constructed to identify conditions that were present in two distinct cohorts of patients:
  • patients who did not acquire a pressure ulcer during hospitalization
  • patients who did
• In absence of clinical data, expert opinion were elicited and aggregated (Bayesian aggregation)
  • Example: Probability of use of assistive devices, given staff adequacy
Bayesian aggregation

Bayesian Aggregation (Mosleh and Apostolakis, 1986)

- Unknown of interest x

Expert Estimates

<table>
<thead>
<tr>
<th>Expert</th>
<th>Most Likely</th>
<th>Most Discrete</th>
</tr>
</thead>
<tbody>
<tr>
<td>Expert 1</td>
<td>20%</td>
<td>30%</td>
</tr>
<tr>
<td>Expert 2</td>
<td>30%</td>
<td>20%</td>
</tr>
<tr>
<td>Expert 3</td>
<td>40%</td>
<td>20%</td>
</tr>
<tr>
<td>Expert 4</td>
<td>40%</td>
<td>20%</td>
</tr>
<tr>
<td>Expert 5</td>
<td>40%</td>
<td>20%</td>
</tr>
<tr>
<td>Expert 6</td>
<td>40%</td>
<td>20%</td>
</tr>
</tbody>
</table>

Distribution of parameters

Average Dist. Of Population variability Lognormal (0.0477, 0.0148)

- Integrating tools to increase the quality of model output, given the quality of available data
Model error
• The modifications made to model structure
• No possibility of calibrating expert opinion
• Model parameters quantified based on 2 years of reliable data
• Hospital acquired pressure ulcer data only available after 2008 (extrapolated for other years)

<table>
<thead>
<tr>
<th>Actual Relative Frequency from Data</th>
<th>BBN Model Prediction</th>
<th>% Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressure Ulcer</td>
<td>2.20E-03</td>
<td>2.40E-03</td>
</tr>
</tbody>
</table>

Bayesian method for model uncertainty treatment (Mosleh and Droguett 2008, Droguett 1999)

Model Prediction: 3.3 e-3
Actual data: 2.2 E-3
Error~30%

Posterior mean:
2.4 e-3
Actual data: 2.2 E-3
Error~8%
Bayesian treatment for model uncertainty

• Prediction error
• Evidence: Model’s prediction
• Objective: develop uncertainty distribution of PU probability given the evidence

• Available information; model performance
• Additive error model
• Flexible likelihood: Normal with mean

• Posterior function of parameters

• Posterior of the new model prediction
A Bayesian Belief Network Model for Risk of Vascular Catheter-Associated Infection
Central Venous Catheter (also called CVC, central line, or Vascular Access Device (VAD)), is a catheter that is placed into a large vein in the neck (internal jugular vein), chest (subclavian vein), or groin (femoral vein) to give medicines, fluids, nutrients or blood products to the patients

- An essential component of modern medical care
- One of the most commonly inserted medical devices
- One of the most common cause of hospital acquired bloodstream infection
## Risk factors

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<th>Factor</th>
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<tbody>
<tr>
<td>Insert Environment</td>
<td>Bedside versus controlled environment</td>
<td>ICU patient room (a semi-controlled environment) or the operating or procedure room. Suboptimal environment: trauma room, ED or regular non-ICU clinical unit, or during an emergency resuscitation.</td>
</tr>
<tr>
<td>Insert IHI Compliance</td>
<td>IHI bundle protocol hand hygiene, skin preparation,</td>
<td>Bundle checklist</td>
</tr>
<tr>
<td>Insert Provider Proficiency</td>
<td>Provider's experience, proficiency and judgment</td>
<td></td>
</tr>
<tr>
<td>Staff Adequacy</td>
<td>Assistance to provider performing the procedure</td>
<td>Nursing or staff availability</td>
</tr>
<tr>
<td>Anatomic Constraints</td>
<td>Influences site selection, de novo vs. change, dressing change</td>
<td>True or false</td>
</tr>
<tr>
<td>Site Selection</td>
<td>Chest, neck, groin</td>
<td>Femoral access is considered suboptimal here.</td>
</tr>
<tr>
<td>Access Frequency</td>
<td>Frequency of port access</td>
<td>No widely accepted standard. Based on concurrent drug use. 4 or more IV infusions is considered high frequency.</td>
</tr>
<tr>
<td>Access Sterility break</td>
<td>Unrecognized break in sterility</td>
<td>Based on documentation of major break</td>
</tr>
<tr>
<td>Access Provider Proficiency</td>
<td>Provider's experience, proficiency and judgment</td>
<td>Primary nurse coverage</td>
</tr>
<tr>
<td>Patient Resistance Factors</td>
<td>Physiological and pharmacological</td>
<td>Evidence of profound immunosuppression such as acute lymphoma resulted in diminish resistance. Patients on broad-spectrum antibiotic are deemed high resistant.</td>
</tr>
</tbody>
</table>
Extracted data from ICU patients
- Data is more reliable
- Most lines are placed in ICU
- 12897 records, 8 years

### Quantification and Validation

<table>
<thead>
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<th></th>
<th>Actual Relative Frequency from Data</th>
<th>BBN Model Prediction</th>
<th>% Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Line Infection</td>
<td>3.06E-02</td>
<td>3.12E-02</td>
<td>2%</td>
</tr>
</tbody>
</table>
The hybrid model

**Graph for Real Risk of PU**

Risk of PU: hybrid model predictions for each year versus actual data calibrating the model using both BBNs

**Graph for Real Risk of Line Infection**

Risk of line infection: hybrid model predictions for each year versus actual data calibrating the model using both BBNs
Could it be improved?

- More expert opinion, from a diverse set of hospitals, on the soft factors in the model
- More adverse event data from a variety of hospitals
  - finding clean reliable clinical data, could be challenging to say the least
- Meticulous modeling of the cost and reimbursement structure
- Modeling more adverse events
BACK UP