A Bayesian Belief Network Model for Risk of Pressure Ulcer

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Abstract: Pressure ulcers, although potentially preventable, are unfortunately a common occurrence specially among high-risk population such as elderly and patients with impaired physical mobility. Its estimated that between 1.3 to 3 million pressure ulcers are treated in the U.S. hospitals every year with estimated cost of 500-40000$ for each case. In this study, we have developed a Bayesian Belief Network (BBN) model to assess the baseline risk of pressure ulcer for. Bayesian Belief Networks or Bayesian Networks are a class of probabilistic graphical models for reasoning under uncertainty. The graphical aspect of BBNs can be used in a qualitative manner to represent relationships between a set of variables while the *strength* of the causal relationship between variables on the other hand, can be quantified using probability calculus. BBNs can capture probabilistic relations between variables and contain historical information about their relationship, and are powerful tools for modeling causes and effect in many domains. They are also very effective in modeling situations where data are uncertain and vague or incomplete and only partially available. These properties of BBN make them an ideal candidate for modeling risk of pressure ulcer. The model has been built based on the risk factors introduced in literature, and the input provided by a panel of seventeen subject matter experts. After the qualitative validation of the structure of the model, we have quantified and validated the model using 70090 deidentified pateint records from 2008-2010 from one of Harvard University's teaching hospitals. This model can be used in decision making, sensitivity analysis and audit to assist the decision maker in understanding how hospital level policies may affect risk of pressure ulcer and what risk factors are most sensitive to potential policy changes. Further it can be used in risk-benefit analysis to highlight the improvements in risk factors (e.g. staff adequacy) would have the greatest impact on risk reduction.

Keywords: Bayesian Belief Network, Healthcare Risk Modeling, BBN, Pressure Ulcer, Risk.

1. INTRODUCTION

A Pressure Ulcer (PU) is a skin break that does not heal and often causes irritation. Heels, elbows and buttocks areas of the body are most at risk. As the National Pressure Ulcer, Advisory Panel (NPUAP) defines it "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".
Though pressure ulcers are potentially preventable, unfortunately they present a common condition specially among high-risk population such as elderly and patients with impaired physical mobility [1].
In the United States, studies suggest that in acute care the prevalence of pressure ulcer ranges from 3.5 to 29% (estimated at 15% by NPUAP) [2], 2.2 to 26% among those in long-term care and 10 to 17% in homecare [1]. Some studies suggest that the prevalence figures in spinal units are as high as 50% [3] Literature also suggests similar prevalence statistics in European hospitals [4].
Pressure ulcers are painful for patients and costly to care for. An estimated 1.3 to 3 million pressure ulcers are treated in U.S. hospitals every year with an estimated cost of $500 to $40,000

to heal each ulcer [5] and may even cost up to $ 75,000 per patient [1,3]. U.S. expenditures on treating pressure ulcers have been estimated to be $11 billion each year. This number in the UK has been estimated in a 1993 study to be in the range £180-£231 million, which accounts for 0.4 - 0.8% of their health spending [6]. The development of pressure ulcers may also indicate neglect and mismanagement and have legal implications; 87% of litigation settlements regarding pressure ulcers in long-term care (LTC) settings have been in favor of LTC residents [1]. If pressure ulcers are to be prevented and the risk of PUs is to be controlled and reduced it is essential to identify patients who are at risk of experiencing this adverse event. Moreover, a range of preventive measures including use of pressure reducing mattresses and patient repositioning are available - even though limited information on their effectiveness exists [7] but before any prevention plans are put in place, some form of risk assessment of individual patient's chances of PU should be carried out [4,8]. Though some clinicians may believe that performing an informal PU risk assessment would suffice, research has shown that when a formal risk assessment is not undertaken, clinicians have consistently tended to intervene only at the highest levels of risk of PU, leaving many patients susceptible to the risk of hospital acquired pressure ulcer. It has also been shown that in studies where formal risk assessment was performed and preventive measures were taken accordingly, the incidence of PUs had dropped by 60%, with decreased severity of PUs and cost of care [2]. In the next session, some of the more popular PU risk assessment tools are reviewed.

1.1. Pressure Ulcer Risk Assessment Approaches

Since a comprehensive and detailed risk assessment of every individual patient's vulnerability to pressure ulcer, based on the principals of wound healing, requires gathering a vast amount of knowledge and may become practically impossible. Several risk assessment tools or risk assessment scales (RAS) have been designed since the 1960's, as a shortcut to produce a quick assessment and help practitioners identify patients who are at risk of developing pressure ulcer. Current guidelines underline that RASs should be used as an addition to provider's clinical judgment and not as a replacement. To date over 20 of such scales are described in the literature [4]. These tools include, among others, the Norton scale [9], the Gosnell scale [10], the Braden scale [11], the Waterlow scale [12]. Some of these scales such as Norton's and Waterlow's have been developed in Europe and others were created in the United States.

Typically, these scales produce assessments of a set of internal and external factors (e.g. mobility, nutrition, etc.) that are generally believed to be contributing factors in development of pressure ulcers. A numerical value is assigned to each of these factors based on patient's conditions, and these values are then summed to create a total score. The total score is usually compared to a critical value or a cut-off point, and hence it is used as an indication of patient's susceptibility to experiencing pressure ulcers.

Keller [2002] has summarized the risk factors considered by some of the well-known risk assessment scales in Figure1.

Factors	Norton	Gosnell	Andersen	Waterlow	CBO	Douglas	Braden	Pressure Sore Prediction Score
Neurology					+			
Sensory perception							+	
Activity	+	+				+	+	+
Mobility	+	+	+	+	+		+	+
Moisture								+
Friction							+	
Nutrition		+					+[a]	+
Physical condition	+					+		+
Mental state	+	+	+		+	+		+
Incontinence	+	+	+	+	+	+		+
Weight			+	+				
Skin state			+	+				
Gender				+				
Age			+	+	+			
Appetite				+				
Special risks				+[b]	+[c]	+[d]		
Pain						+		
Dehydration			+					
Temperature					+			

Figure 1.Pressure ulcer risk factors (Keller, 2002)

Between the above-mentioned risk assessment tools, the Braden scale is perhaps the most widely used in the United States.

1.2. Pitfalls of Scoring Approach to Risk Assessment

Despite the fact that using risk assessment tools, in addition to clinician's judgment, provides some useful information in identifying the patients at risk in developing pressure ulcer and helps practitioners make an informed decision in implementing appropriate preventive interventions, there are methodical shortcomings that are common between these RASs.

In the scoring system that is used in these risk assessment scales to identify patients at risk and patients not at risk, every risk factor contributes equally to the overall risk score. In other words, the scoring approach to risk assessment assumes that all the factors have equal effect on the overall risk of developing pressure ulcer. The equal-weighting approach while being the simplest way to scale scoring, fails to recognize that some factors may play a more significant role and therefore should have a larger contribution to the overall risk score [4]. For a more accurate predictive measure, the magnitude of the effect of each of the risk factors on the overall risk of developing pressure ulcer must be considered, based on the importance that these factors empirically demonstrate. Failing to do so may project unrealistic risk scores that could possibly influence the effectiveness of the interventions and affect the allocation of resources.

Another rather important deficiency of most of risk assessment scales is that the effect of all risk factors contributes linearly to the overall risk score. This completely overlooks the fact that a certain factor in presence of other factors may, for instance, exponentially increase the risk of pressure ulcer. For example, consider the Braden scale. Given that Sensory and Nutrition are influencing factors in risk of pressure ulcer but the magnitudes of this influence is in a) presence of impaired mobility and b) un-impaired mobility could be very different.

2. Developing a Bayesian Belief Network for Pressure Ulcer Risk

To assess the risk of developing pressure ulcer as a function of individual patient's risk factors and patient-provider (i.e. intervention related), a Bayesian Belief Network framework has been chosen. Use of BBNs in modeling the risk of experiencing pressure ulcers, not only alleviates the major criticism to the scaling risk assessment approach, namely the equal weighting of the risk factors, but also offers capabilities that could possibly provide more realistic, relevant and meaningful assessments;

- Since we construct the Bayesian Network based on the conditional probabilities, no equal weighting of the factors is assumed. Based on the importance of each factor and the strength with which these factors influence the risk of pressure ulcer (obtained from field data and expert judgment) we can determine the conditional probability that a patient will experience pressure ulcer given the states of all the risk factors.
- 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 of our assessment of pressure ulcer risk, given the state of all relevant risk factors can be expressed explicitly.

A Bayesian Belief Network, that includes or reflects the factors introduced in literature as factors influencing risk of pressure ulcer, has been developed. Additionally, a panel of 17 experts more than 15 years of clinical experience on average, contributed in the construction of this BBN, providing input on the factors thought to be of importance, and missing from the current risk assessment scales, causal relations between these factors and their subjective assessment on some of the nodes in the model were field data was not available or unreliable.

2.1. Pressure Ulcer BBN

Based on pressure ulcer risk factors introduced in literature and the panel of experts input elicited, a BBN is developed for risk of pressure ulcer. This BBN is depicted in Figure 2 Table 1 provides a brief description of BBN variables.

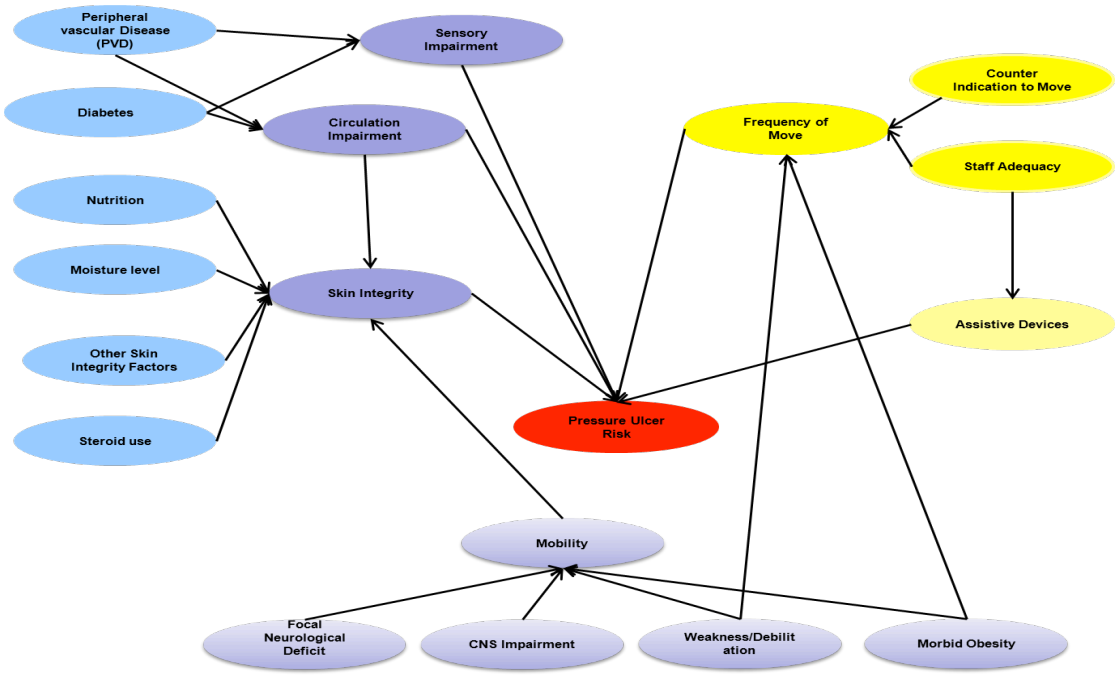

Figure 1. Pressure ulcer BBN

Factor	Description
Circulation Impairment	Poor blood circulation makes patients more susceptible to pressure ulcer
Peripheral Vascular Disease (PVD)	Diseases of blood vessels outside heart or brain
Sensory Impairment	defect in sensing or passing on the impulse, which affects patients' ability to respond to pressure related pain and discomfort
Skin Integrity	description of whether patient's skin is intact
Mobility	patient's ability to change and control his/her body position
Frequency of Move	is whether the patient is being moved to different body positions frequently enough
Assistive Devices	include support surfaces such as cushions, mattress overlays, replacement mattresses or pressure relieving beds

Table 1- Pressure ulcer BBN factors

3. MODEL QUANTIFICATION and VALIDATION

3.1. Data

Building a Bayesian network for a certain application has three steps and involves three tasks [13]. First, important variables and their possible states must be identified. Second, the relationships between these variables are identified and are represented graphically with edges between the variables. The third phase is to obtain the numerical parameters, i.e. probabilities required for the quantification of the network from data or through domain expert elicitation [14]. The first two tasks that are concerned with establishing the structure of the network typically involve iterative and interactive sessions with domain experts. Multiple iterative cycles are required to revise the model(s), identify new variables and links or perhaps delete other variables and links and converge on a valid representation of the phenomenon that is being studied. For the first and the second task we have followed the process proposed by Marcot et al. (2006) [15], for the peer review of the BBNs, where we started with a basic influence diagram as a base model and followed the peer review process using the panel of domain experts to develop, refine and validate the BBN. While the first and second tasks require moderate effort and time, experience indicates that the third task, which is the elicitation of the quantitative information including the conditional probability table or CPT, requires the most effort [13]. Certain Modeling techniques are available to make the third task more manageable, without (or with minimum) compromising the accuracy of the results. We have used some of these techniques in quantifying the BBNs in this study such as parent divorcing and Noisy-OR gates which are discussed in detail in Kazemi. (2011)[16].

Data to establish the conditional probabilities was obtained by querying a clinical data archive at a large urban US medical center. This data repository contains diagnostic codes and clinical outcomes for 70,090 inpatients hospitalized over a 2-year period. After obtaining IRB approval, structured queries were constructed to identify conditions that were present in two distinct cohorts of patients: 1) patients who did not acquire a pressure ulcer during hospitalization and 2) patients who did acquire a pressure ulcer during hospitalization. At the time of discharge, expert codification of up to 15 physiological or disease condition codes are assigned to characterize the patient and the episode of

care. Pharmacy and laboratory data for some of the patients analyzed in some cases either to confirm one or more diagnostic codes, disambiguate clinical conditions or identify additional patients in the cohort. As an example, in the case of the node "Skin Integrity", which may be affected by Nutrition, Moisture Level, Steroid Use, Circulation Impairment and other factors not specified in the model, we extracted all cases of compromised skin integrity due to any reason (specified or unspecified in the BBN model), to ensure that any patient with skin integrity issues is accounted for in this model. Similarly, for the nodes "Circulation Impairment" and "Sensory Impairment" the two most prevalent causing factors for these conditions as experts have identified are "Diabetes" and "Peripheral Vascular Diseases or PVDs", among others (which data may or may not exist for). In the quantification of this model, we have identified all the cases of circulation impairment and sensory impairment among the hospital population regardless of the cause, to make sure that all patients with these conditions are included in the model. One important step was to distinguish those patients who acquired a pressure ulcer during their hospitalization from those who were treated for the condition, but had the condition at the time of admission to the hospital. To do this, we constrained the queries using a special 'Present on Admission' code that is used to classify patient conditions at this medical center. For more details on quantification of this model please see [16].

3.2. Qualitative and Quantitative Model Validation

3.2.1 Qualitative Validation

In developing the Bayesian belief networks for this study, we started with a basic draft of a model that contained the important factors and relations between the factors discussed in the literature and the input of one of the experts. We then consulted the domain experts extensively through multiple sessions of face-to-face interviews and reached to the consensus model that is presented here as the final version. This consensus was reached after many iterations to the point that all experts agreed that model is now presenting all the known major factors affecting the risk of pressure ulcer (and the risk of line infection in the case of vascular catheter associated infection). Naturally, peer review has been a crucial step in developing and qualitatively validating these models. In such a peer review of the BBN models, some steps and methods, suggested by Marcot, et al. (2006) [15] have been generally followed. Last, we asked our panel of experts to evaluate the last version of the model (the qualitative model) in following categories; model completeness, model accuracy, ease of understanding and perceived predictive validity, to ensure sufficient confidence in the structure of the model before proceeding to model quantification.

3.2.1 Quantitative Validation

Using available data from sources introduced in section 3.1, and expert opinion for the nodes that data was unavailable or unreliable the pressure ulcer BBNs have been quantified and the results have been validated against actual data for relative frequencies of pressure ulcer for years 2003 to 2011. We also used a Bayesian model uncertainty treatment [17], which updates BBN model's output based on model's performance data (i.e. historical differences between model prediction and the actual value of the parameter of interest) to adjust model predictions. Table2 shows the average error 8 years, after the Bayesian adjustment.

	Actual Relative Frequency from Data	BBN Model Prediction	% Error
Pressure Ulcer	2.20E-03	2.40E-03	8%

Table 2- Average accuracy of the PU BBN model

4. CONCLUSION

Although pressure ulcers are potentially preventable, unfortunately they present a common condition especially among high-risk population such as elderly and patients with impaired physical mobility.

Given the impact of pressure ulcer on healthcare system in terms of prevalence and cost, it is of immense importance that we have tools that can identify patients that are prone to developing of pressure ulcer; models that can realistically and accurately measure the risk of patients for this adverse events. Shortcomings of current approaches to risk assessment of pressure ulcer that have been discussed in this paper, calls for more suitable and effective methodologies and tools. The relationship between pressure ulcer's risk factors and their impact on a patient's risk of pressure ulcer is probabilistic in nature, which makes Bayesian Beliefe Networks a strong candidate to capture these probabilistic relationships and to represent the associated uncertainties.

Using 8 years of clinical data and a team of subject matter experts we have developed, quantified and validated a Bayesian Belief Network, that includes or reflects the factors introduced in literature as factors influencing risk of pressure ulcer. Additionally, factors that the panel of experts thought to be of importance, and missing from the current risk assessment scales, have also been included. The prediction of the BBN model, produces and average of only 8% error, compared to actual field data, which build more confidence in the structure of the proposed model. Access to more reliable data will enable us to further tests the validity of the model.

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